The Employment of Linear Programming as a Means of Refining Emergency Triage: A Quantitative Optimization Model and Case Study of the 2005 Memorial Hospital Crisis

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Senior Honors Thesis

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Abstract

Throughout modern history, the term triage has become synonymous globally with the strategy of delegating limited resources to those who need it most as a means of maximizing survival rates. Around the world, triages have taken many different forms, yet attempts continue to build a standardized model of the strategy more deeply rooted in quantitative analysis. The 2005 Memorial Hospital Crisis that occurred during the landfall of Hurricane Katrina serves as a cautionary reminder of how difficult triage can be to conduct in mass-casualty events, stressing the importance of improving the strategy's refinement and emergency applications further. This paper works to create a quantitative model of how a triage should have operated during the Memorial Hospital Crisis and seeks to improve the strategy itself through linear programming, with explored applications to the 2019-2021 COVID-19 pandemic. This quantitative model suggests an alternative strategy based both in quantitative logic, optimization, and principles of utilitarianism. Going forward, the study hopes to encourage the use of quantitative models in operational decisions within the field of emergency management and aid in discovering ethical ways to optimize human life in times of crisis.

Section I: The History of Computational Triage

The term "triage" is derived from the French word "trier", which means "to sort" or "to choose". The birth of triage as a concept has been traced back to the Napoleonic wars, in which it was employed to determine medically whose life was to be saved in a time of crisis on the battlefield. Initiating primarily as a term used during medical emergencies, the concept of triage has spread throughout the world, and is now used in most every field as an operational strategy. Triage continues to be a procedural strategy employed by many different fields around the world daily as a means for maximizing output and optimizing outcomes. Yet, for such a standardized word, a surprising diversity exists with regards to how a triage is supposed to operate.

While triage holds a necessity of optimization and delegation deep within its core definition, that's about where similarities to more individualized triage systems end. Most triages differ on who should be prioritized and for what reason, with each individual strategy crafted to the individual crisis. This trend stresses how gravely important it is for a triage strategy to fit an individual emergency situation. This allows it to most accurately address the priorities and delegations of the unique scenario. Therefore, even the most accurate of triages itself differs from institution to institution, as there is no set way to address a single crisis. Yet, in each individual triage, the elements of sorting and delegating are prominently consistent, causing many to wonder if standardization of the strategy could be of benefit.

With this in mind, it is important to note that a few examples of standardized triages have existed, most prominently in the medical field[1]. In 1994, Norway developed The Norwegian Medical Index, which intended to create a systematic and consistent operational procedure for which medical crisis scenarios could be addressed. The system became quite popular in Scandinavia and was later used by the medical sectors of both Finland and Sweden. Further triage systems were developed, inspired by this novel index. In 1997, the Manchester Triage scale was created, followed by the Canadian Triage Assessment Scale in 1998, the Australian Triage Score in 2004, and later work in 2006 by the Cape Triage Group. As introductions to

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[1] Robertson-Steel, Iain. Evolution of triage systems. US National Library of Medicine & National Institutes of Health. February 23rd, 2006. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2564046/

more standardized triage began to be explored, the prioritization procedures employed by triage's innate definition began to be explored numerically, as indexes and scales were developed to rank patients based on illness as well as how and when they should be treated. It is with this development that one can begin to see the beginnings of an originally more qualitative notion of triage being interpreted into a quantitative perspective.

With many of these quantitative triage systems arising during the digital age, questions began to arise about how computational systems could provide support in the operational proceedings of a triage, especially within the emergency medical sector. Unlike human error, computational systems would be able to provide an element of objectivity, which to many was an enticing way to remove bias from emergency management situations. In October of 2015, Scott Levin of Johns Hopkins University developed a program called Hopscore[2] which actively worked to conduct a triage ranking system. Much like earlier indexes and scales of its time, the program assessed the intensity of a patient's needed care and assigned individuals a "Hopscore" that determined their level of triage algorithmically. Hopscore follows in the footsteps of earlier quantitative triage indexes, providing healthcare specialists with an idea of who needs the most intensive medical care first. This provides medical professionals with an extensive database of patients who needs what amount of help and how urgently they need assistance.

While Hopscore opened the door to computational triage standardization, the world of quantitative data analysis certainly has more to offer this strategy's processes of ranking and delegation, particularly in the field of optimization. For years, the process of linear programming had been making headway in the worlds of machine learning and artificial intelligence to optimize human choice and the decision-making process. In the following study, I will build upon prior systems of triage ranking and ascertain the most optimal order in which to treat ranked tiers of patients based on a desire to optimize the total number of years lived in a set of patients. In order to do this, I will apply the procedure of linear programming to a triage case study, as well as use life expectancy as a function of age to determine the remaining number of years to optimize in patients. It is with these proceedings that I hope to continue the upward trend of utilizing mathematical modeling and computational data analysis to improve the operational world of emergency triage.

Section II: Background Information: The Memorial Hospital Crisis Triage

In order to better understand how quantitative analysis could improve the strategic decisions of triage, this study intends to apply linear programming and its optimization benefits to a famous case study of triage in recent history: The Memorial Hospital Crisis.

The Memorial Hospital triage made headlines in Fall 2005 when it was uncovered that the institution's medical triage attempting to save the lives of Hurricane Katrina victims employed the use of doctor-assisted euthanasia. Doctors were subsequently taken to high-profile court cases over these claims. While the Memorial Hospital case is famous for its use of euthanasia as a form of 'mercy killing', this act will not be the main focus of the following study (though, it is of course important to condemn the doctor's inappropriate actions, especially since many of these killings were without the patient's consent). This employment of euthanasia within the confines of this analysis will be seen as a failure to uphold the main objectives of triage (and the Hippocratic Oath), which is to optimize the years of human life- something which euthanasia

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[2] Sepulis, Cai. Hopscore Could Make Triage Decisions Easier. Johns Hopkins Medicine. October 1st, 2015. https://www.hopkinsmedicine.org/news/articles/hopscore-could-make-triage-decisions-easier

staunchly opposes. But it leads one to ask: could the triage have been conducted in such a better way that no doctor would even think about euthanasia?

The Memorial Hospital case has been chosen for analysis because it is a situation that this study feels could have benefited greatly from the objective and quantitative analysis that a computational triage system could have provided in times of turmoil. Because the case was high-profile enough to have resulted in much of the events being publicly covered, the situation serves as a uniquely well-recorded case study with extensive available data. To reiterate, because the main objective of a triage is to save life and not euthanize them, having a standardized quantitative model based with this objectivity engrained in its processing applied to the data of said incident could not only help us understand how medical treatment should have been conducted, but also provide us with more information to avoiding future tragedies.

