Simulation models of patient flow in an intensive care unit

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Outline

- Introduction

- The Cardiothoracic Surgical Unit

- The data

- The simulation

- Optimization

- Conclusions

The Cardiothoracic Surgical Unit

The Cardiothoracic Surgical Unit

The system

- 3 operating theatres + 1 for emergencies

- Intensive care unit (ICU) staffs 9 beds, up to 16 available.
    - 1 nurse per patient + 2 runners + charge nurse + 2 on-call nurses

- High dependency unit (HDU) has 6 beds
    - 1 nurse per 2 patients + 1 runner + charge nurse

- 52 beds in wards

The questions

- Initial question – how to minimize waiting lists and maximize number of patients treated?

- First stage – how many beds should be staffed in intensive care to keep cancellations low, assuming number of beds constant?
(Need to employ around 5 nurses per bed.)

- Second stage – given the staffing level, what is the optimal roster and number of electives that should be scheduled?

The data

Data

3,412 admission records Jan 2006 – Dec 2007, earlier data also available

- Admission date and time

- Length of stay (LOS) in minutes

- Type of procedure

- Ward (ICU or HDU)

- Admission type (e.g. elective, acute, medical, vascular)

Additional data on transfers between ICU and HDU, rosters, schedules, elective patients treated...

Cardiovascular Intensive Care Unit (CV-ICU)

Several patient arrival flows

- Acute – emergency patients

- Medical, vascular and other patients

- Electives – scheduled cardio-thoracic surgical patients.

Varying lengths of stay

- 50% of patients leave ICU within 24 hours,
  96% within 1 week
  1% stay longer than 17 days.

- Mean length of stay (LOS) for electives is 41.34 hours,
  mean LOS for acutes is 98.46 hours.

Empirical distribution of length of stay in ICU

N	1502
Mean LOS	54.2 hr
Median LOS	25.1 hr
Coefficient of variation (Cv)	1.49
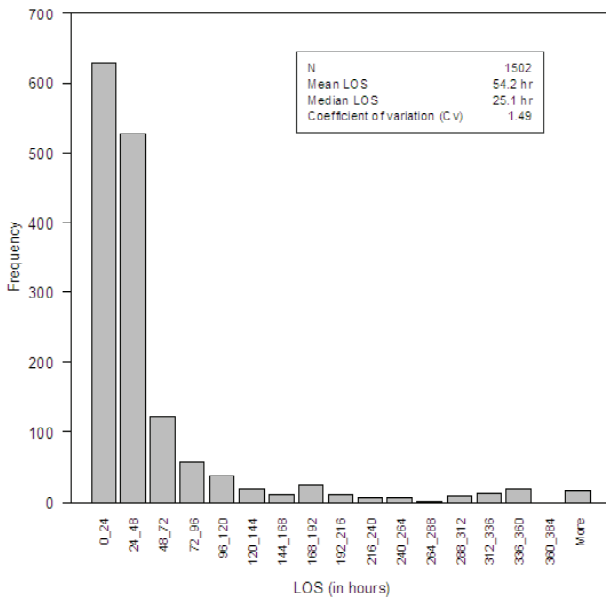
Patients in 2006

Patient	N	Mean LOS	Median LOS	σ
Elective	631	41.34	23.68	60.33
Medical	151	52.27	24.20	72.55
Vascular	95	56.48	21.53	102.67
Non-elective	73	98.46	55.07	137.10
Other	57	90.91	28.55	188.24
Adult congenital	22	32.86	23.36	28.60
Total	1029	50.96	24.08	86.84

The simulation

ICU modelling – analytical model

- A suitable model might be a modified G|G|C|C queue.

- Difficulties in modelling arrivals:-

  - Arrivals vary with time of day and day of week.

  - Arrival rates vary on a faster time-scale than lengths of stay (unlike emergency departments).

- Runners and on-call nurses provide buffer – priority reservation for acute, medical, vascular admissions.

ICU simulation model 24-hour 7-day

- Simulation written in R.

- Simulation splits each day into 5 time periods starting at

  00:00, 7:00, 11:00, 15:00, 19:00.

State of system at beginning of each time period is given by

$$S = (N, \ LOS, \ t, \ \text{shift}, \ \text{day of week})$$

where N = number of patients in ICU
and LOS = residual length of stay for patients in ICU.

- Arrivals

  - Deterministic arrivals of electives on weekdays at 11:00 and 15:00.

