Socially optimal allocation of ATM resources via truthful market-based mechanisms

Tobias Andersson Granberg
Valentin Polishchuk
Market mechanism

Resource 2

User 1

€

Payment 1

Resource 1

Resource 2

€

Owner

User 2

Payment 2

User n

Payment n

Resource 1

Resource k

Resource n

Market rules?
Example: slot allocation

[Castelli, Pellegrini, Pesenti, Ranieri 2009--2012]

http://www.euro-cdm.org/library_scenarios.php
# Second SESAR Innovation Days

27\(^{th}\) - 29\(^{th}\) November 2012  
Braunschweig, Germany

## Day 2: 28\(^{th}\) November 2012

<table>
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<tr>
<th>Time</th>
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| 8:45 - 9:45 | **Keynote 2**  
*Otto Gies, EADS*  
Liabilities and Automation in Aviation  
*Giuseppe Contissa, Giovanni Sartor, European University Institute* |
| 9:45 - 10:15 | **Poster Teaser Session 2**                                                                 |
| 10:15 - 10:30 | **Coffee**                                                                                   |
| 10:30 - 11:00 | **Trajectory Management**  
Conflict Resolution with Time Constraints in Trajectory-Based Arrival Management  
*Damian Rivas, University of Seville*  
Examples of Supervisory Interaction with Route Optimizers  
*Oliver Turnbull, University of Bristol*  
Flight Trial Evaluation Of Automated Paired Approaches Onto Closely Spaced Parallel Runways  
*Bernd Korn, DLR* |
| 11:00 - 12:30 | **Human Factors**  
Remote Towers: Videopanorama Frame  
Rate Requirements Derived from Visual Discrimination of Deceleration during Simulated Aircraft Landing  
*Norbert Fürstenau, DLR*  
Introduction of a more Automated Environment in En-Route ATC  
*Jean-Paul Imbert, ENAC*  
Applying the Resilience Engineering and Management Perspective to Problems of Human Alarm Interaction in ATM  
*Simone Rożni, Middlesex University* |
| 12:30 - 13:30 | **Lunch**                                                                                     |
| 13:30 - 14:00 | **Flow Management**  
Optimization and Prioritisation of Flows                                                        |
| 14:00 - 14:30 | **Safety and Security**  
Agent-Based Modelling of Hazards in ATM (Jean-Paul Imbert, ENAC)                                |
Example: shop locations

http://www.brusselsairport.be/en/passngr/at_the_airport/airport_map/
Fundamental questions

Bid--allocate--pay mechanisms:
● What info to solicit from users?
● How to ensure the users submit true info?
● How to allocate resources?
● How much to charge the users?
Mechanism: desirable properties

- Social Optimality (SO): allocation maximizes benefit to the society
- Incentive Compatibility (IC), or Truthfulness: no user benefits from lying
- Individual Rationality (IR): each user gets a non-negative utility
- Budget Balance (BB): the resource owner's net profit is 0
Social Optimality (SO): allocation maximizes benefit to the society
Incentive Compatibility (IC): no user benefits from lying
Individual Rationality (IR): each user gets a non-negative utility
Budget Balance (BB): the resource owner's net profit is 0
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Definitions
Valuation $v_i(a)$

Users: 1, 2, ..., i, ..., n

A: set of all allocations

$v_i : A \rightarrow \mathbb{R}$

$v_i(a)$: How much user $i$ likes allocation $a$

- number (in Euros)
- monetary value
- can be negative
Selfish rational (envy-free) user

Most often:

\[ v_i(a) \text{ depends only on } a(i) \]

\[ \text{does not depend on what others get} \]

Sometimes:

\[ v_i(a) \text{ depends on not only on } a(i) \]

\[ \text{but also on what others got} \]
Valuation depends on others' allocation
Example:
conference program

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http://sesarinnovationdays.eu
Example: slot allocation

Arrival of latest flight connecting to my outbound flight

http://www.euro-cdm.org/library_scenarios.php
"World" = \( (v_1, v_2, \ldots, v_n) \)

User i has a valuation for each outcome
User i has a function \( v_i : A \rightarrow R \)

User i is a function \( v_i : A \rightarrow R \)

V: the set of all "worlds", all \( v = (v_1, v_2, \ldots, v_n) \)

