Tactical and Operational Strategies for Scheduling Elective and Emergency Patients Under Uncertainty

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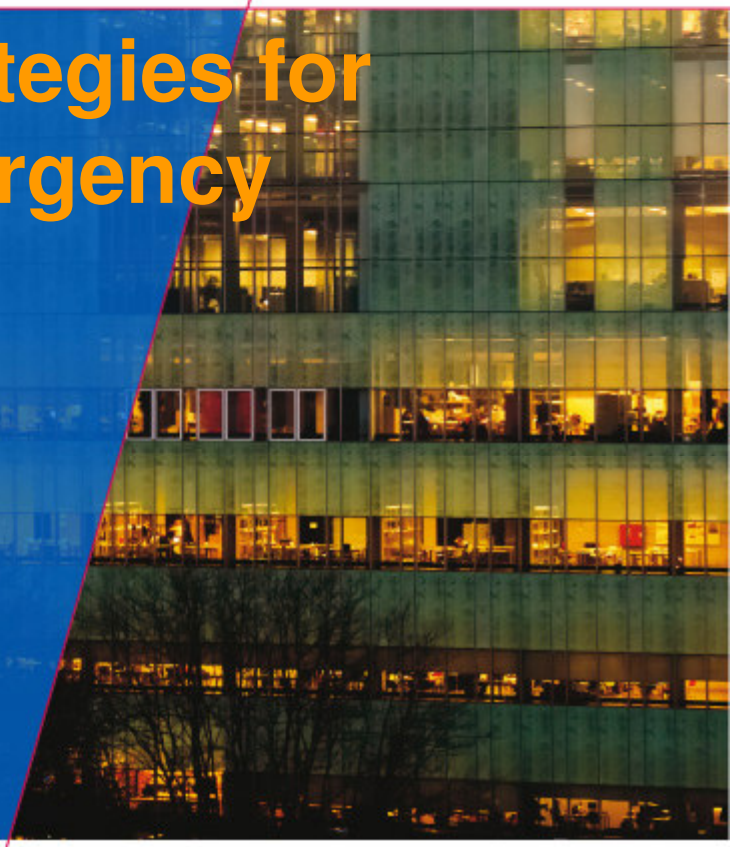

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Where innovation starts

Earlier work on this topic

- First paper by Vissers and Adan, creating cyclical tactical plan for electives, assuming constant Length of Stay (LOS) in IC and MC.
- Second paper by DVA: Developing a platform for comparison of hospital admission systems: An illustration
- Third paper by DVA created tactical plan for electives, assuming stochastic LOS
- Fourth paper by DJ develops an operational plan for electives, with various strategies to deal with deviations from expectations
- All these plans aim at creating a stable reserved capacity for emergency patients

This research

- Uses similar tactical plan for electives as in third paper, but with various capacity levels
- Uses similar operational plan for electives as in fourth paper
- Describes additional rules that are necessary for a good performance:
  - Overtime restrictions for the resources
  - Rules for accepting emergency patients
  - Rules for cancelling planned elective operations
- Tactical plan is based on MIP, operational plan on discrete event simulation

Hospital Planning Problem
Practical illustration

- Type of problem faced by the Thorax Centre Rotterdam where
  - Patients spend 1 day in medium care (MC) unit before operation
  - Patients stay some days in intensive care (IC) unit
  - Patients may stay a few days in MC after recovery

- 8 patient groups, each of them is homogeneous in terms of resources utilization
- 4 resources :
  - Operating theatre (OT)
  - IC beds
  - MC beds
  - IC nursing hours
- Source of uncertainty: each patient group has a random length of stay in MC and IC (probabilities are empirically estimated). Patient arrivals are random (for electives Poisson with a constant parameter, for emergencies parameter depends on period of the week)

Patient Groups, Use of OT and IC and 4-week Volumes elective patients

	patient group	example procedures	operation dur.	IC-stay	average # patients
1	child simple	Closure ventricular septal defect	4	1.1	7.36
2	child complex	Arterial switch operation	8	1.1	9.36
3	adult, short OT, short IC	Coronary bypass operation (CABG	4	1.3	66.00
4	adult, long OT, short IC	Mitral valve plasty	8	1.5	12.73
5	adult, short OT, middle IC	CBAG, with expected medium IC stay	4	1.6	2.64
6	adult, long OT, middle IC	Heart transplant	8	4.0	1.55
7	adult, long OT, long IC	Thoraco-abdominal aneurysm, ELVAD	8	7	0.36
8	adult, very short OT, no IC	Cervical mediastinoscopy	2	0.2	6.91

Patient Groups, Emergency Patients rates

Day	1	2	3	4	5	6	7
(1) Child simple	0.1	0.1	0.05	0.05	0.08	0.06	0.12
(2) Child complex	0.1	0.12	0.15	0.05	0.08	0.16	0.12
(3) Adult, short OT, short IC	0.5	0.7	0.45	0.44	0.5	0.3	0.4
(4) Adult, long OT, short IC	0.1	0.12	0.11	0.09	0.08	0.1	0.12
(5) Adult, short OT, middle IC	0.01	0.02	0.04	0.02	0.02	0.01	0.01
(6) Adult, long OT, middle IC	0.01	0.02	0.03	0.02	0.02	0.01	0.01
(7) Adult, long OT, long IC	0	0	0.01	0	0	0	0
(8) Adult, very short OT, no IC	0.1	0.05	0.05	0.05	0.04	0.06	0.1

