Treatment Planning of Victims with Heterogeneous Time-sensitivities in Mass Casualty Incidents

Nan Liu

Carroll School of Management

Boston College

Joint work with Yunting Shi* and Guohua Wan*

*Antai College of Economics and Management, Shanghai Jiao Tong University

5th Annual Research Roundtable: Data Analytics in Healthcare
Rotman School of Management | University of Toronto

Mass Casualty Incidents (MCI)

- An event which generates more patients at one time than locally available resources can manage using routine procedures (WHO 2007)
  - Disasters (natural or man-made)
  - Terrorist attacks
  - Traffic accidents
  - …

- Emergency response resources are overwhelmed by a sudden jump in demand, making the rationing inevitable

2004 Indian Ocean Earthquake and Tsunami

2008 Wenchuan (Sichuan) Earthquake

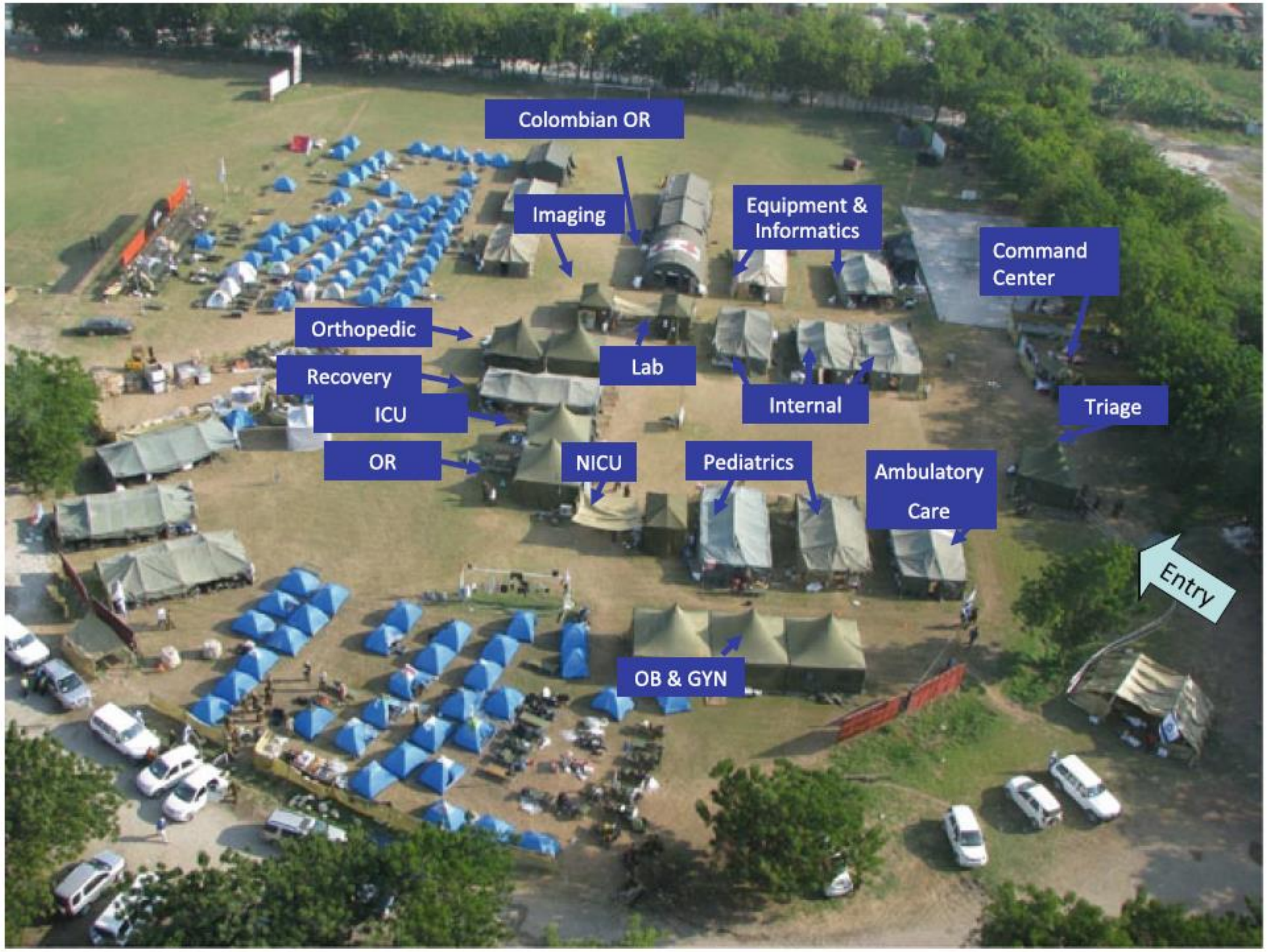
2010 Haiti Earthquake

2020 Aegean Sea Earthquake

Field Hospital

- Temporary medical facilities that take care of casualties on-site before they can be safely transported to more permanent facilities

- To do the greatest good for the greatest number



After the 2010 Haiti Earthquake (Richter scale 7.0), the Israel Defense Forces Medical Corps Field Hospital was launched from a distance of 6000 miles and fully operational on site in 89 hours (Farfel et al. 2011)

Current Practice in Field Hospitals

- Simple triage and rapid treatment (START) is a commonly used triage system in emergency medicine in the US

  - Expectant: victims unlikely to survive --- only palliative care is provided;