In order to understand how to apply linear programming and quantitative modeling to The Memorial Hospital Crisis, it is first important to understand the triage that was conducted and the manner in which it failed. As Hurricane Katrina made landfall on August 23rd-31st of 2005, the skeleton crew at downtown New Orleans' Memorial Hospital found themselves packed with patients seeking help and medical guidance. The hospital was able to sustain itself during the first few days, but as the situation in New Orleans grew all the more dire, the predicament began to worsen. Unlike prior medical crisis, Memorial did have a large supply of available beds and medicine- two resources that were not plagued with shortages. However, shortages of other resources would develop alongside the crisis as the days continued. On August 29th, the levees in New Orleans broke, flooding the downtown area with more than 20 feet of water. This cause Memorial Hospital's generators to fail, as they were situated on the building's second story floor. The hospital began running on auxiliary generators, which provided the hospital with minimal and insufficient power. It also cut off major water routes to the hospital, leaving staff to boil floodwater for use in everything from cooking to emergency dialysis. In particular, Memorial Hospital was known for its intensive care unit, LifeCare, which sought to resuscitate elderly patients so they could return to nursing facilities in better health. Many of these patients required the use of ventilators and life support systems that were now gravely limited due to the loss of power. As such, the hospital began moving towards an ever-impending shortage of life support systems and ventilators due to the limited access to electricity. Additionally, few doctors and nurses had decided to stay behind and wait through the hurricane itself. As such, the medical crew continued to work vigorously against the clock, with most doctors and nurses unable to obtain any semblance of sleep let alone a break. As the crew began to realize the dire shortages and situation they faced, a triage plan began to develop. The hospital had received word that the National Guard would begin flying patients from the hospital out to other medical centers nearby, and many residents prepared to bring patients (often by hand and physical lifting, as all elevators were no longer operational) to the top floor of the building so they could be airlifted out. However, as the process was quite slow and tedious, it was important for residents to continue treating and saving the lives of patients as much as possible during the time being.

Throughout the difficult hours of The Memorial Hospital Crisis, the building's staff constructed a triage ranking system, not unlike a crude triage index used by other hospitals in times of crisis. In this ranking system, patients labeled as "1's" were in fairly good health, "2's" required more assistance, and "3's" had the highest, most pervasive illnesses. These rankings were written on patients, pinned to their hospital gowns. However, in the memorial hospital triage, this category of '"3's" were planned to be evacuated last whereas "1's" were removed from the building first- a unique inversion of the typical triage in medicine which characteristically treats worse-off patients. In addition, the hospital staff began ranking patients with DNRs (Do Not Resuscitate statements) last, no matter the state of their health or condition. As conditions continued to deteriorate, staff (Led by the direction of prominent Dr. Anna Pou[3]) began to inject some of the worst-off patients with lethally high doses of morphine, which remained in high stock at the hospital. When looking over this generalized triage strategy, some glaring errors become quite apparent. Even in a hope to maximize human life and wellbeing, ignoring the most ill patients entirely seems quite a poor strategy at best to save lives. In addition, the use of euthanasia as mentioned earlier is completely contradictory to the purpose of triage and appears to be merely an escape from the responsibilities of healthcare professionals. Finally, the decision to fly out healthiest patients first seems quite contradictory to the sensitivity and urgency of the situation at hand. It is with these shortcomings in mind that one can begin to determine the faults of this case study's implemented triage, and brainstorm where improvements both in logic and operations can be made. As many of these poor decisions seem to be the result of human error making poor decisions under duress, it is this study's firm belief that a standardized computational triage system would have resulted in a higher survival rate than initially occurred. As such, it is also with this background information that the unique situation arising from The Memorial Hospital Crisis scenario can be ascertained for use of creating a mathematical model.

The Memorial Hospital Crisis as a Data Set

Due to its unique levels of world-wide new coverage[4], the Memorial Hospital Crisis has large quantities of publicly attainable data and review. While court cases surrounding the trials of nurses and doctors alongside many of the medical records are sealed to the public, much of this news coverage[5] can be read and interpreted into the form of a data set. For the purpose of this study, detailed coverage [6]of the Memorial Hospital Crisis was researched and translated it into an appropriate synthetic dataset that the below mathematical linear program could be run on. Much of this information was obtained through use of Sheri Fink's day-by-day walk through[7] of the events in *Five Days at Memorial*[8], which helped to get a good sense not just of how many people were in need of treatment but also how many resources were limited and by how much. In doing so, the study was able to put together a primary dataset, which is available for download by contacting the author of this study.

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[3] Bailey, Ryan. The Case of Dr. Anna Pou: Physician Liability in Emergency Situations. AMA Journal of Ethics. September 2010. https://journalofethics.ama-assn.org/article/case-dr-anna-pou-physician-liability-emergency-situations/2010-09

[4] Deadly Choices at Memorial Hospital. The New York Times. September 11th, 2009. https://www.nytimes.com/2009/09/13/magazine/13letters-t-THEDEADLYCHO_LETTERS.html?login=email&auth=login-email

[5] Saul, John B. 'Five Days at Memorial': 45 Patient Deaths in Katrina's Wake. The Seattle Times. September 8th, 2013. https://www.seattletimes.com/entertainment/books/lsquofive-days-at-memorialrsquo-45-patient-deaths-in-katrinarsquos-wake/

[6] During Katrina, 'Memorial' Doctors Chose Who Lives, Who Died. National Public Radio, Morning Edition. September 10th, 2009. https://www.npr.org/2013/09/10/220687231/during-katrina-memorial-doctors-chose-who-lived-who-died

[7] Fink, Sheri. The Deadly Choices at Memorial. Propublica. August 27th, 2009. https://www.propublica.org/article/the-deadly-choices-at-memorial-826

[8] Fink, Sheri. Five Days at Memorial. Crown Publishing Group.

Through researching the case, this project identified five main variables of limited resources: how difficult it was to transfer emergency patients to be medically evacuated by the National Guard, the amount of available electricity, total hours of care each patient needed, the total amount of water each individual needed, and the amount of food each patient was in need of. As such, these five variables became the main focus of the data set, and later this research project. Historically, the triage began with just around 187 patients still left in the hospital, so this data set profiled values for each five variables for every one of those patients. Life expectancy is also factored into the linear program triage calculations below, and as such an estimation of how many more years a person has to live is also put together by the data set. This estimation is based both on how old the individual is (using life expectancy as a general function of age according to the United States Social Security Office[9]) as well as by any provided medical information about the condition they're being treated for. As such, the data set also contains heavily personalized information about each patient, who they are, their age, and even their medical history as is publicly available. Finally, total levels of each resource's availability are also calculated based on the provided context of the crisis.

While information about the provided crisis was quite detailed, there do certainly exist limitations of the data. For example, much of the personal information behind patient's history and background remains relatively unknown. Furthermore, estimations of total food, power, and water are merely educated guesses based on the context provided by new reports and documented first person accounts. In fact, estimations have been color-coded based on their potential accuracy within the used data set. As triage often involves using resources down to their very last components, it's important to get these values as correct as possible- but because true data surrounding the incident was closed to the public, the dataset remains only an estimate of how the situation could have occurred. Yet, data set still provides the information needed for a linear program to be conducted, modeling the situational constraints of the Memorial Hospital Crisis. By performing this described programming, I hope to ascertain a better survival strategy for the crisis as a whole.