- **20 percent arrives during the night**
- **this pattern will be denoted low emergency rate**
- **we will also consider the high emergency rate with doubled values**
- **in practice, emergency rates vary from 20 to 40 percent of the elective rate**
- **this fraction depends a lot on the disease type**

Example: Probability of LOS Post-op MC (Days)

patient group	0	1	2	3	4	5	6	7	8	9	10	>10
1 child simple	0,74	0	0	0	0,02	0,1	0,07	0,05	0,02	0	0	0
2 child complex	0,83	0	0	0	0	0	0,04	0,04	0,02	0,02	0	0,05
3 adult, short OT, short IC	0	0,01	0,01	0,04	0,32	0,24	0,12	0,09	0,05	0,03	0,04	0,05
4 adult, long OT, short IC	0,03	0	0	0,01	0,12	0,16	0,18	0,15	0,1	0,04	0,04	0,17
5 adult, short OT, middle IC	0	0	0	0	0,07	0,07	0,07	0,2	0	0,2	0,2	0,19
6 adult, long OT, middle IC	0	0	0	0	0	0	0	0,14	0	0	0,14	0,72
7 adult, long OT, long IC	0	0	0	0	0	0	0	0	0	0	1	0
8 adult, very short OT, no IC	0,21	0,3	0,08	0,15	0,13	0,05	0	0,05	0	0,03	0	0

Most children return to adjacent children hospital

Similar pattern for IC

Identical patterns for emergencies

The Tactical Hospital Planning Problem

- Objective

  Determine the number of patients of each category to be operated on each day of a 28-day cyclic horizon, so as to:

  Minimize the weighted sum of the deviations of the resources utilization to their target values (over and underutilizations)

- Constraints on the number of patients

  - For each group, the number of operated patients over the cycle must be equal to the target quantities

The Tactical Hospital Planning Problem

We consider three sets of target quantities for planned electives per cycle

Overplanning option	O1	O2	O3	average # patients
(1) Child simple	8	9	9	7.36
(2) Child complex	10	11	11	9.36
(3) Adult, short OT, short IC	67	70	68	66.00
(4) Adult, long OT, short IC	13	15	14	12.73
(5) Adult, short OT, middle IC	3	4	4	2.64
(6) Adult, long OT, middle IC	2	3	3	1.55
(7) Adult, long OT, long IC	1	2	1	0.36
(8) Adult, very short OT, no IC	7	9	8	6.91

- **column O1 is expected arrival number, rounded up**
- **other columns are planning more slots, reducing the waiting time, but also leading to more unused slots (overplanning)**

The Tactical Hospital Planning Problem

By assigning the target quantity of elective patients over the 20 working days of the 4 weeks cycle, we minimize the weighted average deviation from the target use of each of the 4 resources.

The target use of each resource depends on the emergency rate and on the target quantity for electives (so we have 6 sets of targets, in fact all average values)

In general, CPLEX solves this MIP with a gap of less than 3 percent within 10 minutes.

A simple heuristic can do it within seconds and a gap of 10-20 percent.

Example output tactical plan

	Planned patients								Target Deviations			
Category	1	2	3	4	5	6	7	8	OT	IC	ICN	MC
day=1	0	1	5	0	0	0	0	1	0,05	0,42	-0,94	-1,86
day=2	0	0	5	0	0	0	1	0	-0,11	0,49	1,99	-0,47
day=3	0	0	3	2	0	0	0	1	0,52	0,42	11,57	1,03
day=4	0	0	2	2	0	1	0	0	0,63	0,00	8,89	1,09
day=5	0	2	1	1	0	0	0	1	-0,57	0,14	8,38	-0,38
day=6	0	0	0	0	0	0	0	0	0,00	0,08	0,75	-0,60
day=7	0	0	0	0	0	0	0	0	0,00	-0,69	-8,98	0,60
day=8	1	1	4	0	0	0	0	1	0,05	0,46	-0,46	-1,65
day=9	0	0	5	1	0	0	0	0	-0,11	0,35	0,31	-0,78
day=10	0	0	5	1	0	0	0	0	-1,48	0,34	0,50	-0,81
day=11	0	2	3	0	1	0	0	0	0,63	0,15	-1,31	3,12
day=12	0	1	4	0	0	1	0	0	1,43	0,10	0,19	-0,49
day=13	0	0	0	0	0	0	0	0	0,00	-0,51	5,67	1,08
day=14	0	0	0	0	0	0	0	0	0,00	-1,20	-15,10	0,54
day=15	5	0	2	0	0	0	0	1	0,05	0,36	-1,66	-0,49
day=16	0	1	5	0	0	0	0	0	-0,11	0,40	0,91	-1,01
day=17	0	0	5	1	0	0	0	0	-1,48	0,38	0,98	-0,16
day=18	0	0	4	2	0	0	0	0	0,63	0,11	-1,79	0,00
day=19	3	0	2	0	0	1	0	1	-0,57	0,32	-1,46	-0,55
day=20	0	0	0	0	0	0	0	0	0,00	-0,74	2,91	0,27
day=21	0	0	0	0	0	0	0	0	0,00	-1,20	-15,10	3,05
day=22	0	1	5	0	0	0	0	1	0,05	-0,29	-9,46	-0,44
day=23	0	0	5	0	0	0	1	0	-0,11	0,59	3,19	-0,97
day=24	0	0	3	2	0	0	0	1	0,52	0,37	10,97	-0,18
day=25	0	0	2	3	0	0	0	0	0,63	-0,07	8,05	0,38
day=26	0	2	0	0	3	0	0	1	-0,57	0,46	0,22	-0,88
day=27	0	0	0	0	0	0	0	0	0,00	-0,45	1,59	-0,87
day=28	0	0	0	0	0	0	0	0	0,00	-0,83	-10,66	1,44