  - **Immediate**: victims who require medical attention as soon as possible;
  - **Delayed**: victims who have serious injuries but their status are not expected to deteriorate significantly over several hours;
  - Minor (or "walking wounded") --- waiting to be transported.

Research Question

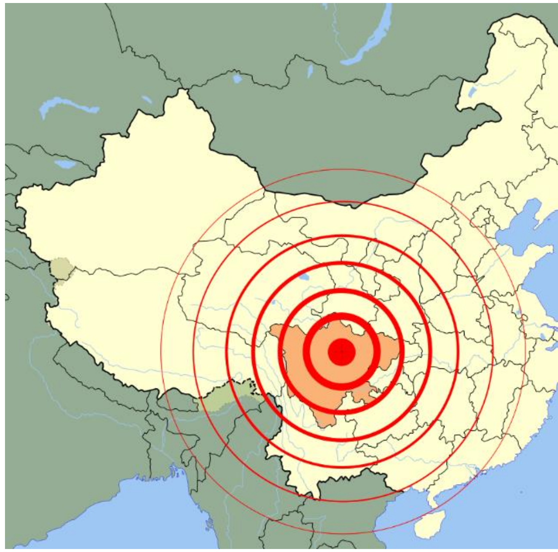
To do the greatest good for the greatest number

- How to schedule (surgical) treatment among those victims admitted?

Agenda

- Exploratory Study: 2008 Sichuan Earthquake
- Model and Key Results
  - Model Extensions & Practical Considerations
- Numerical Study
  - Robustness Test
  - Counterfactual Analysis
- Conclusion

Data from 2008 Sichuan Earthquake



- Struck around 2:28pm local time on May 12, 2008

- Measured at Richter scale 8.0
- One of the deadliest earthquakes to hit China
- The 18th deadliest earthquake of all time in the world

- Over 69,000 people lost their lives in the quake, 374,176 were reported injured, and 18,222 were listed as missing as of July 2008
- The economic loss amounted to over US$ 1.2 billion

- Our data were recorded in a field hospital dispatched by West China Hospital located in Chengdu, Sichuan Province which is about 80km southwest of the epicenter

Data Summary

- 13 surgical teams
- 101 victims
- All surgeries were conducted in the following day of the earthquake
- Data contain surgical sequence, surgical time, type of surgeries
- Data are limited due to challenges in data collection
- Treatment planning on site follows guidelines similar to START (Zhang et al. 2012)