"State of the world": \( v \) in V
Mechanism: \( (f,p) \)

\[ f : V \rightarrow A, \text{ social choice } f(v) \]

\[ p : V \rightarrow R^n, \text{ payments } p(v) = (p_1, p_2, \ldots, p_n) \]

\( p_i < 0 \) -- mechanism pays to \( i \)

For any user:
utility = valuation(allocation) - payment

\[ v_i(f(v)) - p_i(v) \]
Social Optimality (SO)

\( f \) chooses socially optimal allocation

\[ \sum_i v_i(f(v)) = \max_{a \in A} \sum_i v_i(a) \]

Allocations: good and not-so-good
Social welfare -- measure of "goodness"
Incentive Compatibility (IC)

No incentive to lie to mechanism

For every $i$

for any two "worlds":

$v' = (v'_1, v'_2, \ldots, v'_{i-1}, v'_i, v'_{i+1}, \ldots, v'_n)$

$v* = (v'_1, v'_2, \ldots, v'_{i-1}, v_i, v'_{i+1}, \ldots, v'_n)$

$v_i(f(v*)) - p_i(v*) \geq v_i(f(v')) - p_i(v')$
Example: slot assignment, linear valuations

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<tr>
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$v_i(s) = C_i - w_i \cdot s$

$w_1 > w_2 > ... > w_n$

Socially optimal

$p_1 = 0$

$p_2 = 0, p_3 = 0, ... , p_n = 0$

$p_1 = 1000000$

$p_2 = 0, p_3 = 0, ... , p_n = 0$
Vickrey--Clarke--Groves (VCG)

f is SO: \( \sum_i v_i(f(v)) = \max_{a \in A} \sum_i v_i(a) \)

\( p_i(v) = \max_{a \in A} \sum_{j \neq i} v_j(a) - \sum_{j \neq i} v_j(f(v)) \)

= "harm" of i to the society

Theorem [Vickrey'61, Clarke'71, Groves'73]: VCG is SO, IC and IR
Example: slot assignment, linear valuations

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<td>i</td>
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<td>...</td>
<td>...</td>
</tr>
<tr>
<td>n</td>
<td>n</td>
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\[ v_i(s) = C_i - w_i \times s \]
\[ w_1 > w_2 > \ldots > w_n \]

\[ f(v) = a \text{ with } a(i) = i \]

\[ v_i(f(v)) = C_i - w_i \times i \]

\[ \sum_i v_i(f(v)) = \sum_i (C_i - w_i \times i) \]
Example: slot assignment, linear valuations

\[ p_i = \max_{a \in A} \sum_{j \neq i} v_j(a) - \sum_{j \neq i} v_j(f(v)) \]

Users \ 1, 2 , ..., i-1, i+1 ,..., n
get slots \ 1, 2 , ..., i-1, i ,..., n-1

\[ \max_{a \in A} \sum_{j \neq i} v_j(a) = \sum_{j<i} (C_j - w_j * j ) + \sum_{j>i} (C_j - w_j * (j-1) ) \]

\[ \sum_{j \neq i} v_j(f(v)) = \sum_{j<i} (C_j - w_j * j ) + \sum_{j>i} (C_j - w_j * j ) \]

\[ p_i = \sum_{j>i} w_j \]
Example:
slot assignment, linear valuations

\[ p_i = \sum_{j>i} w_j \]
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William Spencer Vickrey (1914 – 1996)

Nobel prize 1996

Bertil Näslund
Royal Swedish Academy:

"Vickrey's contributions in this area have had important practical consequences, for example regarding the design of auctions of government securities, air traffic concessions, and band spectrum licenses.”

Mechanism design for ATM: open problems, challenges
Theory vs applications

- Computational challenges
  - how to find allocation and prices efficiently
- Uncertainty
  - dynamic and stochastic nature of ATM
- Other objectives
  - besides SO
- Other properties
  - besides SO, IC, IR, BB
- Privacy
  - valuation, other private info
- Owner's profit
  - maximization, issues with monopoly
Other settings

Implementation?

Legislative responsibility: Auctions for what ATM resources?
Monetization of preferences

European airline delay cost reference values
University of Westminster for EUROCONTROL
[Cook, Tanner, Anderson '04. Evaluating the True Cost to Airlines of One Minute of Airborne or Ground Delay]

Or airlines determine costs themselves?

Objective function:
total delay or max delay?
Who is the user?

Earlier work: per-flight view
Business entity: airline
Passengers? POEM
Note: users are active; players

Questions, questions...

Questions?