Universidad de Monterrey

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Departamento de Ingeniería, División de Ingenierías y Tecnología
Universidad de Monterrey, México
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Bachelors in:
- Industrial Eng.
- Management Eng.
- Mechanical – Manager Eng.
- Mechatronics Eng.
- Electronic Tech. & Robotics Eng.
- Computational Technologies Eng
- Animation and Digital Effects
- Civil Eng.

~1500 undergraduate students

Master programs in
- Industrial and Systems Eng.
- Product Eng.
- Engineering Management

Departments
- Mathematics & Physics
- Engineering
- Civil Engineering
- Computational Sciences

~120 graduate students
DIT at a glance

- 50 Full time professors
- 96 part time professors
- 16 SNI researchers
- ~420 class groups offered
- >4.6: EvaProf
- 25: Av. Group size
- >97%: Professor attendance
- 58% students graduated with International experience

DIT’s Research in 2017

- Peer review papers: 38
- Diffusion papers: 11
- Conference participations: 83
- Non academic participations: 20
- Books and Book chapters: 7
- External funded projects: 12
- Extension: 6 ($1.5mdp)
- Patents: 4
Jenny at UDEM

- 2 years
- Optimization area: Linear programming and Operations research courses + Design of experiments
- Advisor: 4 Final projects: all of them awarded in international conferences
- SNI since 2016

Recent / Current research
- Eco-driving
- Driving cycles
- Logistics & scheduling
- OR in Health care
- Sustainable routing

• 4 papers in peer review journals
• 5 conference proceedings
• 2 papers under review

Research with M. Gulnara at EAFIT
- 2 conference proceedings
- Ambulance relocation – in process
- Clustering + Rich VRP – In process
A Comparison of Ambulance Location Models in Two Mexican Cases
A Comparison of Ambulance Location Models in Two Mexican Cases

Contents

- Motivation
- EMS: Emergency Medical Services
- Optimization Models: DSM, ARTM, MEXCLP
- The two cases: Monterrey and Tijuana
- Numerical experimentation and Results
- Conclusions
Motivation

- Location of bases for ambulances: Strategic decisions of EMS planning.
- Vast literature: Most of them about European operating conditions. Also in Japan, US, Canada,
- Very few studies in LA: Mexico, Brazil, Colombia
- Mexican situation: Many options to locate them.
- Latin America: No much available data on service quality
Research questions

For the case cities:

- How is the service quality of EMS compared to international standards?
- Which discrete ambulance location model performs better?
- What would be the best configuration, given available resources?
- What suggestions arise for a future dynamic (real-time) location and relocation ambulance system?
EMS: Emergency Medical Services

- The process
- Brief review
- Performance indicators
- Some standards
EMS: Emergency Medical Services

Comparison of Location Models. Díaz, J., Granda, E., Villarreal, B., Frutos, G., 2018

Triage & dispatch
Call arrival
Ambulance assigned
Ambulance departure
On scene time
Arrival at patient
Departure From scene
Travel time to hospital
Handover time
Arrival at hospital
Ambulance available
Travel time To base
Ambulance At base

2 min 4.84 min 1.22 min 12.04 min 15.50 min 21.66 min 49.94 min 18.41 min
σ =7.42 σ =2.78 σ =9.83 σ =16.45 σ =17.62 σ =108.52 σ =34.89

Carranza et al, 2017
Sample taken in sept, 2017.
Mexican Red Cross, Monterrey

van den Berg, 2016
Review on Location Models


Uncertainty:
- demand,
- availability of EMS vehicles, and
- response times.

Main KPIs:
- Response time,
- single, double or multiple coverage,
- preparedness level.

Fig. 1. A classification of discrete location problems.
Performance indicators

Response time

år RTT in US: 9 min
   (most common RTT)* [1]
år RTT in UK: 8 min for most critical calls.

Real
år Tijuana, Mexico:
   ART: 14 min, $\sigma = 7$ min [3]
år Monterrey, Mexico:
   ART: 19.10 min, $\sigma = 12.62$ min. [4]

Covering

A given % demand covered within X min

år Usually 10 min, 15 min or 8 min**
år Once or twice or more times.