Section III: A Linear Programming Model for the Memorial Hospital Triage

As discussed earlier, linear programming is the process in which variables with a set system of constraints are optimized for maximum output. The following application of linear programming will seek to model the initial Memorial Hospital situation to ascertain a more successful strategy than the one employed by staff members during the crisis. In order to do this, the model will have several components. Because large quantities of data are required, matrices will be used as suitable containers for said information.

The Resources Matrix

As seen in the Memorial Hospital Crisis, various resources needed by patients fluctuated in availability. It is thus important when optimizing years of life to consider how many resources each sorted group and/or individual patients will need in order to survive. The Resources Matrix works to store this information for each limited resource on a patient by patient basis. In this

[9] Actuarial Life Table. American Department of Social Security. https://www.ssa.gov/oact/STATS/table4c6.html.

simplified example, we will be considering four of Memorial Hospital's most limited resources: time, water, food, and electricity in kilowatt hours.

$$A = \begin{bmatrix} 1 & 5 & 9 \\ 2 & 6 & 10 \\ 3 & 7 & 11 \\ 4 & 8 & 12 \end{bmatrix}$$

Fig. 2: *The Resources Matrix A.*
Row 1 represents the first limited resource: time, row 2 represents the Second limited resource: water, row 3 represents the third most limited resource: food, and row 4 represents the fourth most limited resource: electricity. Each individual entry is thus the ith row resource for the jth column individual patient.

In the Resources Matrix A, columns 1 through 3 represent the resource requirements of each of the three patients being considered in this. Then, each of the rows represent how much of one of the four limited resources this individual patient needs respectively.

The Total Values Matrix

In order to accurately understand how supplies can be allocated to patients who are in need, it is important to compile a matrix with the total number of available resources. The following Total Values Matrix can be constructed to represent the original supply shortages present during the Memorial Hospital Crisis.

$$b = \begin{bmatrix} 400 \\ 150 \\ 230 \\ 500 \end{bmatrix}$$

Fig. 3: The Total Values Matrix

To reiterate, this matrix lists the amount of total available resources during a given situation- each of the four rows represents the total quantity of one of the four limited resources. While this example only provides available resource totals for supplies that are in high demand and short supply, it should be noted that real-world examples should include detailed accounts of other supplies that are in high supply as well as this could influence developments in the strategy going forward as the situation develops. In this case, each row of this 4x1 matrix lines up with a row of the Resource Matrix A: row one of b represents the total amount of time, row two the total amount of water, row three the total amount of food, and row four the total amount of electricity. Thus, rows can be designed to represent the limitations of particular resources.

It is important however to note that the total number of available resources may be linked to one another, and it is important to investigate how to translate these real-world linked qualities into data appropriately. In this case, the Memorial Hospital Crisis really began to intensify during a three-day period, spanning a total of 72 hours. However, the total number of hours available for treatment is not 72. Seeing as each individual doctor can offer somewhere in between 0 and 72 hours of treatment during this time span, the total amount of time should be represented as the sum total number of hours each staff member can work within this time period. This way, one is able to accurately represent the total number of hours of treatment (not total number hours in general) of the situation. This provides us with a small example of how interlinked variables should be accurately portrayed in this data simulation.

The Age Coefficient

As the primary goal of a triage is to maximize the number of years of human life, it is also important to take into account the estimated remaining number of years of life (and therefore the life expectancy) of each patient and/or group. The age coefficient serves as the remaining years of life left for an individual patient in the triage. This is a factor especially important to the Memorial Hospital Crisis, as many patients in the "3s" group were elderly individuals from the LifeCare facility who were expected to be nearing the end of their lifespan, and many medical professionals were confused as to how a triage should be conducted around this situation. Many doctors feared spending lots of time and resources on these patients, therefore depriving younger patients with a more substantial portion of their life yet from years lived by delegating LifeCare patients. This model thus incorporates lifespan as the center its optimization calculations.

By utilizing life expectancy rates based on age as catalogued by the United State Social Security Office, this study can provide reliable estimates of how old a patient might live to be based on their current age. To see a graph representing life expectancy as a function of age (the dataset this study relied on as a metric of how many years of life a patient might have), you can view the later section on applications to the COVID-19 pandemic in this study. Life expectancy estimates are divided based on the sex of a patient. If medical information is known about a patient in the linear program, a more personalized life expectancy can be conducted based on the severity of a medical prognosis instead of relying on the life expectancy function as a baseline. Further research and the opinion of a medical doctor can be consulted for this estimate.

$$Life\ Expectancy\ Estimate - Patient's\ Current\ Age = AC_1$$
$$Life\ Expectancy\ Estimate - Patient's\ Current\ Age = AC_2$$
$$Life\ Expectancy\ Estimate - Patient's\ Current\ Age = AC_3$$

Fig. 4*: Calculations for each sorted group's Age Coefficient (AC), which is the estimated life expectancy of an individual patient minus their current age, producing the expected number of years they have left to live.*

Thus, the age coefficients of each patient can be represented as a vector with columns (AC1, AC2, AC3). The age coefficient vector will be multiplied against the negated transpose

The Patient Matrix

When run, the linear programming model of a triage situation should be able to return a binary, with a 1 representing that an individual should receive the resources they need and a 0 indicating a patient's resources shouldn't receive priority. As such, the Patient Matrix can be represented as a mx1 matrix where each entry is the corresponding Age Coefficient calculated for each patient, as seen below.

$$f = \begin{bmatrix} AC_1 \\ AC_2 \\ AC_3 \end{bmatrix} \; and \; \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \le x = \begin{bmatrix} x_1 \\ x_2 \\ x_2 \end{bmatrix} \le \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \; where \; -f^T x \; will\ be\ minimized$$

Fig. 1: *The Patient Matrix f of the Age Coefficients is negated and has its transpose taken before being multiplied by x where rows $x_1, x_2,$ and x_3 represent the individual patients being considered in the triage. The upper bound is 1 and the lower bound is 0 allowing for a binary outcome when the linear program is run. In this linear program, x is what will be maximized. f is being negated because MATLAB's linear programming runs a minimization and a negative being minimized is a maximization.*

The negated transpose of the patient matrix will then be multiplied against x, where each entry will have an upper bound of 1 and a lower bound of zero. It is thus this expression that will be minimized by the linear program (minimization of a negative is maximization, allowing one to maximize the total number of years lived). The transpose of this matrix will also be taken in order to allow for proper dimensional multiplication. This procedure is how the linear program run by this mathematical model was conducted on the simulated Memorial Hospital data set. However, it is important to mention that hypothetically groups of patients could be entered into the linear program instead of just individual patients. In the case of group quantities being used in linear programming, the upper and lower bounds could be changed. For example, if row 1 was a group of 4 patients, then 4 could be entered as the upper bound and 0 as the lower bound: at max 4 people could be given resources and at minimum zero people could be given resources. Patients would ideally be grouped based on need for similar if not identical resource requirements. In this case, f^T x represents the total number of years of life saved that will be maximized.

