Emergency-Divisions Simulation in Support of Service-Engineering: Staffing, Design, and Real-Time Tracking

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Original advisor: Late Dr. David Sinreich (02.02.2007)
Motivation - ED overcrowding

- **Staff (re)scheduling** (off-line) using simulation:
  - Sinreich and Jabali (2007) – maintaining *steady utilization*.

- **Alternative operational ED designs**:  
  King et al. (2006), Liyanage and Gale (1995) – aiming mostly at reducing ALOS.

- **Raising also the patients' view**: *Quality of care*  
  Green (2008) – *reducing waiting times* (also the time to first encounter with a physician).
The rest of the presentation

Part 1: Intraday staffing
   a. In real-time.
   b. Over mid-term.

Part 2: Find an efficient operating model for an operational environment.

Part 3: (if time permits) Long-term benefits of using real-time patients tracking (RFID) in the ED.
Part 1a: Intraday staffing in real-time

Special thanks:
Prof. Shtub, Dr. Wasserkrug, Dr. Zeltyn
Objectives

- [Obtain **real data** in **real-time** regarding current state.]
- **Complete the data** when necessary via simulation.
- **Predict short-term** evolution and workload.
- Proceed with simulation and mathematical models (**Staffing**) as **decision support tools**.

- All the above in real-time or close to real-time
Rambam’s ED admits over 80,000 patients per year:
- 58% classified as Internal.
- 42% classified as Surgical or Orthopedic.

The ED has three major areas:
1. Internal acute
2. Trauma acute
3. Walking.
Research framework and basic ED simulation model

Part 1: Intraday staffing in real-time
Research framework and basic ED simulation model

- Generic simulation tool (Sinreich and Marmor, 2005).
- ED resource-process chart:
Research framework and basic ED simulation model

Part 1: Intraday staffing in real-time
Estimation of current ED state

- **Goal** – Estimate current ED state (using simulating):
  - **Number** of the different types of **patients**.
  - **Patients' state** in the ED process (e.g. X-ray, Lab, etc.)
    [cannot be extracted from most of currently installed IT systems]

- **Data available (problem):**
  - **Accurate data** - taking actual arrivals into account.
  - **Inaccurate data** - taking discharges into account:
    - Hospitalization (no ward immediately available).

- **Method to estimate state at t=0:**
  Run ED simulation from “t=-∞”; keep replications that are consistent with the observed data (# of discharged)
Staffing models:

- **RCCP** (Rough Cut Capacity Planning) - Model aims at **operational efficiency** (resource utilization level).

- **OL** (Offered Load) - Model aims at **operational** and **quality of service** (time till first encounter with a physician).
RCCP - Rough Cut Capacity Planning (Vollmann et al., 1993)

\[ RCCP_r(t) = \sum_i A_i(t)d_{ir} \]

\( RCCP_r(t) \) - total expected time required from each resource \( r \) at time \( t \).

\( r \) – resource type ; \( t \) - forecasted hour ; \( i \) – patient type

\( A_i(t) \) - average number of external arrivals of patients of type \( i \) at hour \( t \).

\( d_{ir} \) - average total time required from each resource \( r \) for each patient type \( i \).

\[ n_r(RCCP,t) = \frac{RCCP_r(t)}{f_s} \]

\( n_r(RCCP,t) \) - recommended number of units of resource \( r \) at time \( t \), using RCCP method.

\( f_s \) - safety staffing factor, e.g. \( f_s=0.9 \) (90%).

We expect RCCP to achieve utilization levels near \( f_s \), but to fail in quality of service. This is remedied by our next OL approach.
In the simplest time-homogeneous steady-state case:

\[ R = \lambda \times E(S) \]

\( R \) - the offered load is:
\( \lambda \) – arrival rate,
\( E(S) \) – expected service time,

The “Square-Root Safety Staffing” rule: (Halfin & Whitt, 1981):

\[ n \approx R + \beta \sqrt{R} \]

\( \beta > 0 \) is a tuning parameter.