år 95% call <10 min (The EMS Act of 1973, in [5])
   US Real: 90% life-threatening calls in < 9min.
år UK Std: 75% most critical calls in < 8 min;
   UK Real: 65-75% in 3 cities. [6]
år Germany Std: 95% life-threatening calls in < 15 min; all non life-threatening calls in < 30 min. [6]
år Japan Real: < 5min once: ~60%, twice:~10%, <10 min twice: ~80% [2]

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* RTT: Response Time Threshold
** US National Fire Protection Association's recommendation
[1] (Aringhieri et al., 2017)
[2] (Limpattanasiri, 2016)
[3] (Dibene et al., 2017)
[4] (Garranza et al., 2017)
[5] (Li et al., 2011)
Optimization Models

• DSM
• ARTM
• MEXCLP
Coverage, double coverage and response time illustration

100% coverage in $r_2$:
- Min: 2 bases
- 2 or 3 or 4 & 7 or 9
- or: 1, 2, 3 or 4 & 7

100% coverage in $r_1$:
- Min: 3 bases
- 4, 8 or 9 & 0

min response time:
- 1 base: 7
- 2 bases: 3, 9
- 3 bases: 3, 8 & 0

Li et al, 2011
Some common notation

Sets:
- $i \in I$: demand zones $\{1,2,3,\ldots,D\}$
- $j \in J$: potential bases $\{1,2,3,\ldots,p\}$
- $k \in K$: ambulances $\{1,2,3,\ldots,A\}$
- $s \in S$: service types $\{1,2,3\}$
- $t \in T$: time slots $\{1,2,3,\ldots,T\}$

Variables:
- $y_{ikt} = \begin{cases} 1 & \text{if demand point } i \text{ is covered } k \text{ times at time interval } t, \text{ within } r_1 \\ 0 & \text{otherwise} \end{cases}$
- $x_j = \begin{cases} 1 & \text{if a base is open at location } j \\ 0 & \text{otherwise} \end{cases}$
- $u_{jt} = \text{Number of identical ambulances assigned at base } j \text{ at time } t.$
- $Z_{DC} = \text{Weighted double coverage}$

Parameters:
- $\alpha$: Minimal coverage in $r_1$ (%) 
- $W_{its}$: Weighted demand in zone $i$, for service type $s$, at time $t$
- $v_j$: Maximum number of ambulances at location $j$
- $a_{ij}^1 = \begin{cases} 1 & \text{if location } j \text{ covers demand point } i \text{ within } r_1 \\ 0 & \text{otherwise} \end{cases}$
- $a_{ij}^2 = \begin{cases} 1 & \text{if location } j \text{ covers demand point } i \text{ within } r_2 \\ 0 & \text{otherwise} \end{cases}$
**DSM: Double Standard Model**

**Sets:**
- $i \in I$: demand zones $\{1, 2, 3, \ldots, D\}$
- $j \in J$: potential bases $\{1, 2, 3, \ldots, p\}$
- $k \in K$: ambulances $\{1, 2, 3, \ldots, A\}$
- $s \in S$: service types $\{1, 2, 3\}$
- $t \in T$: time slots $\{1, 2, 3, \ldots T\}$

**Variables:**
- $y_{ikt} = \begin{cases} 1 & \text{if demand point } i \text{ is covered } k \text{ times at time interval } t, \text{ within } r_1 \\ 0 & \text{otherwise} \end{cases}$
- $x_j = \begin{cases} 1 & \text{if a base is open at location } j \\ 0 & \text{otherwise} \end{cases}$

\[
\begin{align*}
\text{max } Z_{DC} &= \sum_i \sum_s \sum_t (w_{its} y_{i2t}) \\
\text{Subject to:} \\
\sum_j a_{ij}^2 u_{jt} &\geq 1 \quad \forall i, t \\
\sum_s \sum_i w_{its} y_{i1t} &\geq \alpha \sum_s \sum_i w_{its} \quad \forall t \\
y_{i,k+1,t} &\geq y_{ikt} \quad \forall i, k, t \\
\sum_j a_{ij} u_{jt} &\geq y_{i1t} + y_{i2t} \quad \forall i, t \\
u_{jt} &\leq v_j x_j \quad \forall j, t \\
\sum_j u_{jt} &= A \quad \forall t \\
\sum_j x_j &\leq p \\
x_j &\in \{0,1\} \quad \forall j; \quad y_{ikt} \in \{0,1\} \quad \forall i, t \\
u_{jt} &\geq 0, \text{ integer} \quad \forall j, t
\end{align*}
\]
ARTM: Average Response Time Model