Optimization Calculations

As discussed earlier, the optimization calculations will be carried out through the MATLAB linear programming function. In doing so, we will compute the optimized values of $x_1, x_2,$ and x_3. In order to understand how this optimization function works, it's important to understand how all the components of this analysis work together. As we can see below, the negative transpose of the Patient Matrix is multiplied against x, which is given a set of binary lower and upper bounds. The constraint of the Resource Matrix A being multiplied against x having to be less than all the values in b is also applied to x under the provided minimization, where $-f^T x$ is the number of years that can be saved that should be maximized.

$$Minimize\ -f^T x\ \ such\ that \begin{cases} A \cdot x \leq b \\ lb \leq x \leq ub \end{cases}$$

$$where\ lb = \begin{bmatrix}0\\0\\0\end{bmatrix}, ub = \begin{bmatrix}1\\1\\1\end{bmatrix}, x = \begin{bmatrix}x_1\\x_2\\x_3\end{bmatrix}, b = \begin{bmatrix}400\\150\\230\\500\end{bmatrix}, A = \begin{bmatrix}1 & 5 & 9\\2 & 6 & 10\\3 & 7 & 11\\4 & 8 & 12\end{bmatrix}, and\ f^{10} = \begin{bmatrix}AC_1\\AC_2\\AC_3\end{bmatrix}$$

…which gives us that…

$$\begin{bmatrix}1 & 5 & 9\\2 & 6 & 10\\3 & 7 & 11\\4 & 8 & 12\end{bmatrix} \cdot \begin{bmatrix}x_1\\x_2\\x_3\end{bmatrix} \leq \begin{bmatrix}400\\150\\230\\500\end{bmatrix}$$

Fig. 6*: A birds eye view of how all the different sections of data interact to supplement a linear programming problem.*

While the above figure works to depict how the many different sections of the linear program interact with one another, one can find the direct MATLAB pseudo-code for this example listed as Appendix 1 of this paper. Upon computing this example, the output is as follows:

$$x = \begin{bmatrix}1\\0\\1\end{bmatrix}$$

This example solution[11] shows us that all the resources needed by patients 1 and 3 should be delegated to them whereas patient 2 should not have their needed resources delegated. This shows clear prioritization of patients 1 and 3 in the triage, as by treating them a professional would be maximizing the total number of possible years of life. However, refusing to delegate resources to patient 2 does not necessarily mean that this individual will die. As summarized earlier, Memorial Hospital was in the process of shipping out patients to other hospitals during their treatment proceedings. As such, this simplified strategy recommends that medical efforts fixate on treating patients 1 and 3 while medically evacuating patient 2 to an exterior medical facility with more resources. It is with this equation that one can ensure the maximum number of lives is being optimized throughout the quantitatively simulated Memorial Hospital Crisis. In some cases, a decimal might result instead of a binary number. These decimals should be delegated in order from largest to smallest value in the following order: all patients of priority 1 should receive the resources they require, followed by patients of largest to then smallest decimal value. Patients of decimal values can be delegated the percentage of their resources indicated by their decimal. For example, a patient with a decimal value of 0.6 could have 60% of their

[10] Reminder that AC_1, AC_2, and AC_3 are actual numerical values being calculated, not variables.

[11] As this is a hypothetical demonstration of the linear triage with no designated numerical age coefficients, the results of the linear program are imagined, demonstrating a point about strategy. Though this exact procedure with numerical age coefficients could be completed to produce accurate results.

resources delegated to them. As such, this decimal can also become a percentage measure of how probable treatment is for a patient. Thus, this example patient has a 60% chance of receiving treatment with 60% of its resources. Should excess resources be left over from prior medical treatments (that perhaps earlier patients ranked as 1s on the binary no longer needed), these resources can be delegated to decimal-ranked patients in the same order as treatment.

Section IV: Results & Discussion

When a linear programming minimization is run on the simulated Memorial Hospital Data Set, a collection of ratings is produced. These ratings correlate to individual patients or groups of patients, displaying how many individuals should be saved. When a singular patient is listed, the result is binary- a 1 represents that the individual should be saved and therefore receive the total number of resources they are in need. A 0 however represents that the individual should not have resources delegated to them. It is possible that a resulting decimal between 0 and 1 could result from the linear program. In this case, the result should first be considered as a 0, and then leftover resources are to be delegated to these non-binary results in an order from highest ranking decimal to lowest ranking decimal. When a grouping of patients is listed, the resulting rating indicates how many people within the group should be saved and therefore receive the total number of resources they are in need of. For example, if the linear program produces a result of 3 for a group of 5 individuals, then 3 of these five individuals should be saved and the others should not have resources delegated to them.