- The data
  - Allow us to investigate whether victims' wait time affects their procedure time, and if so, how
  - Provide a testbed for our model

Data Analysis Results

- Surgical times may or may not depend on wait time.
  - Unstable vs. stable victims

- Among unstable victims, whose surgical time depends on wait time
  - Their procedure times increase in their wait times for surgeries
  - After waiting for some time, delayed patients deteriorate (clinically) and their procedure times increase at a faster rate in their wait times

Model

- Patients arrive at time 0, ready to be operated on

Unstable patients
  - Delayed patients (N^d)
  - Immediate patients (N^i)

Base model – focus of the talk

  - Stable patients, whose procedure times do not depend on wait time

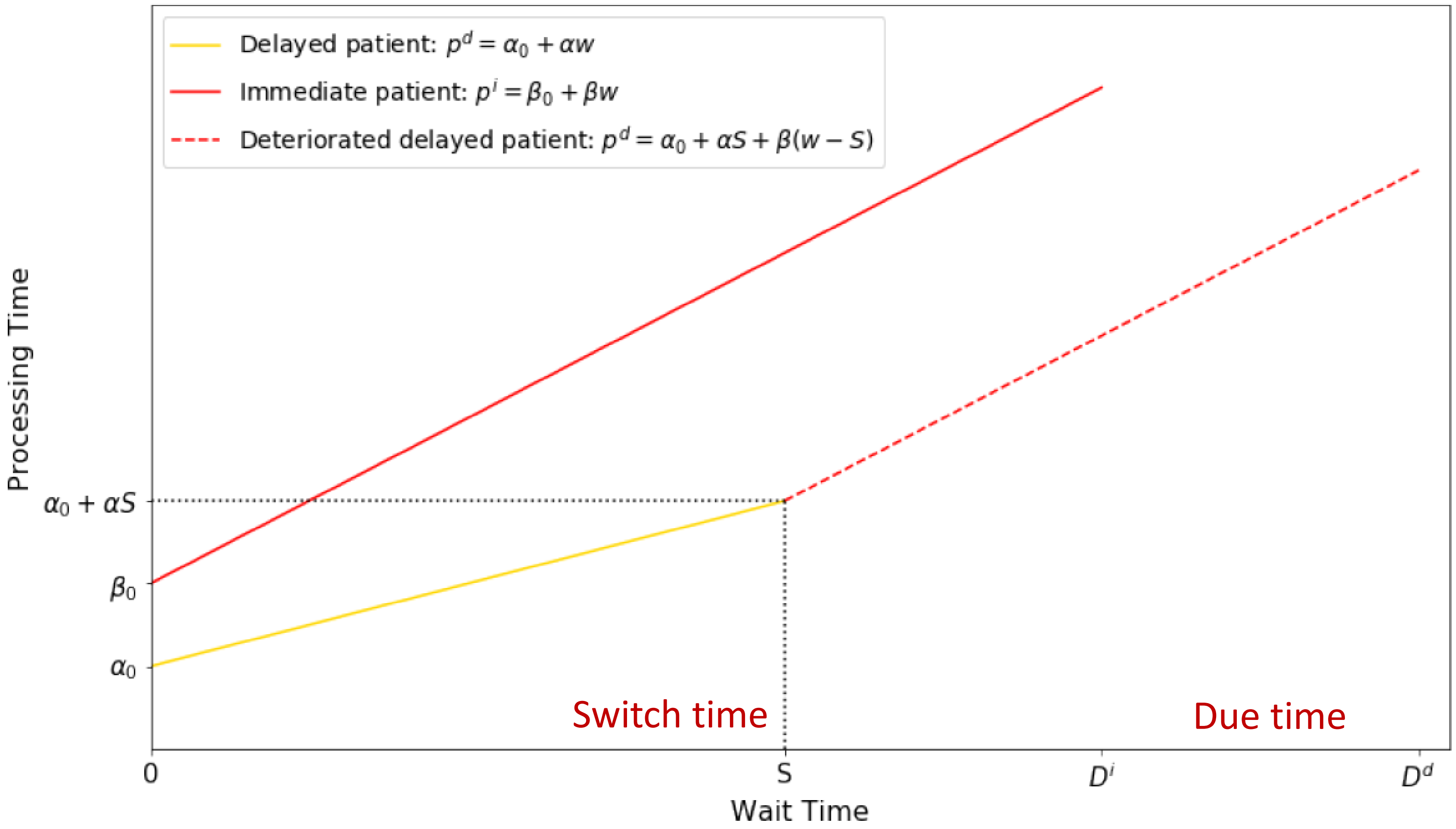
- Surgical time of immediate patients: $p^i(w) = \beta_0 + \beta w$