This tactical plan is the basis for the agenda of the surgeons. Changes lead to 'penalties'.

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Operational Strategy Electives

At the operational level, the number of arriving patients will be fluctuating and the target number to be admitted will not always be available

The number of occupied beds at IC and MC can deviate strongly from expectations

Excess emergencies during the night may use daytime OT

Therefore deviations from the tactical plan are inevitable

Operational Strategies

For the planned admission of patients we will focus on the OT schedule that we obtained from the tactical plan and consider some adaptions to deal with arrival fluctuations:

- Overplanning
- Patient type flexibility
- Cancellation of scheduled operations

We assume that elective patients are assigned to slots 7 days before the operation. Until the morning of the operation, cancellation is possible in case of unacceptably high resource use.

Operational Strategies
overplanning

We modify the target number of patients in the tactical plan

- **(P1) no overplanning**
  Plan the minimum number of patients per group (110 in total in 4 weeks)
- **(P2) overplanning**
  Plan the number of patients per group in such a way that less than 5% have to wait more than 1 cycle according to steady state probabilities(120 in total)
- **(P3) medium overplanning**
  Plan the number of patients per group in such a way that less than 50% have to wait more than 1 cycle according to steady state probabilities(115 in total)

Operational Strategies
flexibility

We can modify the number of patients from the various categories in the tactical plan (while not exceeding the total number of scheduled patients as dictated by the tactical plan):

- (F0) no flexibility

  Cancel the operations for which there is a lack of patients.

- (F1) group change + schedule change

  If the tactical plan suggests on some days more operations than patients for a certain category, plan patients from other categories:

