Optimization through Simulation: How to improve TMA operations

Miquel Angel Piera
MiquelAngel.Piera@uab.cat

Systems Engineering Group
Dept. of Telecomunication
Universitat Autonòma de Barcelona
Barcelona (Spain)

Dr. Miquel Àngel Piera
RelStat 2013, October 17th
Outline

• Introduction to the ATM Systems
• SESAR
• Decision Support Systems
• Managing System Complexity using Causal Formalism
• Case Studies: Boeing, AENA, Indra, EuroControl, AirEuropa,…
• Conclusions
Optimization through Simulation: How to improve TMA operations

Introduction: ATM Actors

ATM Actors:
- ATC
- ATFM
- Airports
- AU’s

Dr. Miquel Àngel Piera

RelStat 2013, October 17th
Optimization through Simulation: How to improve TMA operations

ATFM Emergent Dynamics

Assume NO conflicts

Dr. Miquel Àngel Piera

RelStat 2013, October 17th
Optimization through Simulation: How to improve TMA operations

ATC Emergent Dynamics

Dr. Miquel Àngel Piera

RelStat 2013, October 17th
* Bilimoria (NASA) performed several experiments that confirm the importance of taking into account the Domino effects of the CR trial trajectories.
Optimization through Simulation: How to improve TMA operations

RelStat 2013, October 17th
Dr. Miquel Àngel Piera

<table>
<thead>
<tr>
<th>AIRCRAFT</th>
<th>TRIAL TRAJECTORIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>760_1, 520_1, 231, 452, 964, 672, 741, 392, 175, 712, 672</td>
</tr>
<tr>
<td>2</td>
<td>760_2, 520_3, 231, 452, 964, 672, 741, 392, 175, 712, 672</td>
</tr>
<tr>
<td>3</td>
<td>520_1, 231, 452, 964, 672, 741, 392, 175, 712, 672</td>
</tr>
<tr>
<td>4</td>
<td>520_3, 231, 452, 964, 672, 741, 392, 175, 712, 672</td>
</tr>
<tr>
<td>5</td>
<td>520_1, 231, 452, 964, 672, 741, 392, 175, 712, 672</td>
</tr>
</tbody>
</table>

New Pareto-efficient solution:

\[[760_1, 2_2, 3, 4_4, 5_5, \ldots, N-1_{N-1}, N_N]\]

<table>
<thead>
<tr>
<th>AIRCRAFT</th>
<th>CONFLICTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>idt1</td>
</tr>
<tr>
<td>2</td>
<td>x1</td>
</tr>
<tr>
<td>3</td>
<td>x3</td>
</tr>
<tr>
<td>4</td>
<td>x4</td>
</tr>
<tr>
<td>5</td>
<td>x5</td>
</tr>
</tbody>
</table>

New Pareto-efficient solution:

\[[1_1, 2_2, 3_3, 4_4, 5_5, \ldots, N-1_{N-1}, N_N]\]
Optimization through Simulation: How to improve TMA operations

Airport Emergent Dynamics

Dr. Miquel Àngel Piera

RelStat 2013, October 17th
Optimization through Simulation: How to improve TMA operations

SESAR: Single European Sky ATM R&D

4 Main Objectives: European Commission

- High Level Targets
  - Capacity: \( x \ 3 \)
  - ATM Costs: \( \frac{1}{2} \)
  - Safety: \( x \ 10 \)
  - Environmental Impact: \(-10\%\)

RelStat 2013, October 17th
Optimization through Simulation: How to improve TMA operations

SESAR: **Single European Sky ATM R&D**

**SWIM** and information sharing are key enablers for the **CDM planning** in target ATM

Dr. Miquel Àngel Piera

RelStat 2013, October 17th
Optimization through Simulation: How to improve TMA operations

CDM: Collaborative Decision Making

Coexistence of economic, technological, logistic and human behaviour aspects

Holding trajectory of an Aircraft waiting for landing (generally from 1 to 3 minutes)

Dr. Miquel Àngel Piera

RelStat 2013, October 17th
Events are propagated through the system, and can lead to poor KPI’s due to idleness and over saturation in key critical resources.

**Why ATM is considered Complex?**

Complexity becomes apparent to humans each time we are asked to take a decision in a context that it is not possible to predict all the consequences of a certain action.