- Surgical time of delayed patients: $$p^d(w) = \begin{cases} \alpha_0 + \alpha w, & \text{if } w \leq S, \\ \alpha_0 + \alpha S + \beta(w - S), & \text{if } w > S, \end{cases}$$

- Delayed patients <u>deteriorate clinically</u> after the switch time: S $\beta_0 \geq \alpha_0, \beta > \alpha$

e.g., irrecoverable organ damage, amputation …

Base Model cont'd



Delayed patients deteriorate clinically

Input: N^d delayed patients, N^i immediate patients

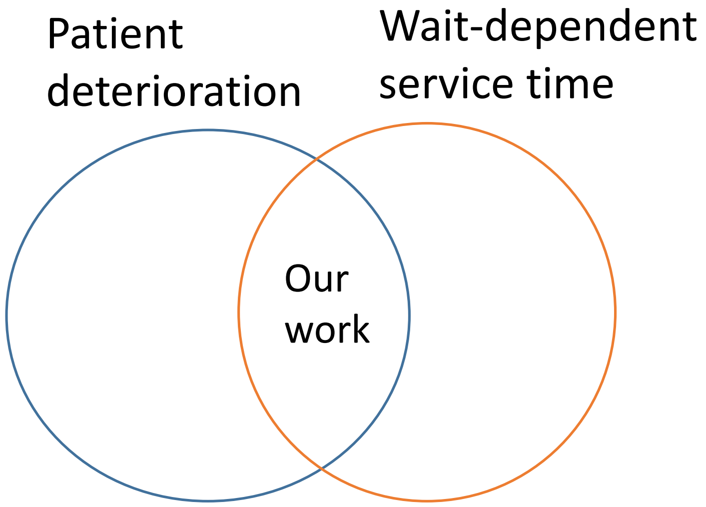
Decision: surgical sequence and start time

Goal: to minimize the number of clinically deteriorated delayed patients, subject to the due time requirements

Interpretation: among schedules which minimize the loss of life, find one with the fewest amputations

(Very) Brief Literature Review

- Resource allocation among patients with heterogeneous health conditions that may deteriorate over time
  - Jacobson et al. (2012), Mills et al. (2013), and Hu et al. (2021)
- Appointment and surgical scheduling
  - See reviews by Cayirli and Veral (2003), Ahmadi-Javid et al. (2017), Gupta (2007), and May et al. (2011)
- Traditional job scheduling
  - Baker and Smith (2003), Agnetis et al. (2004), Leung et al. (2010), Alidaee and Womer (1999), Cheng et al. (2004)