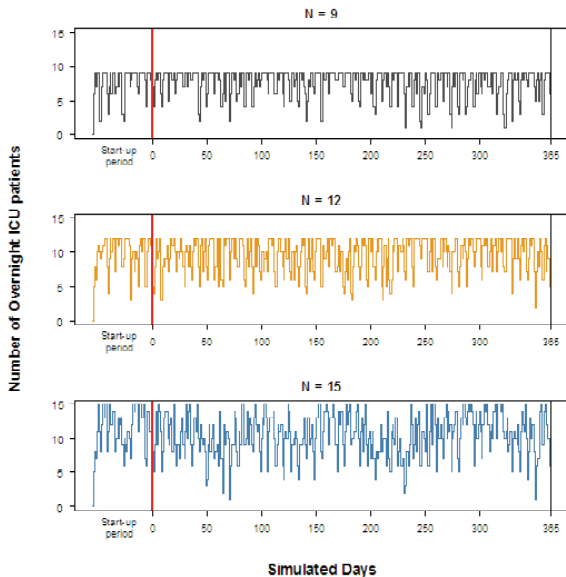 | | Mon | Tue | Wed | Thur | Fri | Sat | Sun |
    |------|-----|-----|-----|------|-----|-----|-----|
    | a.m. | 3 | 3 | 0 | 3 | 3 | 0 | 0 |
    | p.m. | 2 | 2 | 2 | 2 | 2 | 0 | 0 |

  - Other patients arrive as a Poisson process – rate depends on time of day, day of week and type of patient.

- Length of stay in ICU drawn from empirical distribution of lengths of stay.

- Surgery for elective patients is cancelled if a bed is not available.
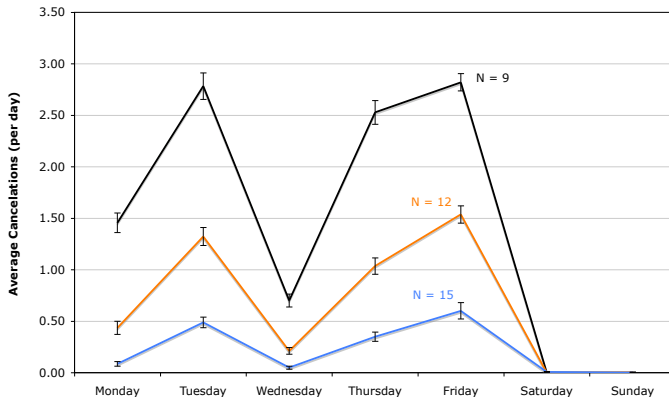
Inputs and outputs to simulation

- Inputs

  - Elective schedule

  - Nursing roster (how many nurses working each time period)

  - Data file containing admission times, discharge times, type of patient

- The simulation gives a wide variety of outputs, including estimates of:-

  - Number of cancellations per week/shift.

  - Number of occupied beds per shift – bed utilisation.

- Number of elective patients treated/admitted per week/shift.
- Number of additional nurses called in per shift.

Simulations of number of occupied beds at 4 pm

Estimated number of cancellations per day

Chart showing Average Cancellations (per day) on the y-axis (0.00 to 3.50) and days of the week (Monday through Sunday) on the x-axis. Three lines: N = 9 (black), N = 12 (orange), N = 15 (blue).

Optimization

What is the optimal roster?

Objective function?

- Minimize number of cancellations.

- Maximize number of electives treated.

- Keep low the number of additional nurses called in.

- A workable roster.

Typical elective operating schedule

	Mon	Tue	Wed	Thur	Fri	Sat	Sun
a.m.	3	3	0	3	3	0	0
p.m.	2	2	2	2	2	0	0

Typical baseline nursing roster, including runners

	Mon	Tue	Wed	Thur	Fri	Sat	Sun
a.m.	8	12	12	11	12	12	10
p.m.	12	12	12	11	12	10	9

Mean cancellation per week 6.66 ± 0.45 (95%CI).

And after searching for improved roster

<div align="center">Starting roster</div>

	Mon	Tue	Wed	Thur	Fri	Sat	Sun
a.m.	8	12	12	11	12	12	10
p.m.	12	12	12	11	12	10	9

Mean cancellations per week 6.66 ± 0.45 (95%CI).

<div align="center">Improved roster</div>

	Mon	Tue	Wed	Thur	Fri	Sat	Sun
a.m.	11	14	12	14	15	10	7
p.m.	12	12	10	11	12	8	7

Mean cancellations per week 2.84 ± 0.30 (95%CI).

Conclusions and further work

- Important to model lengths of stay accurately.

- Rostering changes may reduce cancellations.

- Further work needed on:-

  - Finding improved rosters.

  - Analytical model incorporating time-varying rates.