  - Take a patient from a group whose operation is also scheduled that day

  - Take the group with the longest expected waiting time

    - If there is no such patient, then choose longest waiting other patient

- (F2) group change

  As F1, but now operation is cancelled if there is no patient from ‘ right ’group

Operational Strategies
cancellations

Elective patients that are scheduled for operations are cancelled if

- **the expected use of resource r on day t of the schedule exceeds**

$$C_{rt} Cap_{rt}$$

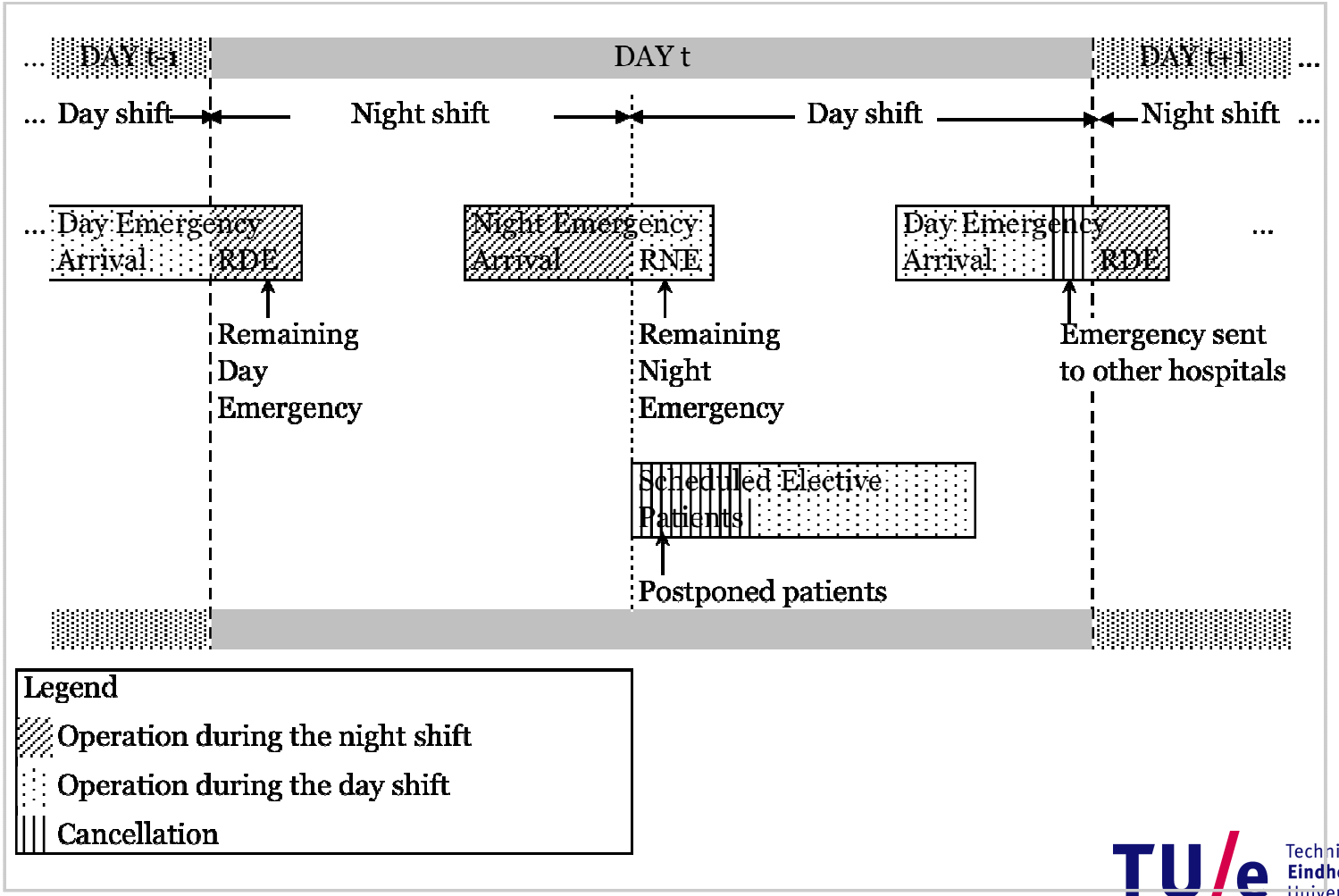
- **we check the expected capacity use by adding patients one by one, the one that leads to overuse is removed**

For emergencies we do a similar check, but parameter choice can be different.