Impact of I2D Ratio on the Optimal Sequence

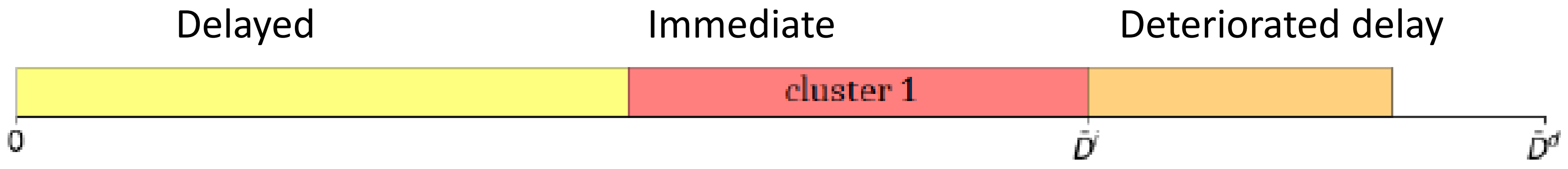
Proposition 1 *(Browne and Yechiali 1990) Consider an scheduling problem* $1|p_j = a_j + b_j w_j|C_{max}$*, where* p_j *is the processing time of job* j*,* $a_j, b_j > 0$ *are job-specific constants, and* w_j *is the wait time of job* j *before its service. The objective is to minimize* C_{max}*, i.e., the makespan. It is optimal to process jobs in an increasing order of the ratio* a_j/b_j*, i.e., a job with a smaller ratio of* a_j/b_j *goes first.*

Initial condition-to-deterioration speed ratio (I2D ratio)

Lemma 1 *Deteriorated delayed victims always have a smaller I2D ratio than immediate victims.*

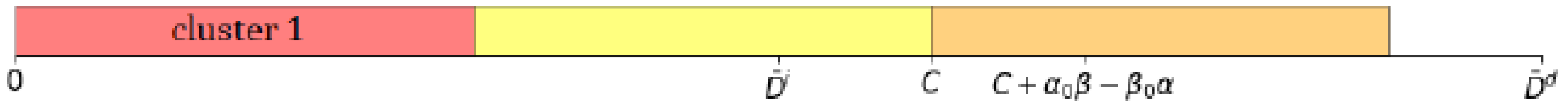
Structure of the Optimal Schedule in Base Model

Delayed patients have a smaller I2D ratio



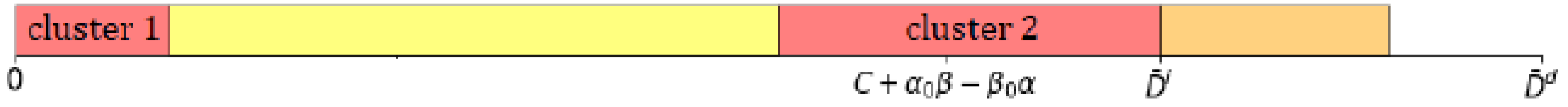
(a) $\frac{\alpha_0}{\alpha} \leq \frac{\beta_0}{\beta}$

Very urgent to treat immediate patients (D^i is small)



(b) $\frac{\alpha_0}{\alpha} > \frac{\beta_0}{\beta}$ and $\bar{D}^i \leq C + \alpha_0\beta - \beta_0\alpha$

Less urgent to treat immediate patients (D^i is large)



(c) $\frac{\alpha_0}{\alpha} > \frac{\beta_0}{\beta}$ and $\bar{D}^i > C + \alpha_0\beta - \beta_0\alpha$

Model Extensions

- A different setting/objective
  - Among schedules with the smallest number of victims served beyond due times, find the one with the smallest makespan
- Delayed patients with a general post-switching time wait sensitivity

$$p^d(w) = \begin{cases} \alpha_0 + \alpha w, & \text{if } w \leq S, \\ \alpha_0 + \alpha S + \rho(w - S), & \text{if } w > S, \end{cases}$$

$\rho \leq \beta$ (in base model, $\rho = \beta$)

- Model with both unstable and stable patients

- In all these extensions, delayed patients may have higher priority than immediate ones in the optimal schedule.

Practical Considerations

- Arrival of a second batch
  - Re-optimize the schedule

- Care coordination among multiple surgical teams
  - Dynamic program to allocate victims, upon arrival, among multiple teams
  - Motivation: # of surgeries per team in our data ranges from 6 to 11

Numerical Study

- Robustness Test
  - We show that even when the procedure time is random, our schedule is mostly on time and if not has fairly limited tardiness.