**Cause - effect relationship** should be properly formalized and analyzed to improve logistic systems performance.

Dr. Miquel Àngel Piera  
RelStat 2013, October 17th
The Rule of Seven Rs: Logistics is ensuring the availability of the right product, in the right quantity and right condition, at the right place, at the right time, for the right customer, at the right cost.
Optimization through Simulation: How to improve TMA operations

Decision Support Systems

- Optimisation
  - Poor model
  - Optimal (real?)

- Simulation
  - Good model
  - Poor results

Scheduling policy

Dr. Miquel Àngel Piera

RelStat 2013, October 17th
Optimization through Simulation: How to improve TMA operations

How to tackle Flexibility?

Simulation Approach

Simulation limitation arises out of an inability to evaluate more than a fraction of the immense range of options available

Dr. Miquel Àngel Piera

RelStat 2013, October 17th
How to tackle complexity?

- Keep it simpler and add complexity later
- Reduce the scope of the model
- Reduce the level of detail using hierarchy

It is enough a fiability around the 99.9%?

- More than 4 accidents per day in the main airports
- 20,000 objects lost per day in a mail service
- 5,000 wrong surgical operations per week
Workflow Modeling Methods

When a process is understood to be a specific ordering of work activities, with a beginning, an end, and clearly identified inputs and outputs, then models can be easily formalized by mapping elements in the real world into modeling components.

Present simulation languages provide the modeler with powerful tools that greatly facilitate building models.
Optimization through Simulation: How to improve TMA operations

Petri Net Formalism

Modeling Goal:

Specify the sequence of activities that a certain event can activate/propagate/freeze.

Methodology:

• Describe modularly each subsystem

• Describe the set of logical relationships that determine the interaction between subsystem components.

• Set up the whole simulation model by coupling shared elements together with their interactions.
Petri Net Formalism

Petri net definition: PN = (P,T,I,O,Mo)

- P = \{p_1,p_2...,p_n\}, a set of \textit{places},
- T = \{t_1,t_2,...,t_n\}, a set of \textit{transitions},
- I : (P \times T) \rightarrow N, directs arcs from places to transitions;
- O : (P \times T) \rightarrow N, directs arcs from transitions to places;
- Mo = \{#P_1,#P_2,...,#P_n\}, an initial marking.

Mo = [0,0,1]
Optimization through Simulation: How to improve TMA operations

Petri Net Formalism: The Reachability Tree

Petri Net Formalism

Dr. Miquel Àngel Piera

RelStat 2013, October 17th
Optimization through Simulation: How to improve TMA operations

Petri Net Formalism: The Reacheability Tree

Petri Net Formalism

Levels: 3
Solutions: 3

Root: Initial State
Reachable Nodes
End Nodes
Solution Nodes

RelStat 2013, October 17th

Dr. Miquel Àngel Piera
Optimization through Simulation: How to improve TMA operations

Petri Net Formalism: The Reachability Tree

Petri Net Formalism

A tool to determine the optimal plan

Dr. Miquel Àngel Piera

RelStat 2013, October 17th
Optimization through Simulation: How to improve TMA operations

Managing System Complexity

- Simplified Models
  - Optimal solution?
- Operative Research
- Artificial Intelligence
  - Knowledge Representation
  - Search methods
- Realistic Models
  - Poor results

Dr. Miquel Àngel Piera
RelStat 2013, October 17th
Optimization through Simulation: How to improve TMA operations

New Heuristics

Further Research

RelStat 2013, October 17th

Dr. Miquel Àngel Piera
Optimization through Simulation: How to improve TMA operations

Coloured Petri Net Formalism

Dr. Miquel Àngel Piera
Optimization through Simulation: How to improve TMA operations

Practical Applications using Petri Net Formalism

Dr. Miquel Àngel Piera

RelStat 2013, October 17th
Petri Nets modeling features

- Allow description of a system at different abstraction levels.
- Easy use due to graphics visualization.
- Allow checking for undesirable properties such as deadlock.
Optimization through Simulation: How to improve TMA operations