By considering several parameter sets we can influence strongly

- **overtime of resources**
- **number of cancellations**

Operational Strategies
daily routines



Experimental Framework

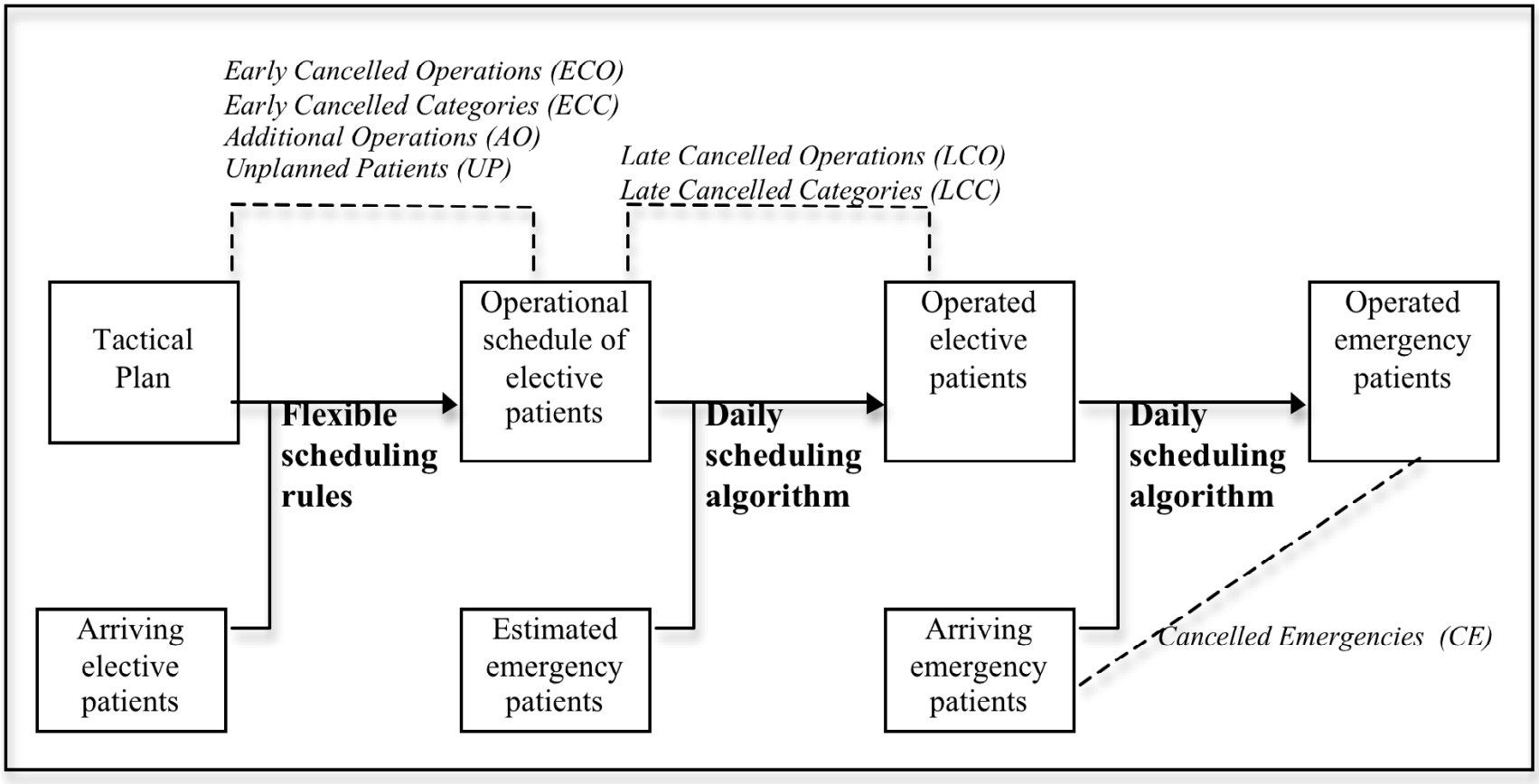
The data

- Stochastic length of stay in IC and MC based on empirical data of 2006 (thorax centre)
- 8 categories of patients and 4 resources
- 20 years simulation of arrivals according to a poisson distribution (with fixed parameter) for each strategy

Performance criteria

- Average waiting time electives (until planning)
- Cancelled electives (early and late)
- Refused emergencies
- Deviations from the schedule (different types)

Plan changes



Results

		(WT) Waiting time	(CE) Cancelled emergencies (%)	(WLCO) Weighted late cancelled operations (%)	(AO) Additional operations of planned categories	(UP) Patients of unplanned categories	(ECO) Early Cancelled Operations	(ECC)+(LCC) Total cancelled categories	(ECC) Early cancelled categories	(DR) Dissatisfaction of elective	(DE) Dissatisfaction of emergency	(E) Exceeding capacities	(SC) Schedule change	(DRE) Dissatisfaction of all patients	(HI) Hospital inefficiency
Demand	**Flexibility**														
high	No (F1)	71.29	16.20	15.63	0.00	0.00	3.36	7.54	3.84	10471	5810	110.59	51.91	16281	8125
high	Intermediate (F3)	31.19	17.86	18.21	7.74	0.00	6.57	9.41	5.59	7012	6402	118.27	77.06	13414	9766
high	Large (F2)	29.82	18.10	19.21	8.30	3.36	7.51	11.43	7.71	7090	6491	121.17	118.05	13581	11961
Low	No (F1)	23.80	6.68	1.23	0.00	0.00	3.28	5.36	5.25	2643	1197	32.71	20.15	3840	2643
Low	Intermediate (F3)	13.25	8.45	2.84	10.82	0.00	9.12	8.48	8.20	1931	1516	40.59	58.15	3447	4937
Low	Large (F2)	11.06	8.52	4.45	12.63	11.43	12.33	14.52	14.12	2058	1527	42.20	198.27	3585	12024
Demand	**Overplan**														
high	No (O1)	71.02	15.34	12.69	2.52	0.18	2.88	5.11	2.24	9815	5501	107.65	45.16	15316	7641
high	Intermediate (O3)	36.18	17.67	17.03	6.40	1.18	5.91	10.57	6.67	7260	6335	115.65	89.50	13595	10257
high	Large (O2)	25.10	19.15	23.33	7.11	1.99	8.64	12.72	8.23	7498	6868	126.73	112.37	14366	11955
low	No (O1)	22.56	6.73	1.40	5.42	2.33	4.99	4.73	4.62	2555	1207	33.02	54.06	3762	4354
Low	Intermediate (O3)	13.59	7.97	2.50	9.12	3.78	8.15	11.10	10.86	1894	1429	38.33	99.14	3323	6873
low	Large (O2)	11.97	8.95	4.61	8.90	5.32	11.59	12.54	12.09	2183	1604	44.16	123.37	3787	8376
Demand	**Exc. Capa. El.** (ρ_{elc})														
high	No (option 1)	55.25	19.11	21.16	4.69	0.80	5.53	9.44	4.95	10049	6851	66.40	82.72	16900	7456
high	Yes (option 2)	27.37	14.81	12.47	6.32	1.59	6.23	9.50	6.86	5404	5311	192.09	81.77	10714	13693
low	No (option 1)	15.64	9.11	3.17	7.80	3.74	8.15	9.41	9.09	2242	1633	20.31	91.62	3875	5596
low	Yes (option 2)	16.64	6.04	2.34	7.84	3.91	8.37	9.53	9.34	2164	1084	65.78	93.05	3247	7942
Demand	**Exc. Capa. Em.** (ρ_{emcy})														
High	No (option 1)	37.92	29.23	17.04	5.72	1.09	5.86	9.50	5.96	7435	10482	21.77	81.44	17918	5161
High	Small (option 2)	40.24	19.67	16.24	5.73	1.47	6.05	9.64	6.30	7497	7052	75.40	84.48	14549	7994
High	Large (option 3)	51.04	9.19	19.44	4.77	0.79	5.56	9.27	5.01	9262	3294	205.41	80.65	12556	14303
Low	No (option 1)	16.22	15.43	2.51	7.87	3.83	8.18	9.55	9.30	2160	2766	7.75	92.63	4926	5019
Low	Small (option 2)	16.33	8.70	2.85	7.73	3.82	8.19	9.43	9.16	2243	1559	29.87	91.98	3802	6092
Low	Large (option 3)	15.68	3.36	3.06	7.88	4.02	8.44	9.71	9.44	2222	602	63.94	95.44	2825	7969