\[
\text{min } Z_{RT} = \sum_i \sum_s \sum_t \sum_j w_{its} \, tp_{ij} \, y_{ijt} \\
\text{Subject to:}
\begin{align*}
    \sum_j y_{ijt} &= 1 \quad \forall i, t \\
    y_{ijt} &
    \leq x_j \quad \forall i, j, t \\
    u_{jt} &
    \leq v_j \, x_j \quad \forall j, t \\
    \sum_j u_{jt} &= A \quad \forall t \\
    \sum_j x_j &\leq p \\
    x_j &\in \{0,1\} \quad \forall j; \\
    u_{jt} &\geq 0, \text{ integer} \quad \forall j, t \\
    y_{ijt} &\in \{0,1\} \quad \forall i, j, t
\end{align*}
\]

Additional Parameters:
- \(tp_{ij}\): Response time from location \(j\) to point \(i\).
- \(w_{its}\): Weight of demand \(i\) at time \(s\) and location \(t\).
- \(x_j\): Binary variable indicating whether \(j\) is open.
- \(u_{jt}\): Auxiliary variable.
- \(y_{ijt}\): Binary variable indicating whether \(j\) is the nearest open base to \(i\) at time \(t\).

Additional Variables:
- \(Z_{RT}\): Average response time

References:
- ReVelle and Swain, 1989
- Dzator and Dzator, 2013
MEXCLP: Mean Expected Covering Location Problem

\[
\max Z_{XC} = \sum_i \sum_s \sum_t w_{its} \sum_k q^{k-1} (1 - q) y_{ikt}
\]
Subject to:

\[
\sum_k y_{ikt} = \sum_j a_{ij}^1 u_{jt} \quad \forall i, t
\]
\[
y_{i,k+1,t} \geq y_{2ikt} \quad \forall i, k, t
\]
\[
u_{jt} \leq v_j x_j \quad \forall j, t
\]
\[
\sum_j u_{jt} = A \quad \forall t
\]
\[
\sum_j x_j \leq p
\]
\[
x_j \in \{0,1\} \quad \forall j; \quad y_{ikt} \in \{0,1\} \quad \forall i, t
\]
\[
u_{jt} \geq 0, \text{ integer} \quad \forall j, t
\]

**Additional Parameters:**

\(q\): Probability that an ambulance is busy (or not available/ not working) within \(r_1\).

**Additional Variables:**

\(Z_{XC}\): Expected coverage

Daskin, 1983
Two Mexican Cases: Monterrey and Tijuana

- Demand zones
- Potential base locations
- Demand behavior and scenerios
- Travel time
Monterrey

- Capital of the northeastern state of Nuevo Leon, in Mexico.
- Third-largest metropolitan area.
- Metropolitan area >5,300 km² and >4.7 million inhabitants (INEGI, 2015).
Monterrey

- 42 equal quadrants
- ~23km$^2$ each
- Each demand zone corresponds to a quadrant.

Demand zones

(INEGI, 2015).
Monterrey

- Convenience stores all over the city.
- Each potential base with basic features: space, electricity, etc.
- 884 possible sites

(INEGI, 2015)
Tijuana

- The largest city on the Baja California Peninsula.
- Located at the northwestern of Mexico, next to the US border.
- Metropolitan area >1,390 km\(^2\) and 1.8 million inhabitants

(INEGI, 2015)
Tijuana

- 15 equal quadrants
- ~25 km² each
- Each demand zone corresponds to a quadrant.