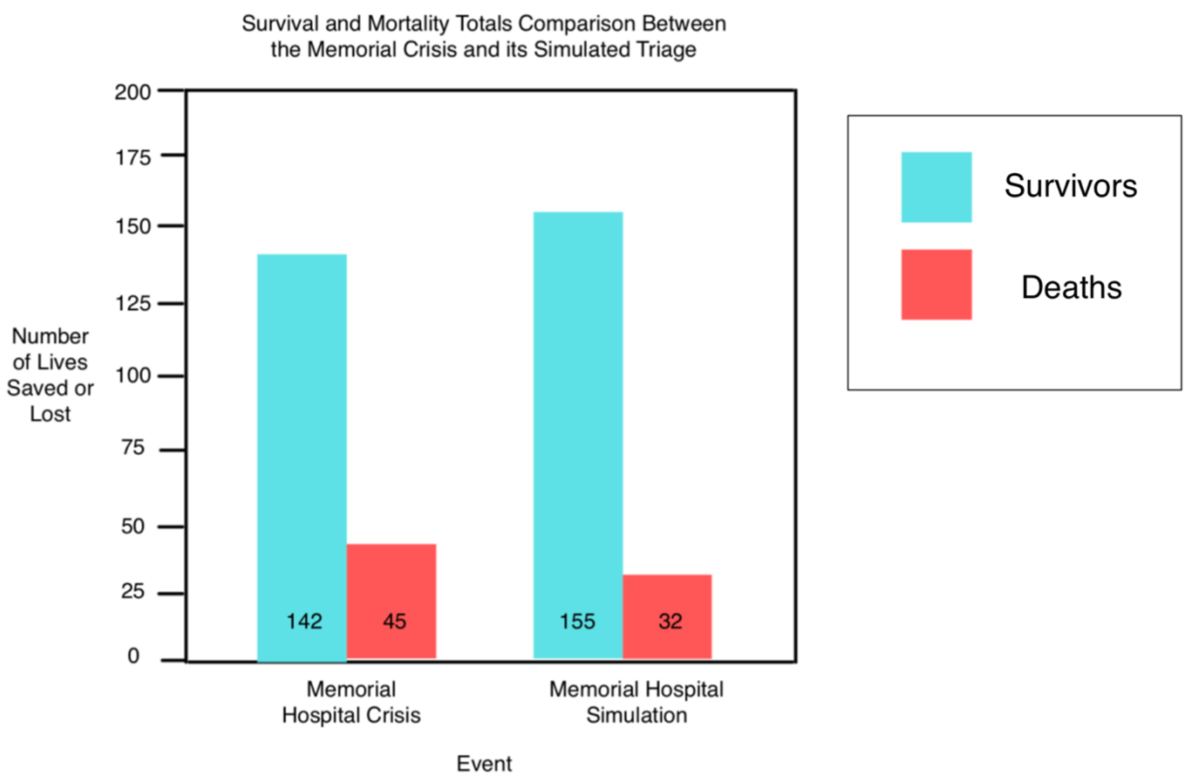

Fig. 7: *The Survival and Mortality Totals Comparison Between the Memorial Crisis and its Simulated Triage*

The simulated Memorial Hospital Data Set took patients into account on an individual level, creating a collection of binary results. As we can see in Figure 7, the simulated linear program did indeed save 13 more individuals who originally died in the Memorial Hospital Incident. This may indicate that linear programming can work to decrease mortality rates amidst disaster scenarios, as there exists a substantial difference in survival rates between the simulation and the resulting historical occurrence. However, it is important to recognize that this simulation is based off of estimated data, and that this total of 13 additional lives saved is arbitrary. The simulated data is distanced from the information of the real-world event, and therefore the quantitative simulation may be quite different from the metrics available throughout the real historic event. Furthermore, there is no public record as to when the 45 deaths occurred. The data set run through the linear program tracks patients stuck in the hospital during the Wednesday through Friday period of the disaster- it is possible that some of these 45 deaths occurred before this time period and therefore prior to the triage even beginning, making these 45 recorded deaths an inflated number.

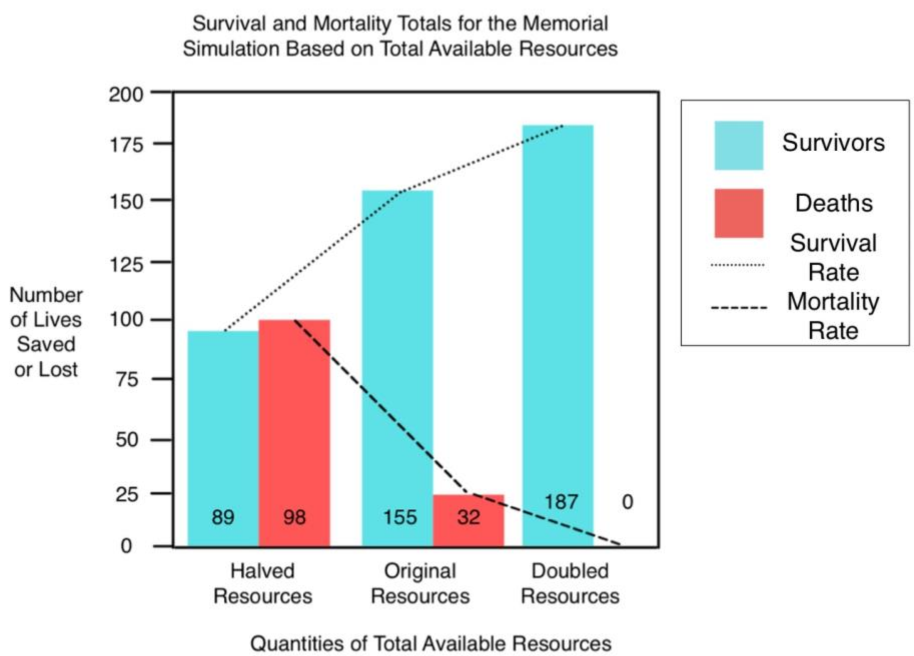

Fig. 8: *Survival and Mortality Totals for the Memorial Simulation Based on Total Available Resources*

As seen in Figure 8, multiple linear programs can be run on the simulated data, exploring how many lives would be hypothetically saved if resources were cut down by half or doubled. As we can tell from the results of these simulations, simply doubling the resources could save all patients in danger. However, halving the resources could increase the mortality rate drastically, causing it to rise past the survival rate. These controlled variations in the simulated data not only show us how varying total quantities of resources effect the mortality and survival rates of patients, but also give us a better idea of how these rates would differ based on estimations of the data set. For example, if the data set is an underestimation of total resources, even more patients could have been saved during the emergency. However, if less resources were available than the data set represents, it might indicate higher fatality rates. Similarly, analysis of the provided outcomes alongside the simulated data set revealed that in fact food by number of calories was the most limited resource, followed closely by total amount of transportation, total amount of electricity, total hours of available care, and finally the amount of available water. These results were obtained by multiplying the equation's binary results per patient by each individual patient's required resources and summing up all these resources, comparing them to the values stored in b as the Total Values Matrix.

Additionally, the ability to iterate through a multitude of simulated triages through repeated linear programming execution exposes the possibility of an additional triage strategy linear programming could provide. Inspired by the simulations in Figure 8, one could hypothetically iterate through all possible multiplications of the total Quantities Matrix to find exactly how many resources would be needed in order to save participants. In a time of emergency, this could become vital as it would allow response teams to request just enough resources as needed to save lives without risking overestimations. After all, overestimations of resources could lead to limitations later down the line or could deplete needed supplies at neighboring hospitals weathering a shortage. This thus shows how linear programming not only helps advise triage strategy, but also aids in communicating to operational leaders just how much of a particular resource is needed in times of rationing.

In closing, it is also important to note that just because a patient doesn't have resources delegated to them doesn't mean they won't be saved, complicating the model and its results further. It is quite possible that other patients will not use all the resources they are delegated, and those remaining supplies can be put towards the use of saving remaining patients. Once again, triage indicates a strategy and procedure with which to save patients, not a determination of who finitely lives and dies.

Section V: The Ethics of Quantitative Triage Models

During an interview on NPR's RadioLab with Memorial Hospital[12] expert and award-winning author of *Five Days at Memorial* Sheri Fink, acclaimed journalist Robert Krulwich famously mentioned how triage "is an impossible piece of human business. Rationing, triage, whatever you call it, is an inhuman act which humans are trying to do, but the fact of their humanity makes it impossible. So what we've got here is a real deep problem- you have a god role, and nobody fits it". Ethical studies on the nature of triage have forever been divided amongst extremes. On one end of triage exists the strategy's ruthlessness; the giving of rations to some and leaving others to die. Yet, on the other end is the philanthropic use of the strategy, as the triage works to spread resources thin throughout a community to those who need it most. Fundamentally, this idea of triage is one that wields a double-edged sword of harm and help, yet still seeks at its very core to make the best of a bad situation. Yet, much like Krulwich accentuates in his discussion, the design of how to create a triage is so ethically unstable that it almost invites human nature to get in the way of decisions.