Flexibility

Demand	Flexibility	(WT) Waiting time	(CE) Cancelled emergencies (%)	(WLCO) Weighted late cancelled operations (%)	(AO) Additional operations of planned categories	(UP) Patients of unplanned categories	(ECO) Early Cancelled Operations	(ECC)+(LCC) Total cancelled categories	(ECC) Early cancelled categories	(DR) Dissatisfaction of elective	(DE) Dissatisfaction of emergency	(E) Exceeding capacities	(SC) Schedule change	(DRE) Dissatisfaction of all patients	(HI) Hospital inefficiency
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Low	No (F1)	23.80	6.68	1.23	0.00	0.00	3.28	5.36	5.25	2643	1197	32.71	20.15	3840	2643
Low	Intermediate (F3)	13.25	8.45	2.84	10.82	0.00	9.12	8.48	8.20	1931	1516	40.59	58.15	3447	4937
Low	Large (F2)	11.06	8.52	4.45	12.63	11.43	12.33	14.52	14.12	2058	1527	42.20	198.27	3585	12024

Flexibility brings :

- **large reduction in waiting time**
- **more (early + late) cancelled operations**
- **more exceeding capacities**
- **more schedule changes**
- **in general positive for patient, but more inefficient for hospital**

Low	Large (option 3)	15.68	3.36	3.06	7.88	4.02	8.44	9.71	9.44	2222	602	63.94	95.44	2825	7969

Overplanning

Demand	Overplan	(WT) Waiting time	(CE) Cancelled emergencies (%)	(WLCO) Weighted late cancelled operations (%)	(AO) Additional operations of planned categories	(UP) Patients of unplanned categories	(ECO) Early Cancelled Operations	(ECC)+(LCC) Total cancelled categories	(ECC) Early cancelled categories	(DR) Dissatisfaction of elective	(DE) Dissatisfaction of emergency	(E) Exceeding capacities	(SC) Schedule change	(DRE) Dissatisfaction of all patients	(HI) Hospital inefficiency
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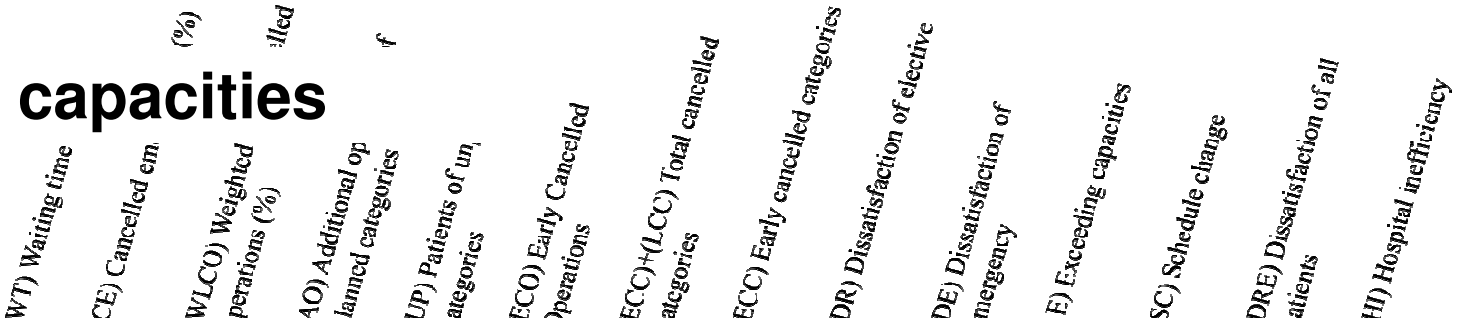
Overplanning brings :

- **large reduction in waiting time**
- **more (early + late) cancelled operations**
- **more exceeding capacities and schedule changes**
- **intermediate overplanning is most positive for patient**
- **overplanning is inefficient for hospital**

Exceeding capacities



Allowing capacities exceeding (6 percent):

- **is only important in case of high emergency demand**
- **big effect on waiting times (positive for electives, negative for emergencies)**
- **big effect on cancelled emergencies**
- **small effect on schedule changes**
- **obvious effect on exceeding capacities**