This rule gives rise to Quality and Efficiency-Driven (QED) operational performance, in the sense that it carefully balances high service quality with high utilization levels of resources.
Arrivals can be modeled by a **time-inhomogeneous** Poisson process, with arrival rate $\lambda(t); \ t \geq 0$:

**OL** is calculated as the number of busy-servers (or served-customers), in a corresponding system with an **infinite** number of servers (Feldman *et al.* ,2008):

$$R(t) = E\left[\int_{t-S}^{t} \lambda(u)du\right] = \int_{-\infty}^{t} \lambda(u)P(S > t-u)du$$

$S$ - a (generic) service time.
QED approximation for achieving service goal $\alpha$:

$$n_r(OL,t) = R_t + \beta_t \sqrt{R_t}$$

$$1 - \alpha = P(W_q > T) \approx h(\beta_t) e^{-T\mu\beta_t \sqrt{n_r(OL,t)}}$$

$n_r(OL,t)$ - recommended number of units of resource $r$ at time $t$, using OL method,

$\alpha$ - fraction of patients that start service within $T$ time units,

$W_q$ – patients waiting-time for service by resource $r$,

$h(\beta_t)$ – the Halfin-Whitt function (Halfin and Whitt, 1981),
Offered Load methodology for ED staffing

- **∞ servers**: the simulation model is run with “infinitely-many” resources (e.g. physicians, or nurses, or both).

- **Offered Load**: for each resource \( r \) (e.g. physician or nurse) and each hour \( t \), we calculate the number of busy resources (equals the total work required), and use this value as our estimate for the offered load \( R(t) \) for resource \( r \) at time \( t \). (The final value of \( R(t) \) is calculated by averaging over simulation runs).

- **Staffing**: for each hour \( t \) we deduce a recommended staffing level \( n_r(OL, t) \) via the formula:

\[
\begin{align*}
    n_r(OL, t) &= R_t + \beta_t \sqrt{R_t} \\
    1 - \alpha &= P(W_q > T) \approx h(\beta_t) e^{-T \mu \beta_t \sqrt{n_r(OL, t)}}
\end{align*}
\]
Our simulation-based methodology for short-term staffing levels, over 8 future hours:

1) Initialize the simulation with the current ED state.
2) Use the average arrival rate, to generate stochastic arrivals in the simulation.
3) Simulate and collect data every hour, over 8 future hours, using infinite resources (nurses, physicians).
4) From Step 3, calculate staffing recommendations, both $n_r(RCCP,t)$ and $n_r(OL,t)$.
5) Run the simulation from the current ED state with the recommended staffing (and existing staffing).
6) Calculate performance measures.
Simulation experiments – current state (# patients)

n=100 replications, Avg-simulation average, SD-simulation standard deviation, UB=Avg+1.96*SD, LB=Avg-1.96*SD, WIP-number of patients from the database

Comparing the Database with the simulated ED current-state (Weekdays and Weekends)
Simulation experiments – current state (index)

Simulation performance measures - current staffing

Utilization:
- $I_p$ - Internal physician
- $S_p$ - Surgical physician
- $O_p$ - Orthopedic physician
- $N_u$ - Nurses.

Used Resources (avg.):
- #Beds – Patient’s beds,
- #Chairs – Patient’s chairs.

Service Quality:
- $%W$ - % of patients getting physician service within 0.5 hour from arrival (effective of $\alpha$).

