The Role and Impact of Algebraic Modeling Languages in and on Industrial Optimization

Franz Nelissen: FNelissen@gams.com
Company

- Roots: World Bank, 1976
- Went commercial in 1987
- Locations
  - GAMS Development Corporation (Washington)
  - GAMS Software GmbH (Germany)
- Product: The General Algebraic Modeling System
GAMS - System Highlights

- Powerful algebraic modeling language with open architecture
- Robust, scalable state-of-the-art modeling technology for complex, large-scale modeling applications
- Uniform interface to all major commercial and academic solvers (30+ integrated)
Broad User **Community and Network**

- **11,500+ licenses**
- **Users: 50% academic, 50% commercial**
- **GAMS used in more than 120 countries**

25+ Years
GAMS Development
but...

“... - asking yourself why you would do optimization in GAMS, software that looks as modern and friendly as Richard Nixon.”

Agenda

GAMS – Elements, Enhancements, and Examples

Enhancements around GAMS

Some Case Studies

Past – Presence – Future
1976 - A World Bank Slide

The Vision

GAMS came into being!

RESULT:
- Limited drain of resources
- Same representation of models for humans and machines
- Model representation is also model documentation
What did this vision give us?

- Simplified model development, changes, and transfer
- Made mathematical optimization available to a broader audience (domain experts)
- Increased productivity tremendously
Foundation of GAMS

Powerful algebraic modeling language

Open architecture and interfaces to other systems, independent layers (platform, solver, data, interface)
Simple Declarative Language

Similar to mathematical notation

Easy to learn - few basic language elements: sets, parameters, variables, equations, models

Model is executable description of the problem
The algebraic representation of this problem is usually presented in a format similar to the following:

Indices:
- \( i = \) plants
- \( j = \) markets

Given Data:
- \( a_i = \) supply of commodity of plant \( i \) (in cases)
- \( b_j = \) demand for commodity at market \( j \)
- \( c_{ij} = \) cost per unit shipment between plant \( i \) and market \( j \) ($/case)

Decision Variables:
- \( x_{ij} = \) amount of commodity to ship from plant \( i \) to market \( j \) (cases), where \( x_{ij} \geq 0 \), for all \( i, j \)

Objectives:
- Observe supply limit at plant \( i \): \( \sum_j x_{ij} \leq a_i \)
- Satisfy demand at market \( j \): \( \sum_i x_{ij} \geq b_j \)
- Minimize total transportation costs: \( \sum_i \sum_j c_{ij} x_{ij} \)

Sets
- \( i \): canning plants / seattle, san-diego /
- \( j \): markets / new-york, chicago, topeka /

Parameters
- \( a(i) \): capacity of plant \( i \) in cases
- \( b(j) \): demand at market \( j \) in cases
- \( c(i,j) \): transport cost in thousands of dollars per case

Variables
- \( x(i,j) \): shipment quantities in cases
- \( z \): total transportation costs in thousands of dollars

Equations
- \( \text{cost} \): define objective function
- \( \text{supply}(i) \): observe supply limit at plant \( i \)
- \( \text{demand}(j) \): satisfy demand at market \( j \)

\[ \text{cost} .. \quad z = = \text{sum}((i,j), c(i,j) \cdot x(i,j)) \]
\[ \text{supply}(i) .. \quad \text{sum}(j, x(i,j)) \ = \ = \ a(i) \]
\[ \text{demand}(j) .. \quad \text{sum}(i, x(i,j)) \ = \ = \ b(j) \]

Model transport /all/ ;
### Sets

- **i**: canning plants / seattle, san-diego /
- **j**: markets / new-york, chicago, topeka

### Parameters

- **a(i)**: capacity of plant i in cases
- **b(j)**: demand at market j in cases
- **c(i,j)**: transport cost in thousands of dollars per case

### Variables

- **x(i,j)**: shipment quantities in cases
- **z**: total transportation costs in thousands of dollars

### Equations

- **cost**: define objective function
- **supply(i)**: observe supply limit at plant i
- **demand(j)**: satisfy demand at market j

#### Model transport /all/ ;

#### Symbols

<table>
<thead>
<tr>
<th>Name</th>
<th>Domains</th>
<th>Description</th>
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<td>j</td>
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<td>markets</td>
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#### Parameters