Inevitably, the inspiration for this study comes from substituting inhuman logic and informational processing into this decision-making situation, to fill such a complicated role. The idea of placing the accountability and authority of these difficult decisions onto a well-built

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[12] Abumrad & Krulwich. Playing God. National Public Radio, Radiolab. August 21st, 2016. https://www.wnycstudios.org/podcasts/radiolab/articles/playing-god

mathematical model seeks to offload the complicated burden of these choices from humanity's shoulders. In addition, the lack of subjectivity in a mathematical model decreases risk of human bias in the decision-making process. In many ways, quantitative systems could seek to prevent human prejudices such as racism[13], homophobia[14], and sexism[15] from interfering with medical treatment- pervasive biases that have been statistically shown to result in poorer care for minorities and women in America. Yet, it would be irresponsible to create such a model without appropriately addressing of the grandiose ethical dilemmas and debates that a system such as this might bring into question. After all, humanity, ethics, and philanthropy are heavily qualitative topics known to most as socially created structures within society- not the ones and zeros of a computational system. Therefore, the creation of such a model begs the question: is it even possible to create a mathematical model that implements notions of ethics to serve in this deemed "god-like" decision-making process?

As established extensively throughout this paper, the main objective of a triage strategy is to maximize the quantity and quality of as many individual's lives as possible. This desire strictly falls under the utilitarian school of thought[16], which claims "the morally right action is the action that produces the most good". From this connection, one can better understand that the morality of any mathematical triage system can be assessed based on its ability to do more good than would arise if the situation played out naturally or furthermore was under human direction. To refine this further, as long as every part of the system is designed to improve the situation and optimize a higher number of favorable outcomes than if the system itself did not exist, it can be seen as an ethically beneficial contribution to society. In order to uphold this standard of ethicality, it is essential that mathematical models of this nature are built to offer every opportunity for optimization that can be feasibly provided in an emerging situation.

Following this utilitarian logic, it is also important to view the unit of one year of life equally across all demographics. The idea that one year of life is more valuable in one person as opposed to another brings about opportunities for bias and prejudice to creep into the system being produced, valuing certain lives over other's- something which not only invalidates utilitarianism's idea of perpetuating more good than bad, but also conflicts with the Hippocratic oath as patients cannot be treated to the best of one's ability if viewed unequally. When discussing ethical dilemmas, it is also important to address the fact that life expectancy often varies by demographic, with minority groups often reporting shorter lifespans. When designing the above system, it's inevitable that one will come face to face with these inequities and consider reporting life expectancy based on demographic. However, I argue that not dividing life expectancy by demographic (and perhaps not even separating it on the basis of sex) might in fact be a built-in mechanism to discourage against discrimination. Disadvantaged populations suffering a shorter lifespan as the result of discrimination will inevitably result in a national decrease of life expectancy when all citizen's lives are averaged together. As such, it is to the benefit of the entire population as a whole to help bolster the survival rates of these

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[13] Carlson, Rosemary. The Racial Life Expectancy Gap in the U.S. April 5th 2021. https://www.thebalance.com/the-racial-life-expectancy-gap-in-the-u-s-4588898

[14] Sheard, Alan. Homophobia in Medicine. November 28th 1998. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1114367/

[15] Roeder, Amy. America Is Failing Its Black Mothers. Winter 2019. https://www.hsph.harvard.edu/magazine/magazine_article/america-is-failing-its-black-mothers/

[16] The History of Utilitarianism. Stanford Encyclopedia of Philosophy. March 27th, 2009. https://plato.stanford.edu/entries/utilitarianism-history/

demographics as a means of increasing their life expectancy estimate in times of triage. Therefore, helping the community with regards to equity becomes a matter of self-preservation, perpetuating cooperation and encouraging altruism within the triage system being designed.

Continually, it is important that systems going forward should be fluid in nature. As situations change and resources vary, it is essential that the system itself can develop to account for said changes, for only then will the predictions and advice of the model be able to accurately advise upon a strategy with which to ensure the most optimal outcome. This malleability towards development can similarly leave room for human ingenuity and design. Perhaps members of an emergency might realize how to bring in more doctors and therefore increase the amount of time and care that can be given to patients in need. The mobility of this system and the dynamic nature of being able to restructure a linear program time and time again allows for large quantities of data to be adjusted due to a situational development in mere seconds, providing a completed and updated strategy that might take hours or longer for human agents to conclude on their own. Needless to say, the root of understanding the ethicality of quantitative triage systems of this nature comes from the notion that this developing system caters to its individual situation. Therefore, the model does not and should not advise in isolation away from reality but is to be created in order to work alongside the human intelligence of many different principle agents.

Section VI: Applications to the COVID-19 Pandemic

As discussed earlier in the paper, the life expectancy of male and female patients can be understood as a function of age based on data provided by the United State Social Security Office, as depicted in the following graph. This proves to be an important point of study as life expectancy estimates play a direct role in the optimizing years of life in the according linear program.

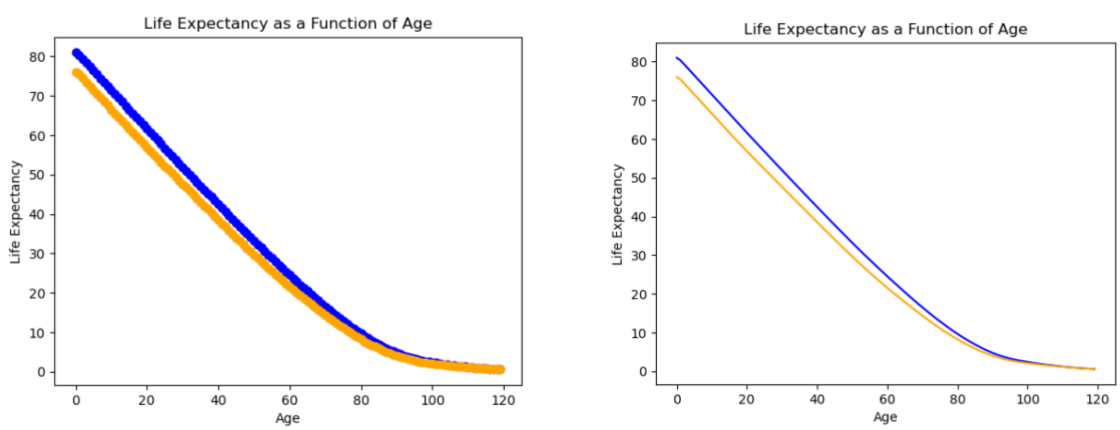

Figure 9: *Life Expectancy as a Function of Age (Blue = Female function, Orange = Male[17]).*

In today's day and age, the COVID-19 pandemic continues to play an active role in not only day-to-day life but also medical short supplies. As deaths continue to rise globally due to the virus, triage is becoming an essential issue with regards to hospital beds and most importantly vaccine distribution. Emergency management specialists continue to study how deaths due to COVID-19 vary by age demographic. As such, an importance arises for studying

[17] Male and Female as assignments of sex, not indicative of a gender binary.

coronavirus death rates as a function of age, as seen in the graph below. The information regarding US-based COVID-19 deaths based on age group has been obtained by the Center for Disease and Control[18]. Furthermore, the death rates have been calculated based on dividing these death totals by the population of a particular age range, found via Statista[19].