<table>
<thead>
<tr>
<th>Hour</th>
<th>$I_p$</th>
<th>$S_p$</th>
<th>$O_p$</th>
<th>$N_u$</th>
<th>#Beds</th>
<th>#Chairs</th>
<th>$%W$</th>
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Simulation experiments – staffing recommendation

Staffing levels (present and recommended)

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<thead>
<tr>
<th>Hour</th>
<th>n (Current)</th>
<th>Offered Load</th>
<th>n (OL)</th>
<th>RCCP Load</th>
<th>n (RCCP)</th>
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<td>I_p, S_p, O_p, N_u</td>
<td>I_p, S_p, O_p, N_u</td>
<td>I_p, S_p, O_p, N_u</td>
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<td>17-18</td>
<td>I_p, S_p, O_p, N_u</td>
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<td>I_p, S_p, O_p, N_u</td>
<td>I_p, S_p, O_p, N_u</td>
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### Simulation experiments – comparisons

#### Part 1: Intraday staffing in real-time

OL method achieved good service quality: \( %W \) is stable over time.

RCCP method yields good performance of resource utilization - near 90%.

<table>
<thead>
<tr>
<th>Hour</th>
<th>Ip</th>
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Simulation experiments – comparisons

Part 1: Intraday staffing in real-time

Comparing RCCP and OL given the same average number of resources

The simulation results are conclusive – OL is superior, implying higher quality of service, with the same number of resources, for all values of $\alpha$. 
Part 1b: Intraday staffing over the mid-term

Special thanks: Dr. S. Zeltyn
Mid-term staffing: Results

%W (and #Arrivals) per Hour by Method in an Average Week (α = 0.3)
Conclusions and future research

- We develop a staffing methodology for achieving both high utilization and high service level, over both short- and mid-term horizons, in a highly complex environment.

- More work needed:
  - Refining the analytical methodology (now the $\alpha$ is close to target around $\alpha = 50\%$).
  - Introducing constrains into our staffing methodology.
  - Incorporate more detailed data (e.g. from RFID).
Part 2: Fitting an efficient operational model to a given ED environment

Special thanks: Prof. B. Golany
Current practice: Priority queues at the ED are based on patients' urgency and illness type (e.g. Garcia et al., 1995).

Problem: No account of operational considerations, e.g. relieving over crowding by accelerating discharges (SPT).

Managerial solution: To use ED structure in order to enforce operational considerations:

- Illness-based (ISO)
- Triage
- Fast Track (FT)
- Walking-Acute (AC)
ED design - Illness-based (ISO)

Wrong ED placement
Wrong ward placement

Patient Arrival

Admission

“Hospital”

ED Area 1
ED Area 2
ED Area 3

Patient Departure
ED design - Triage

Patient Arrival

“Hospital”

Triage

ED Area 1

ED Area 2

ED Area 3

Patient Departure
ED design– Fast Track (FT)

* operational criteria (short treatments time) – acute or walking patient
ED design – Walking Acute (WA)

Part 2: DEA

Walking Area

Room1 → Room2

Acute Area

ED Area 1 → ED Area 2

Patient Arrival → Admission

Walking Area Acute Area

Patient Departure

“Hospital”

Wrong ED placement
Wrong ward placement
Data Envelopment Analysis (DEA)

- DEA is a mathematical technique for evaluating relative performance (efficiency).
- CCR is the basic model (by Charnes et al., 1978) that calculates relative efficiencies of complex systems with heterogeneous inputs and outputs.
- Decision Making Units (DMU's): compared systems / subsystems (e.g. Hospital X working in operating model Y at month Z).
Data Envelopment Analysis (DEA)

- Including uncontrolled inputs (Banker and Morey, 1986), Equation *

\[
\begin{align*}
\text{Outputs} & \quad \sum_{j=1}^{s} w_j y_j - \sum_{k=1}^{t} u_k z_k \\
\text{Uncontrollable inputs} & \quad \sum_{i=1}^{r} v_i x_i \\
\text{Efficiency} & \quad \max \theta_0 = \frac{\sum_{i=1}^{r} v_i x_i}{\sum_{j=1}^{s} w_j y_j - \sum_{k=1}^{t} u_k z_k} \\
\text{Controllable inputs} & \quad \sum_{i=1}^{r} v_i x_i \\
\text{s.t.} & \quad 1 \geq \frac{\sum_{j=1}^{s} w_j y_j m - \sum_{k=1}^{t} u_k z_k m}{\sum_{i=1}^{r} v_i x_i m}, \quad m = 1, \ldots n \\
\text{weights for outputs} & \quad w_j > 0, \quad j = 1, \ldots s \\
\text{weights for controllable inputs} & \quad v_i > 0, \quad i = 1, \ldots r \\
\text{weights for uncontrollable inputs} & \quad u_k > 0, \quad k = 1, \ldots t
\end{align*}
\]
Objectives and structure

- Goal: Identify the “best” (most efficient) ED operating strategy, via simulation and based on real data, to match an operational model with a given operational environment.