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#### Variables

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#### Equations

- **cost**: define objective function
- **supply(i)**: observe supply limit at plant i
- **demand(j)**: satisfy demand at market j

#### Equation Definitions

- **cost**: 
  \[ z = \sum_{i,j} \left( c_{i,j} \cdot x_{i,j} \right) \]
- **supply(i)**: 
  \[ \sum_{j} x_{i,j} \leq a_{i} \quad \forall i \]
- **demand(j)**: 
  \[ \sum_{i} x_{i,j} \geq b_{j} \quad \forall j \]

\[ x_{i,j} \geq 0 \; \forall i, j \]
Mix of Declarative and Imperative Elements

Control Flow Statements (e.g. loops, for, if,...), macros and functions

1. Build complex problem algorithms within GAMS
2. Simplified interaction with other systems:
   - Data exchange
   - GAMS process control
Strong Development Environment

GAMS IDE

- Project management
- Editor / Syntax coloring / Spell checks
- Tree view / Syntax-error navigation
- Model Debugging & Profiling
- Solver selection & setup
- Data viewer
  - Export
  - Charting
- GAMS Processes Control
Each new release incorporates major new components. A selected list of newer components is included in each release note. New features are defined in terms of solver libraries. Additionally, the License Check Date remains the same for major releases if the user worked with the prior major release.

Major releases contain a major new component, and major changes to the modeling language. License Check Date remains the same for major releases if the user worked with the prior major release.

Minor releases are used to maintain the set of solver libraries. Additionally, the License Check Date remains the same for major releases if the user worked with the prior major release.

Distribution History

24.4.2 (Maintenance release)
24.4.1 (Major release)
Free Model Libraries

GAMS Model Library
GAMS Test Library
GAMS Data Utilities Models
GAMS EMP Library
GAMS API Library
Practical Financial Optimization Models
Nonlinear Optimization Applications (N. Andrei)

More than 1400 models!
Foundation

Powerful algebraic modeling language

Open architecture and interfaces to other systems, independent layers (platform, solver, data, interface)
Independence of Model and Platform

Supported Platforms

- Windows
- Linux
- Mac OS X
- Solaris
- AIX

➤ Move models between platforms with ease!
Independence of Model and Platform

Local and distributed / remote execution
- Distributed MIP (CPLEX, GUROBI)
- Grid Computing Facility
- NEOS (Kestrel)
GAMS Grid Computing Facility

GAMS jobs in a **distributed** environment
- Scalable: supports large grids, but also works on local machine
- Platform independent, works with all solvers/model types
- Only minor changes to model required

1. Submission of jobs
2. “Grid Middleware”
   - Distribution of jobs
   - Job execution
3. Collection of solutions
4. Processing of results
```gams
hs store the instance handle;

dem(s,j) = b(j)*uniform(.95,1.15); // create some random d

loop(s,
    b(j) = dem(s,j);
    solve transport using lp minimizing z;
    hs = transport.handle; // save instance handle
)

parameter repx(s,i,j) solution report
    repy summary report;

repy(s,'solvestat') = na;
repy(s,'modelstat') = na;

* we use the handle parameter to indicate that the solution
repeat
    loop(s$handlecollect(h(s)),
        repx(s,i,j) = x.l(i,j);
        repy(s,'solvestat') = transport.solvestat;
        repy(s,'modelstat') = transport.modelstat;
        repy(s,'resusd') = transport.resusd;
        repy(s,'objval') = transport.objval;
    
    display$hdelete(h(s)) 'trouble deleting handle
    h(s) = 0; // indicate that we have loaded the
    display$sleep(card(h)•0.2) 'was sleeping for some time
    until card(h) = 0 or timeelapsed > 10; // wait until all

display repx, repy;

abort$sum(s$(repy(s,'solvestat')=na),1) 'Some jobs did no
```
Grid Computing Facility - HTCondor

- Submission started Jan 11, 16:00
- All jobs submitted by Jan 11, 23:00
- All jobs returned by Jan 12, 12:40
  - 20 hours wall time, 5,000 CPU hours
  - Peak number of CPU’s: 500