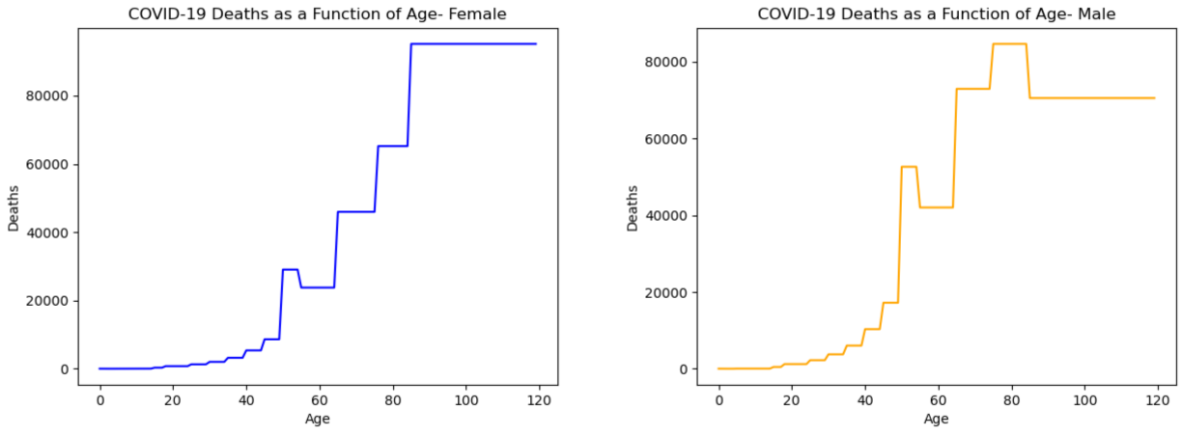

Figure 10: *COVID-19 Death Rates as a Function of Age (Blue = Female function, Orange = Male).*

Current vaccine distributions target patients at highest risk for COVID-19. However, it's important to ascertain what exactly is meant by risk. In this case, the life expectancy of an individual's age can be multiplied against the death rate due to COVID for that same age group, producing a risk metric as suggested by the following formula.

$$Risk\ Metric\ for\ Age\ n = (Life\ Expectancy\ of\ Age\ n) \cdot (COVID\ Death\ Rate\ for\ Age\ n)$$

This risk metric can then be used to assess who is in the greatest danger for death due to the COVID-19 pandemic. As it too is dependent on the age of the individual patient, it can also be graphed as a function of age, as seen in the figure below.

[18] CDC's COVID-19 Vaccine Rollout Recommendations. Center for Disease and Control. March 25 2021. https://www.cdc.gov/coronavirus/2019-ncov/vaccines/recommendations.html

[19] Resident population of the United States by sex and age as of July 1, 2019. Statista. July 1, 2021. https://www.statista.com/statistics/241488/population-of-the-us-by-sex-and-age/

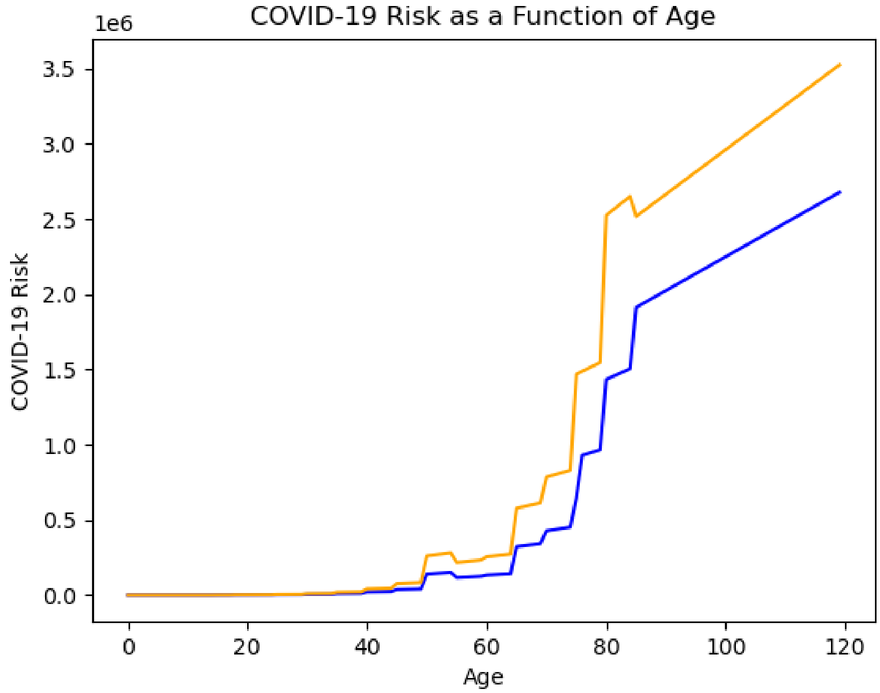

Figure 11: *COVID-19 Risk as a Function of Age (Blue = Female function, Orange = Male).*

As one can see, the risk increases somewhat exponentially for designated age groups until about the late 80s. Following this, the risk tapers off. It is important to realize that this tend occurs because average life expectancy plateaus around this age, and that the number of deaths due to COVID-19 may also decrease as a result of there being fewer living individuals past the mean life expectancy. As such, this graphic demonstrates that the risk for death due to COVID-19 begins to more noticeably rise in patients starting around 50 years of age and leading up until about 100, providing one with an idea about American demographic with the highest risk of potential death due to COVID-19.

As we can tell from early rollouts of the COVID-19 authorization triage, patients of this age range were not in the first category of triage. In fact, first responders and frontline healthcare workers were authorized first; perhaps a strategy to maximize the ability to distribute the vaccine and continue treating critical patients in the first place. However, following these allocations of the virus, patients of 75 years and older were granted access to the vaccine. Next, ages 65-74 have been and/or will be vaccinated, following with all other ages 16-64 with underlying medical conditions and additional essential workers. As we can see, the COVID-19 vaccine distribution did incorporate a strong aspect of triage based on maximizing life and minimizing “death and serious disease as much as possible” (CDC). However, additional strategies regarding maximization of vaccinated healthcare professionals was also a dominant strategy, most likely tied to the ability to carry through the triage in the first place.