- Contents:
  - ED Design (EDD) methodology
  - Available Data
  - Parameters
  - Results
1. Prepare model data (Golany and Roll, 1989):
   - Select DMUs to be compared.
   - List relevant efficient measurements, operational elements, and uncontrollable elements influencing ED performance.
   - Choose the measurements and elements that would enter the DEA model by:
     - Judgmental approach (I).
     - Statistical (correlation) approach (II).

2. Evaluate the model:
   - Compare the methods (Brockett and Golany, 1996).
   - Identify the uncontrollable elements (Environment) that determine the operating methods to reach an efficient system.
Identifying a preferred policy from available options (originally for 2, in Brockett and Golany, 1996):

I. Split the group of all DMUs \((j = 1, \ldots, n)\) into \(k\) programs consisting of \(n_1, \ldots, n_k\) DMUs \((n_1 + n_2 + \ldots + n_k = n)\). Run DEA separately (e.g. Equation *).

II. In each of the \(k\) groups separately, adjust inefficient DMUs to their “level at efficiency” value by projecting each DMU onto the efficiency frontier of its group (e.g. by changing the controllable inputs at Equation *).

III. Run a pooled (or “inter-enveloped”) DEA with all the \(n\) DMUs at their adjusted efficient level (again like in Equation *).

IV. Apply a statistical test to the results of III to determine if the \(k\) groups have the same distribution of efficiency values within the pooled DEA set (or is it varies according to different uncontrollable parameters).
### Available Data

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<thead>
<tr>
<th>Hospital</th>
<th>Start Date [Month-Year]</th>
<th>End Date [Month-Year]</th>
<th>Operating Model</th>
<th>Average Monthly Patient Arrivals</th>
<th>ED Scale</th>
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<td>5700</td>
<td>Medium</td>
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# Enriching data via simulation

## Part 2: DEA

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<th>Hospital</th>
<th>Month Arrivals</th>
<th>3000 – 5000</th>
<th>5000 – 7000</th>
<th>7000+</th>
<th>Represented Operating model</th>
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Choosing parameters (output)

- **Countable1W**: Number of patients who exit the ED (excluding abandoning, deaths, ED returns after less than one week) (2,699-7,576 ; 5,091).
- **Countable2W**: Same as Countable1W but with two weeks (2,586-7,306 ; 4,906).
- **Q_LOS_Less6Hours**: Total number of patients whose length of stay is reasonable (2,684-8,579 ; 5,580).
- **Q_ALOS_P_Minus1**: Average length of stay (ALOS), to the power of -1, multiplied by the average number of hours in a month (119-445 ; 276).
- **Q_notOverCrowded**: Total number of patients who arrived to the ED when the ED was not overcrowded (more patients than beds and chairs) (2,388-8,368 ; 5,290).
Choosing parameters (Controllable inputs)

- **Beds**: Number of bed-hours available per month (840-2,573; 1669).
- **WorkForce**: Number of “cost-hours” per month (physician’s hour costs 2.5 times nurse’s hour) (10,900-35,914; 18,447).
- **PatientsIn**: Total number of patient arrivals to the ED per month (2,976-8,579; 5,717).
- **Hospitalized**: Total number of patients hospitalized after being admitted to the ED per month (541-2,709; 1,496).
- **Imaging**: Total “imaging-costs” ordered for ED patients per month (1,312-14,860; 2,709).
Choosing parameters (Uncontrollable inputs)

Age:
- **Child**: Number of patients under the age of 18, arriving to the ED during a month (95-1,742 ; 611).
- **Adult**: Ages 18-55 (1,429-5,728 ; 3,178).
- **Elderly**: Ages over 55 (728-3,598 ; 1,914).