Demand zones (INEGI, 2015)
Tijuana

- Convenience stores all over the city.
- Each potential base with basic features: space, electricity, etc.
- 434 possible sites
Demand Behavior for both cities

**Monterrey**
- 14,368 calls. Red Cross of Monterrey
- November 2016 to April 2017.

**Tijuana**
- 10,176 calls. Red Cross of Tijuana
- January 1 to August 31, 2014.

GPS location and priority levels of each call (Siren, Silent Urgency, Make the service brief).
Demand Scenarios and Travel Times

Monterrey and Tijuana

Scenarios:
• Morning, afternoon, night, and an overall case.

Travel time:
Average speed using Google Maps and its forecast of average transfer times between strategic points in the city.
Numerical Experimentation

- Settings
- Performance indicators
- Results
Numerical experimentation

Experimentation setting
- Models: in GAMS 23.5 - CPLEX
- Standard laptop
- Post-processing in Matlab or GAMS.
- Parameters
  - $\alpha = 15$ minutes, $\beta = 30$ minutes
  - $\alpha = 0.7$
  - $\alpha = 20$ for Tijuana and $\alpha = 40$ for Monterrey
  - $\alpha = 6, 7, ..., 4$ scenarios (am, pm, night, day)

Erkut et al., 2009
Numerical experimentation

Calculation of $q$

$\Lambda(\rho, A)$ is the Erlang Loss Function which measures the fraction of lost calls in an $M/G/\infty/\infty$ queueing system.

$$q = \frac{\lambda(1 - B(\rho, A)\tau(u))}{A}$$

$$B(\rho, A) = \left[\frac{\rho^A / A!}{\sum_{i=0}^{A} \rho^i / i!}\right]$$

<table>
<thead>
<tr>
<th>TIJUANA</th>
<th>MONTERREY</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$</td>
<td>$\lambda$</td>
</tr>
<tr>
<td>$E(\tau)$ [min]</td>
<td>$E(\tau)$ [min]</td>
</tr>
<tr>
<td>$q$</td>
<td>$q$</td>
</tr>
<tr>
<td>Max $A$</td>
<td>Max $A$</td>
</tr>
<tr>
<td>0.022</td>
<td>0.055</td>
</tr>
<tr>
<td>90.04</td>
<td>85.98</td>
</tr>
<tr>
<td>[0.09-0.29]</td>
<td>[0.12-0.63]</td>
</tr>
<tr>
<td>[6-20]</td>
<td>[6-40]</td>
</tr>
</tbody>
</table>

Erkut et al., 2009
Dibene et al., 2017
Numerical experimentation

*Performance measures*

**Coverage related criteria:**
- % of locations covered once, twice, and three times within \( A \) (equity).
- % weighted demand covered once, twice (DSM), and three times within \( A \).
- % of locations and weighted demand covered once within 10 min and \( A = 30 \) min.

**Response time related criteria:**
- Maximum response time,
- Average response time (ARTM)

**Evolution as A increases**

**Current capacity performance**
Results...on coverage

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Description</th>
<th>TIJUANA</th>
<th>MONTERREY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Single location coverage</td>
<td>91.6%</td>
<td>86.3%</td>
</tr>
<tr>
<td>2</td>
<td>Double location coverage</td>
<td>87.1%</td>
<td>74.8%</td>
</tr>
<tr>
<td>3</td>
<td>Triple location coverage</td>
<td>12.0%</td>
<td>4.6%</td>
</tr>
<tr>
<td>4</td>
<td>Single Demand Coverage</td>
<td>99.7%</td>
<td>94.9%</td>
</tr>
<tr>
<td>5</td>
<td>Double Demand Coverage</td>
<td>98.6%</td>
<td>88.4%</td>
</tr>
<tr>
<td>6</td>
<td>Triple Demand Coverage</td>
<td>43.9%</td>
<td>7.1%</td>
</tr>
</tbody>
</table>

**Latin America**

- DSM better in 2Cov, not significantly better than MEXCLP
- DSM also better in 2Loc-Cov, not much than MEXCLP
- MEXCLP better in 1Cov and 3Cov, both demand and location
- ARTM worst in all coverage: though 1Cov is acceptable, 2Cov is deficient, and 3Cov is the worst.
Results... on others