Results for 4096 MIPS on HTCondor
GAMS/Kestrel

- Remote Solver Execution on NEOS Servers
- Stay in your GAMS environment
- Results are being processed as with any local solver

--- Executing KESTREL: elapsed 0:00:00.006
Connecting to: http://neos-server.org:3332
NEOS Solver: xpress
NEOS job#=3631352, pass=iJLdAkhP

Check the following URL for progress report:
http://neos-server.org/neos/cgi-bin/nph-neos-solver.cgi?admin=results&jobnumber=3631352&pass=iJLdAkhP
Job 3631352 dispatched
password: iJLdAkhP
---------- Begin Solver Output ----------
Job submitted to NEOS HTCondor pool.

FICO-Xpress 24.3.3 r48116 Released Sep 19, 2014 LEG x86 64bit/Linux
### Independence of Model and Solver

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* Deterministic global solver

One environment for a wide range of model types and solvers
Independence of **Model and Solver**

### Solver/Model type availability - 24.4

<table>
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<th>Solver/Model</th>
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</table>

**Average number of commercial solvers per license:**
- Academic clients: 2.9
- Commercial clients: 2.2
Independence of Model and Solver

Uniform interface to all major solvers:

- Switching between solvers with one line of code
- Documentation
- Licensing (GAMS as a „license broker“)
Independence of Model and Solver

One environment for a wide range of model types and solvers

Commercial LP/MIP solver available in GAMS

Switching between solvers with one line of code
Independence of **Model and Solver**

**One** environment for a wide range of model types and solvers

- Open Source Solver (COIN) available in GAMS
- Bonmin
- CBC
- CUENNE
- IPOPT
- SCIP
Independence of Model and Solver

CyBio Scheduler

- Scheduling software for high throughput screening
- Used in the pharmaceutical industry (drug discovery)
- Model optimizes throughput of robotic screening systems
- Solver
  - COIN for smaller instances
  - Commercial MIP solver for large problems
- Developed by analytikjena
Independence of Model and Solver

One environment for a wide range of model types and solvers

Commercial NLP Solvers available in GAMS

Switching between solvers with one line of code
Independence of Model and Solver

CAPRI
- Global agricultural sector models with focus on EU27 members
- Evaluates impacts of agricultural and trade policies on production income, markets, trade, and the environment
- Different NLP solvers
- Open source approach with an active network of developers and users coordinated by University of Bonn
Independence of Model and Solver

One environment for a wide range of model types and solvers

Commercial MINLP or Global Solver available in GAMS

Switching between solvers with one line of code
Independence of Model and Solver

INTEGRATION

- Identifies, evaluates and selects energy efficiency projects in complex industrial facilities
- Solver:
  - BARON: MINLP
  - COIN: MIP
  - CONOPT: NLP
- Developed by Natural Resources Canada’s CanmetENERGY research center
Independence of **Model and Solver**

*One* environment for a wide range of model types and solvers

Stochastic Optimization in GAMS

- **DE**
- **DECIS**
- **LINDO**
- **Scenred**

> Switching between solvers with one line of code
Independence of Model and Data

Sets
- i canning plants,
- j markets;

Parameters
- a(i) capacity of plant i in cases
- b(j) demand at market j in cases
- d(i,j) freight in dollars per case per thousand miles
- c(i,j) transport cost in thousands of dollars per case

Variables
- x(i,j) shipment quantities in cases
- z total transportation costs in thousands of dollars

Positive Variable x

Equations
- cost define objective function
- supply(i) observe supply limit at plant i
- demand(j) satisfy demand at market j;

z =e= \sum((i,j), c(i,j)*x(i,j));
supply(i) \sum(j, x(i,j)) =l= a(i);
demand(j) \sum(i, x(i,j)) =g= b(j);

Model transport /all/;

Declarative Modeling

Model
Platform Solver Data Interface
Independence of Model and Data

- ASCII: Initial model development

- GDX: Binary Data layer ("contract") between GAMS and applications
  - Platform independent
  - Direct GDX interfaces and general API
Scheduling and Planning at BASF