Demand	Exc. Capa. El. (ρ_{elec})													
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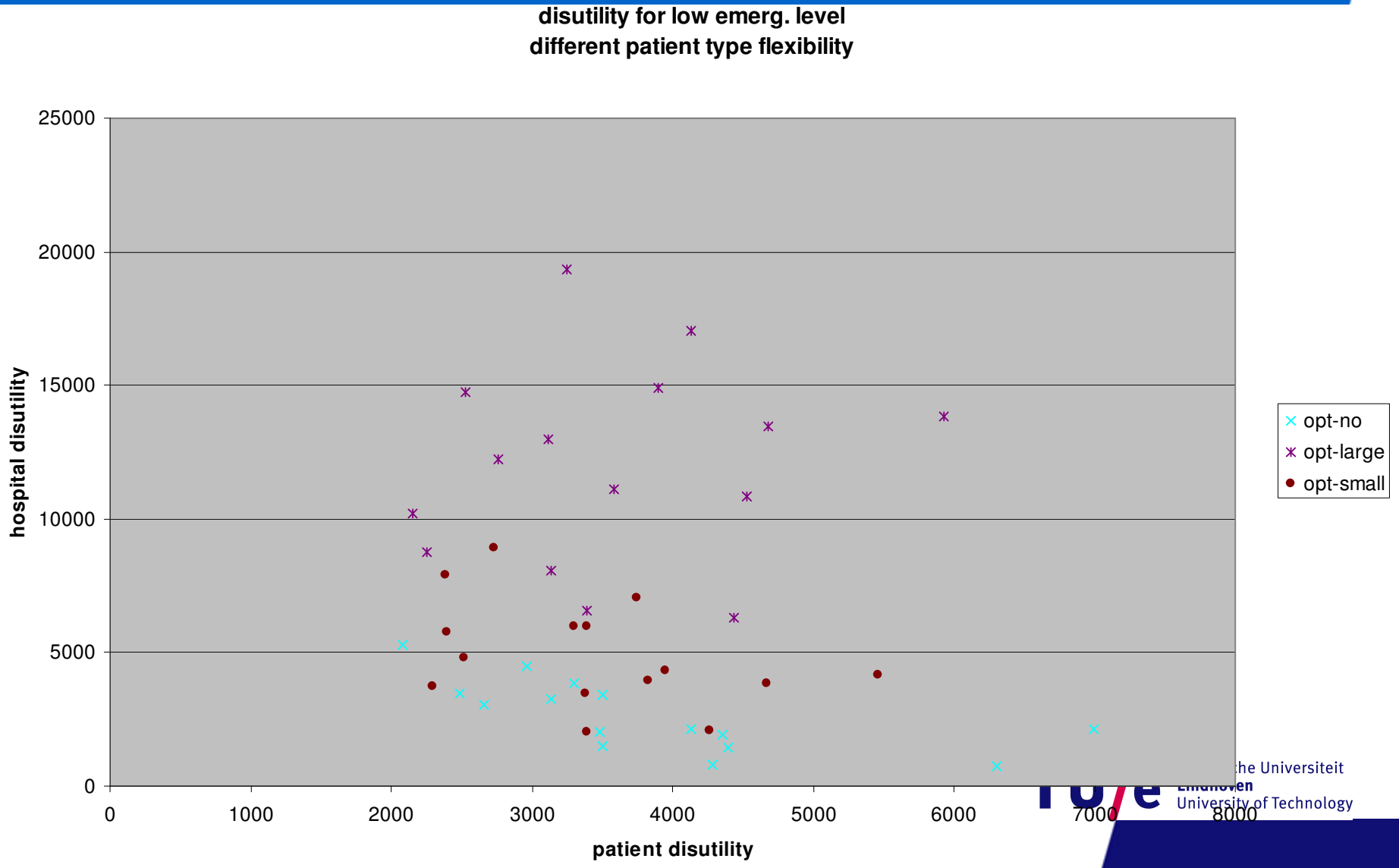
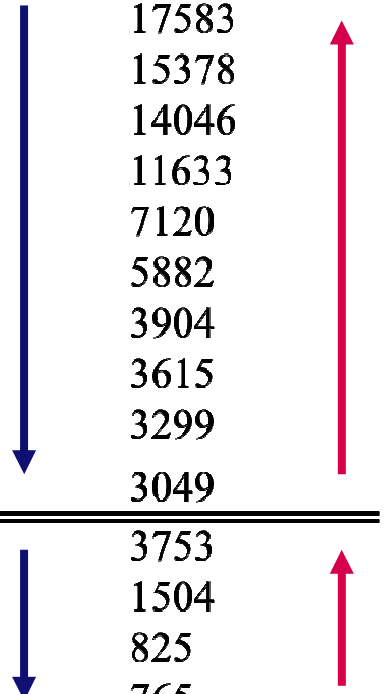
Low	Large (option 3)	15.68	3.36	3.06	7.88	4.02	8.44	9.71	9.44	2222	602	63.94	95.44	2825	7969

Example Flexibility for low emerg. level



Efficient strategies

Demand	Overplan	Flexibility	Exc. Capa. Elective	Exc. Capa. Emergency	Patients Dissatisfaction *(DRE)*	Hospital Inefficiency *(HI)*
High	Intermediate	Intermediate	Yes	Large	8263	17583
High	No	Large	Yes	Large	8650	15378
High	No	Intermediate	Yes	Large	8799	14046
High	Intermediate	Intermediate	No	Large	9974	11633
High	No	Intermediate	Yes	Small	10860	7120
High	Intermediate	Intermediate	No	Small	13426	5882
High	Large	No	No	No	15588	3904
High	No	Large	No	No	15970	3615
High	No	Intermediate	No	No	17057	3299
High	No	No	No	No	22034	3049
Low	No	Intermediate	No	Large	2292	3753
Low	Intermediate	No	No	Small	3507	1504
Low	No	No	No	Small	4288	825
Low	No	No	No	No	6301	765