Admission reason:
- **Illness**: Number of patients with admission reason related to illness, arriving to the ED during a month (1,853-6,153 ; 3,775).
- **Injury**: Reason related to injury (779-3,438 ; 1,849).
- **Pregnancy**: Reason related to pregnancy (0-16 ; 3).
Arrivals mode:
- Ambulance (157-1,887 ; 795).
- WithoutAmbulance (2,679-7,416 ; 4,921).

Additional information:
- WithLetter (1,624-6,536 ; 3,741).
- WithoutLetter (803-3,651 ; 1,976).
- OnTheirOwn (786-3,579 ; 1,952).
- notOnTheirOwn (1,744 - 6,576 ; 3,765).

Type of treatment:
- Int (1,431 - 5,176 ; 3,062).
- Trauma (378 - 4,490 ; 2,655).
Choosing participating parameters via correlation

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Results – comparing ED designs

Part 2: DEA

Conclusion: no dominant design across all data
Identifying models that are more efficient in a given operational environment (interactions)

Part 2: DEA

Child

Elderly
Identifying models that are more efficient in a given operational environment (interactions)

Part 2: DEA
Identifying models that are more efficient in a given operational environment (interactions)

Part 2: DEA

Ambulance

WithoutLetter

Average Efficiency

FT
ISO
Triage
WA
Identifying models that are more efficient in a given operational environment (CART)

**Conclusion:**
Elderly is the most influential parameter for choosing an operating model
Conclusion and future research

- There is no dominant operating model for all ED environments.
- EDs exposed to high volume of elderly patients, are most likely to need a different lane for high-priority patients (FT model).
- Other EDs (Low volume of elderly patients) can use a priority rule without the need for a distinguished space for high priority patients (Triage model).
- When Triage and FT are not feasible options (e.g. no extra nurse is available for Triage or place for FT), it is recommended to differentiate lanes for Acute and Walking patient (WA).

**Future Research:**
- Adding operational models (e.g. Output-based approach and Specialized-based approach).
Part 3: long-term benefits of using real-time tracking (RFID) in the ED

Special thanks:
Prof. Shtub, Dr. Wasserkrug, Dr. Zeltyn
(M.D. Schwartz – ED Manager, Tzafrir – IT Head)
Part 3: RFID

Goal

Present a multi-stage methodology to evaluate the potential benefits of introducing RFID technology, supported by examples of its application (operational, clinical, financial).
Step 1: Define required process changes

- We established a team of **physicians**, **operations managers**, and **IT experts**, at Rambam.
- We proposed **requirements** sorted into three categories: **operational** (reducing ALOS), **clinical** (high level of care), and **economical** (reducing abandonments without pay).
- We identify three process for evaluating the methodology:
  1. Left without being seen (/ pay).
  2. Long queues in the X-Ray.
  3. Long queues in the CT.
CT: Implementing an alerting RFID system that helps reduce unnecessary waiting times, after a CT scan:

- the time a patient completes his/her CT scan,
- the time the patient has the CT scan results,
- the patient's waiting time in excess of 10 minutes. (same with X-Ray)

Using patients' RFID that prevents unregistered patient's abandonments, thus enhancing the hospital payment collection:

- patient tag is near the hospital gate,
- tag removed by non-approved personal.

Two technologies to compare: Passive and Active
Considering all three aspects (clinical, economical, operational), one is lead to prefer the **Passive RFID technology** which, in our context, yields the best overall performance (smaller ALOS, and less physician needed). Other hospitals might choose differently depending on specific preferences (for example, extra income from non-abandonments could be higher that the cost of adding physicians).
Thank you for your attention!