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Description</th>
<th>TIJUANA</th>
<th>MONTERREY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DSM</td>
<td>ARTM</td>
<td>MEXCLP2</td>
</tr>
<tr>
<td>7</td>
<td>Max. Response time (min)</td>
<td>27.94</td>
<td>30.81</td>
</tr>
<tr>
<td>8</td>
<td>Avg. Response time (min)</td>
<td>11.88</td>
<td><strong>6.58</strong></td>
</tr>
<tr>
<td>9</td>
<td>z_ExpCov</td>
<td>0.976</td>
<td>0.868</td>
</tr>
<tr>
<td>10</td>
<td>10 min threshold</td>
<td>30%</td>
<td>77%</td>
</tr>
<tr>
<td>11</td>
<td>30 min threshold</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

**ARTM**: ~60% ART of others, and better in 10 min 1Cov

**MEXCLP** thought better in expected coverage (as expected), not much than DSM.

**DSM** and **ARTM** similar! With no dominated solutions (Covs and ExpCov), DSM lightly better in ARTs.
1, 2, and 3 Coverage + response time for different number of ambulances

Monterrey case

>90% 2Cov:
DSM: 23 amb (10.7 min)
ARTM: Never
MEXCLP: 33 amb (10 min)
1, 2, and 3 Coverage + response time for different number of ambulances

>90% 2Cov:
DSM: 10 amb (13.3 min)
ARTM: Never
MEXCLP: 11 amb (12.6 min)

Tijuana case

Better backup coverage
## Results – Current capacity

<table>
<thead>
<tr>
<th>Performance indicator</th>
<th>TIJUANA (A=8 ambulances)</th>
<th>MONTERREY (A = 14 ambulances)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DSM</td>
<td>ARTM</td>
</tr>
<tr>
<td>Response time (min)</td>
<td>14</td>
<td>10</td>
</tr>
<tr>
<td>Single zone coverage</td>
<td>87%</td>
<td>53%</td>
</tr>
<tr>
<td>Double zone coverage</td>
<td>84%</td>
<td>0%</td>
</tr>
</tbody>
</table>

ÅDSM performs better in coverage: both cities, both types (demand and location), and in 1Cov, 2Cov, and 3Cov.

ÅDifferences with ARTM in terms of ART, suggests potential improvements of O.F. for DSM (multi-objective)

ÅTwo cases: not enough to see correlation among A, city size, and demand.
Conclusions

Service Quality
For Monterrey & Tijuana:
- ART = 14 min
- 87% (& 81%) calls can be reached within 15 min. (DSM)

Best Models
- Current capacity: DSM
- DSM: in general
- MEXCLP: only best in multiple coverage
- ARTM: bad coverage performance

Best Configuration
Monterrey
- DSM: 20 veh: 12 min, >90% once, 80% twice
Tijuana
- DSM: 10 veh: 90% once, 90% twice, 13min

Recommendations
- DSM + RT or ARTM + backup coverage
- Pay attention to \( \sigma \)
Conclusions and further work

• Done: comparison based on LA real data
• Extensions: different service priorities, zone coverage
• Further: priority analysis, combining models, multiperiod, continuous (dynamic) location
Thank you

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Gerardo Frutos gerardo.frutos@udem.edu

Universidad de Monterrey, Monterrey, Nuevo Leon, Mexico
Coverage, double coverage and response time illustration
## Results

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<td>80.4</td>
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<td>Double location coverage</td>
<td>87.1</td>
<td>26.2</td>
</tr>
<tr>
<td>3</td>
<td>Triple location coverage</td>
<td>12.0</td>
<td>9.8</td>
</tr>
<tr>
<td>4</td>
<td>Single Demand Coverage</td>
<td>99.7</td>
<td>96.4</td>
</tr>
<tr>
<td>5</td>
<td><strong>Double Demand Coverage</strong></td>
<td>98.6</td>
<td>46.6</td>
</tr>
<tr>
<td>6</td>
<td>Triple Demand Coverage</td>
<td>43.9</td>
<td>20.6</td>
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Comparison of Location Models. Díaz, J., Granda, E., Villarreal, B., Frutos, G., 2018
Location Coverage versus response time for different number of ambulances

Monterrey case
Location Coverage versus response time for different number of ambulances

Tijuana case

Universidad EAFIT, Medellín, Colombia, July 2018