Section VII: A Look Forward

Inevitably, there are further improvements that can be made to this model of the Memorial Hospital Crisis as well as the procedure in which linear programming is applied to triage systems. As described earlier in the paper, the data set utilized for the majority of this experiment was one pulled from pre-existing secondary sources of the event, applying statistics and personal accounts documented in public articles and books like *Five Days at Memorial*. The data set currently reflects the faults of its estimations, as limited evidence was available to scrap together a usable collection of quantitative observations to run the linear program on. Within the discrete Memorial Hospital application of this study, the experiment itself could be improved upon by obtaining the actual medical records of all patients involved- something that would require both legal access to the case's depositions as well as HIPPA permission with regards to original medical documents. As this experiment was an undergraduate thesis, many of the qualifications for a prominent study to obtain information of this kind were not met. But if the study were to be perfected later in graduate and post-graduate research, obtaining this data set might be a more viable option, providing a valuable opportunity for improvement. In addition, obtaining this data might also provide one with the chance to get a better estimation on life expectancy due to preexisting medical conditions as well as age. When discussing improvements to the current study, it would also be quite helpful to get a doctor's formal opinion on the life expectancy of each patient based on their given medical conditions; life expectancy as a function of age could be relied upon as a backup in the case one's medical history didn't impede their expected age.

With regards to getting more informed opinions on provided data, I'd also ideally like to speak to operations coordinators at Memorial Hospital to get a better sense of how much electricity per hour was available amidst the crisis. Furthermore, it would be important to get a better sense of how much food, water, and staff existed during the crisis as well as learn more about how difficult it was to transfer patients up to the helicopter landing pad and how much energy life support systems really take. This would have given the experiment a much better perspective on the total number of available resources, only further refining the situation. In the case that the desired data is unattainable, future studies could also implement data refinement procedures such as k-nearest neighbor fold validation, which could produce a larger collection of data based on the smaller batch of more known patients within the estimated data set by predicting how the data might be reflected in a larger capacity. This serves as a strong backup for cultivating an even more refined data set in the face of physical obstacles to obtaining records.

Much of this research's purpose is to provide a standardized platform in which to extract real-time quantitative data analysis for the construction of an operational strategy in times of crisis. While it is an endeavor currently beyond the scope of the project, this study would be interested in working further to produce a software program that could allow for easy manual data entry in order to configure an optimized strategy. This could be placed in hospitals as a way to equip medical centers for necessary operational decisions during a time of crisis. Going forward, it is of utmost importance that this quantitative analysis becomes more easily accessible and useful to the public and healthcare providers. In providing easy access to optimization programming, strategies and plans can be refined further in a multitude of fields which triage plays a role in, creating the potential for more strategic and innovative operational decisions.

Linear Programming and Individualized Treatment

In addition to aforementioned improvements that can be made to the linear programming model itself, one additional mode of analysis comes to mind for consideration. As one can see throughout the model's depiction in this paper, individuals were considered by the triage on a person-by-person basis. However, it was discussed how groups of similar patients could be combined together and triaged as a group. This grouping of individuals on a basis of illness often lessens the possibility for more individualized treatment. Because the medical issues within a given category are being standardized or averaged together, the decisions made about a particular group are less representative of the actual predicaments that individuals face. Because linear programming through use of matrices allows for larger portions of data to be explored, this study recommends the possibility of eliminating the sorting portion of a triage altogether. The Patient Matrix could instead be filled with as many entries as there are participants, each place into an inequality ranging from 1 to 0, as was conducted in this study as opposed to Memorial Hospital's use of grouped patients labeled 1 through 3. In addition, the Resources Matrix could code for each individual patient's needs instead of the generalized needs of a group. Additionally, the exact Age Coefficient could be calculated for each individual and could be attuned to gender. This in many ways would make the Age Coefficient all the more representative, as it wouldn't be averaged or standardized across a large group of people. This procedure of ascertaining individualized treatment using the same linear programming procedure could in many ways refine the model even further, increasing its ability to accurately create operational strategies for emergency situations. Because of its strong benefit, this mode of individualized treatment is an aspect of the research going forward that this study hopes to investigate even deeper.

Section VIII: Conclusions

Triage remains one of the most prominent operational strategies used around the world when navigating crisis and emergency situations. Existing to increase the survival rate of a detrimental situation, a triage looks to optimize both the quantity and quality of human life. This focus on optimization makes triage well-suited to the quantitative modeling process, in which linear programming can provide a tailored way to advise upon how resources and time should be delegated to individuals in need with a hope of saving as many people as possible. The quantitative strategy outlined in the provided study produces a successful and unbiased strategy which could have been employed to the 2005 Memorial Hospital Crisis as a means of saving more lives of those who were originally lost. Guided by the ethical principles of utilitarianism, it looks to improve the way operational decisions are made in times of crisis and hopes to open the door to more quantitative models in emergency management, with possible applications to the 2019-2021 COVID-19 Pandemic.

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Appendix I: MATLAB Pseudocode for Linear Program Execution

>> A = ResourcesMatrix
>> A = A' #A needs to be the transpose of how it was entered into the dataset in order for matrix multiplication to be run

>> b = QuantitiesMatrix

>>f = LifeExpectancy
>>f = -f #linprog in MATLAB naturally runs a minimization linear program, negation allows for a maximization linear program to be run

>>Aeq = [];
>>beq = []; #We do not need Aeq or beq values as defined by MATLAB's linprog linear program function, so we simply define them as empty sets

>>lb = LowerBound #This is the lowest number of singular patients or a patient category i.e. 0
>>ub = UpperBound #This is either a matrix of all ones if there is just a singular patient listed or the maximum number of individuals in a grouping/category. Note that this program would facilitate a combination of singularly and categorically listed patients.

>>X = linprog(f, A, b, Aeq, beq, lb, ub)

[Result from code can be copy and pasted next to patient names/information in order to determine who should be treated with priority. Any decimals below 1 should be viewed first as zeros in initial estimates of survivability, and then treated on priority of highest to lowest decimals]

Appendix II: Guide to Additional Study Materials
Available by a request, made to the study's author.

Memorial Data Set.xlsx – The simulated data set produced from researching the Memorial Hospital Crisis, as well as all data obtained from running the set through the created linear programming model.

covidrisk.csv – The provided data set used to calculate Life Expectancy as a Function of Age, COVID-19 Deaths as a Function of Age, and COVID-19 Risk as a Function of Age.

covidriskgraphs.py - Covidrisk.csv – The provided python code used to calculate Life Expectancy as a Function of Age, COVID-19 Deaths as a Function of Age, and COVID-19 Risk as a Function of Age.

Independent Study Weekly Responses.doc – A document detailing the weekly progress made during 2021 regarding the study's developments (weekly responses from the study's 2020 work is also available