- Counterfactual Analysis

Counterfactual Analysis

- 13 surgical teams and 101 victims
- Stable and unstable victims with procedure times depending on initial condition and sensitivity to wait time

- Evaluate both the then-implemented schedules (i.e., START policy which always treats immediate patients first) and those generated by our model
  - Team schedule optimization alone
  - Partial coordination
  - Full coordination

Team Schedule Optimization Alone Leads to 32% Reduction in # of Deteriorated and 8% Reduction in Surgical Makespan

	Victim Mix				Original Schedule		Proposed Schedule	
Surgical Team	SD	UD	SI	UI	Makespan (mins)	# of deteriorated	Makespan (mins)	# of deteriorated
A	2	2	1	1	522	0	470	0
B	5	2	2	0	810	3	769	3
C	6	2	1	1	863	4	842	3
D	4	3	1	1	768	3	735	2
E	3	2	2	1	775	3	654	1
F	6	2	0	3	987	5	977	5
G	3	3	1	0	722	1	563	0
H	4	3	1	0	689	2	656	1
I	1	4	1	1	604	1	553	0
J	2	2	1	1	550	0	470	0
K	5	0	0	2	601	1	601	1
L	2	1	1	2	578	1	485	0
M	4	0	1	2	599	1	599	1
Total	47	26	13	15	9068	25	8374	17

SD: stable delayed; UD: unstable delayed; SI: stable immediate; UI: unstable immediate.

Care Coordination Leads to Further Improvement

Load balancing within each of the three "pods"

	Partial Coordination					Complete Coordination				
Team	SD	UD	SI	UI	# of Deteriorated	SD	UD	SI	I	# of Deteriorated
A	4	4	0	0	1	4	3	0	1	1
C	4	3	0	1	1	4	3	0	1	1
F	4	2	1	1	1	4	2	1	1	1
J	3	0	1	3	1	4	2	1	1	1
L	3	0	2	3	2	4	2	1	1	1
B	4	4	0	0	1	4	2	1	1	1
D	3	4	1	0	1	4	2	1	1	1
G	3	2	2	1	1	4	2	1	1	1
I	3	2	2	1	1	4	2	1	1	1
E	7	0	0	0	1	4	2	1	1	1
H	4	3	0	1	1	4	2	1	1	1
K	3	2	2	1	1	2	2	2	1	0
M	2	0	2	3	1	1	0	2	3	0
Total #	47	26	13	15	14	47	26	13	15	11

Load balancing among all 13 surgical teams

44% reduction from original schedule

56% reduction from original schedule

Conclusion

- We develop scheduling models to inform treatment planning in field hospitals, taking into account patient deterioration and wait-dependent service time.
- We identify conditions under which delayed patients have higher (or lower) priority than immediate ones in an optimal schedule.
- We demonstrate that data-driven approaches can significantly improve patient outcomes and operational efficiency in MCI response.
- We suggest that policy makers should pay attention to data and scientific modeling approaches, rather than using intuition and simple heuristics, in emergency response.

A Prototype of Web-based Tool: www.tinyurl.com/mci-rescue

Planning Tool for Patient Treatment in Mass Casualty Incidents

Please enter the information below and click the submit button. This tool provides the optimal treatment schedule. (If no feasible schedules can be found, the webpage will not update after clicking the submit button.)

Immediate patients:

Count: [ ]

Treatment time (in min): [ ] + [ ] * wait time(in min)

Deadline: [ ]

Delayed patients:

Count: [ ]

Treatment time (in min): [ ] + [ ] * wait time(in min)

Switch time: [ ]

Deadline: [ ]

submit

Note
1. Treatment time of a patient is an increasing linear function of his wait time before treatment.
2. Deadline is the time by which patients should finish treatment.
3. Switch time is the time at which untreated delayed patients deteriorate.
4. The objective is to minimize the total number of deteriorated delayed patients, subject to the requirement that all patients finish treatment before their respective deadlines.

Thank you!

Questions?

nan.liu@bc.edu