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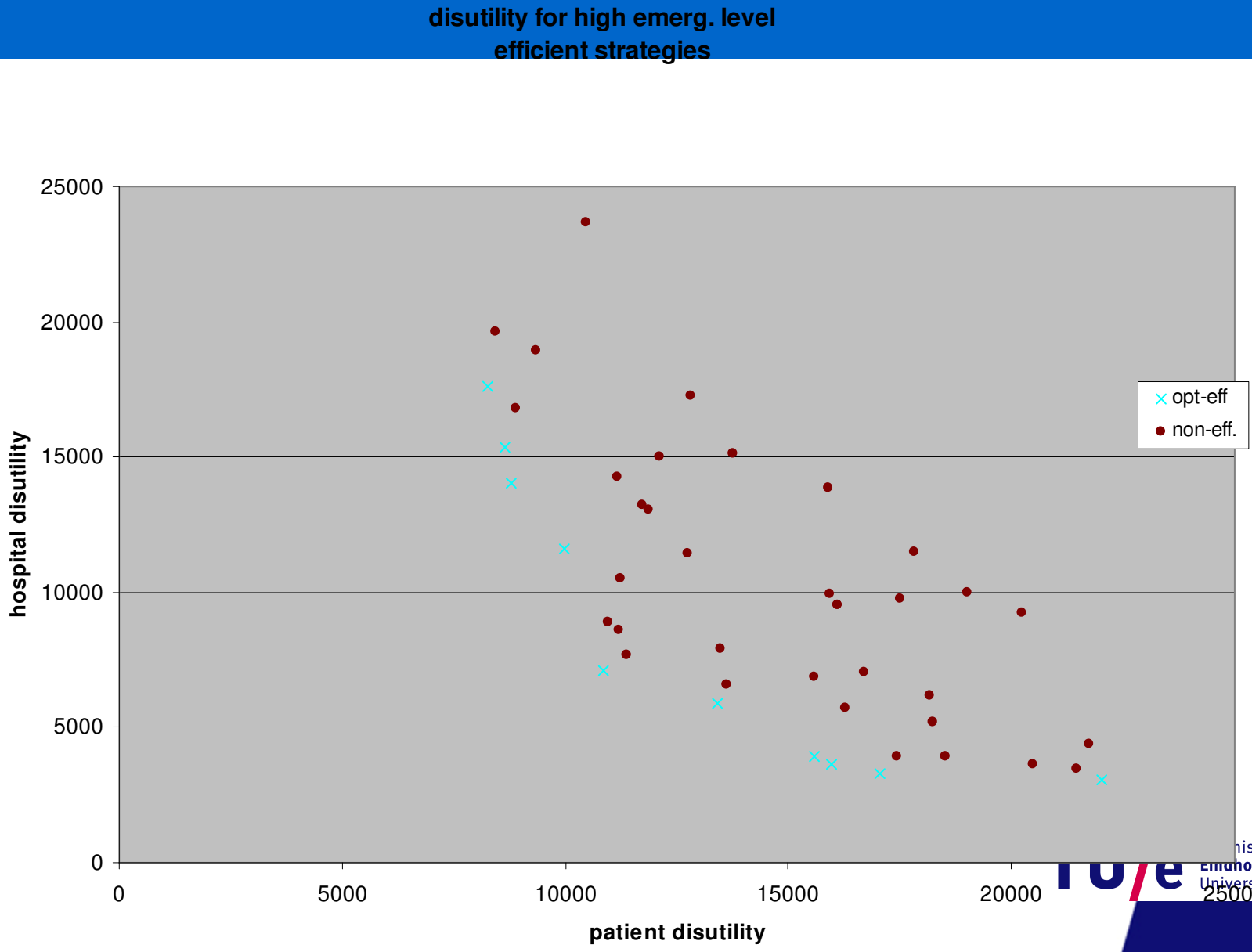
Efficient high emergency demand



Conclusions

For low emergency demand, only limited measures are needed to decrease patients' disutility

They may decrease patients' disutility by 60 percent, however increasing hospital's disutility by 400 %

For high emergency demand, (a combination) of more measures are needed to come to acceptable patients' disutility

Hospital management has to select the best combination to

- position themselves good in the market to attract patients
- have acceptable additional overtime costs
- have a good utilization rate of resources
- have limited schedule deviations for surgeon teams

Conclusions and further work

We created a tool that calculates the patients' and hospitals disutility for numerous strategies and for given patient rates.

For any similar situation, a set of efficient strategies can be selected to offer the hospital management a motivated choice

Future work contains

- conservative patients, for which no operation is required
- comparison with dedicated emergency resources (MMC)
- comparison with other planning methods from literature