Practical Applications using Petri Net Formalism

<table>
<thead>
<tr>
<th>Waypoint</th>
<th>Latitude</th>
<th>Longitude</th>
<th>FL</th>
<th>Distance (NM)</th>
<th>TAS (Kts)</th>
<th>TAWS (Kts)</th>
<th>Arrival (HHMM)</th>
<th>Rate (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RUSI</td>
<td>2° 5′</td>
<td>4° 4′</td>
<td>4 0′</td>
<td>0′</td>
<td>3 0′</td>
<td>3 0′</td>
<td>1621</td>
<td>0</td>
</tr>
<tr>
<td>WPT6</td>
<td>2° 5′</td>
<td>7° 9′</td>
<td>2 0′</td>
<td>64</td>
<td>3 0′</td>
<td>3 0′</td>
<td>1629</td>
<td>8</td>
</tr>
<tr>
<td>CANIS</td>
<td>2° 0′</td>
<td>14° 8′</td>
<td>3 0′</td>
<td>64</td>
<td>3 0′</td>
<td>3 0′</td>
<td>1638</td>
<td>17</td>
</tr>
<tr>
<td>ENETA</td>
<td>5° 0′</td>
<td>14° 9′</td>
<td>3 0′</td>
<td>19</td>
<td>3 0′</td>
<td>3 0′</td>
<td>1641</td>
<td>20</td>
</tr>
</tbody>
</table>

Dr. Miquel Àngel Piera

RelStat 2013, October 17th
Optimization through Simulation: How to improve TMA operations

Practical Applications using Petri Net Formalism

Dr. Miquel Àngel Piera

RelStat 2013, October 17th
Optimization through Simulation: How to improve TMA operations

Practical Applications using Petri Net Formalism

Dr. Miquel Àngel Piera

RelStat 2013, October 17th
Optimization through Simulation: How to improve TMA operations

Dr. Miquel Àngel Piera

1200 trajectories over Europe
Optimization through Simulation: How to improve TMA operations

Results with 7NM and 10NM in CR (5NM in CD):

<table>
<thead>
<tr>
<th></th>
<th>7NM</th>
<th>10NM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal trajectories</td>
<td>4010</td>
<td>4010</td>
</tr>
<tr>
<td>Resolution trials generated</td>
<td>752</td>
<td>723</td>
</tr>
<tr>
<td>Total trajectories after RTG</td>
<td>4762</td>
<td>4733</td>
</tr>
<tr>
<td>Nominal conflicts</td>
<td>211</td>
<td>211</td>
</tr>
<tr>
<td>2on and 3rd order conflicts</td>
<td>743</td>
<td>629</td>
</tr>
<tr>
<td>Total conflicts after RTG</td>
<td>954</td>
<td>842</td>
</tr>
<tr>
<td>HAC manoeuvres in solution</td>
<td>190</td>
<td>180</td>
</tr>
<tr>
<td>FL Changes in solution</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Total modified trajectories</td>
<td>193</td>
<td>186</td>
</tr>
</tbody>
</table>

CD&R runtime:

<table>
<thead>
<tr>
<th>Module</th>
<th>Runtime</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD</td>
<td>8 sec.</td>
</tr>
<tr>
<td>RTG+CD</td>
<td>41 sec.</td>
</tr>
<tr>
<td>Clustering</td>
<td>9 sec.</td>
</tr>
<tr>
<td>ICS</td>
<td>20 sec.</td>
</tr>
<tr>
<td>Total</td>
<td>78 sec.</td>
</tr>
</tbody>
</table>

Dr. Miquel Àngel Piera

RelStat 2013, October 17th
Conclusions

The use of a formalism to specify all the events that affect the system performance has been introduced as an indispensable task to be made previously to optimize a cost function.

PN are a very suitable formalism to model and visualize patterns of behaviour comprising: concurrency, synchronization and resource sharing.

The proposed approach allows the integration of OR (optimization algorithms), Heuristics (search methods), and Simulation (evaluation methods) methods which are essential to deal with quasi-optimal solutions in complex problems.
Conclusions

System Complexity should not be seen as a property inherent to the system, instead it should be seen as a lack of a methodology and tools that would allow the engineer to specify and formalize the knowledge we got about a system.

Miquel Angel Piera
MiquelAngel.Piera@uab.cat

Systems Engineering Group
Dept. of Telecomunication
Universitat Autònoma de Barcelona
Barcelona (Spain)