- Project Partners: BASF, Princeton University, University of Omsk, SAP, Mathesis GmbH
- Optimization of the operation of batch and continuous plants
- Used on a daily basis to improve planning and scheduling
- Hybrid methods and decomposition schemes to handle large instances of MIP problems
- New interfacing technology and integration approaches to connect to SAP-APO
## Independence of Model and User Interface

1. Open architecture and interfaces to other systems → No preference for a particular user interface

2. (OO) Application Programming Interfaces

3. Smart Links to popular environments: Excel, MATLAB, R, ...
Independence of Model and User Interface

**API’s**

- **Low Level**
- **Object Oriented**: .Net, Java, Python
- No modeling capability: Model is written in GAMS
- Wrapper class that encapsulates a GAMS model

**Getting Started**

This section takes you through the basic steps of creating and configuring a C# project in Visual Studio 2010 for use with the GAMS C# API. At the end of this section, there is also a paragraph about Mono as an alternative in Microsoft Visual Studio.

**Open a new Project**

After opening Microsoft Visual Studio, you can open the New Project wizard by clicking **File > New > Project** from the ribbon menu and type a name for your application, e.g. `GAMSApplication`.

**Model**

- Platform
- Solver
- Data
- Interface
Simple Encapsulation of a GAMS Model

**Very simple interface**

- Properties to communicate input data and results
- Properties to change options like the solver to use
- Run() method to run the model
Smart Links to other Applications

- User keeps working in his productive tool environment
- Application accesses all optimization capabilities of GAMS through API
- Visualization and analysis of model data and results in the application
 Agenda

GAMS – Elements, Enhancements, and Examples

Enhancements around GAMS

Some Case Studies

Past – Presence – Future
## Quality Assurance at GAMS

### Solver/Platform availability - 24.4

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<tr>
<th>Solver/Platform</th>
<th>x86 32bit MS Windows</th>
<th>x86 64bit MS Windows</th>
<th>x86 64bit Linux</th>
<th>x86 64bit MacOS X</th>
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- **7 supported Platforms**
- **30+ Integrated Solvers**

- What are the impacts of
  - new features
  - updated or new solvers?
- Is the new distribution backward compatible?
Quality Assurance - Motivation

Quality Assurance
• Essential component in most industries
• Important in most software engineering sectors

Mathematical Programming
• Less attention to quality assurance (small community)
• Specific QA issues for modeling systems (initially expensive)
• Different focus for industry and academia

Industry
Focus on reliability

Academia
Focus on performance
Quality Test Model Library

- Tests to verify proper behavior of the system
- More than 680 quality test models, each containing numerous pass/fail tests
- Assurance about the basic functionality of the software!
- Give the tools in the hand of the user: Included in any distribution!

- Automatically executed every night for all solver combinations:
  - 13,000+ runs / platform (all tests)
  - Test summaries with different level of information
### Latest GAMS System Builds and Test Results

**NOTE:** The (nightly) alpha builds are internal development versions of the GAMS system. They may have known bugs, unfinished features, beta versions of third-party software, or may not function at all! Not for production use!

<table>
<thead>
<tr>
<th>Nightly α System</th>
<th>Libraries</th>
<th>Build</th>
<th>Rev</th>
<th>Status and Time (UTC)</th>
<th>Initial Tests</th>
<th>Full Tests</th>
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<td>24.5.0</td>
<td>51758</td>
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<td>385 runs 0 failures (q=0,s=0)</td>
<td>Report 3569 runs 1 failures (q=0,s=1)</td>
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<tr>
<td>Saturday deg</td>
<td>Download</td>
<td>24.5.0</td>
<td>51758</td>
<td>Test started 11Apr2015 01:47:52</td>
<td>619 runs 1 failures (q=1,s=0)</td>
<td>Report results pending</td>
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<tr>
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<td>647 runs 0 failures (q=0,s=0)</td>
<td>Report results pending</td>
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<td>Report 13030 runs 0 failures (q=0,s=0)</td>
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Nightly Quality Tests: Reports

GAMS System Builds and Test Results Archive

Sunday 12Apr15 15:26 (UTC)

[ Latest Builds | Alpha Builds | Beta Builds | Nightly Builds | Glossary ]

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<td>1117 runs</td>
<td>0 failures</td>
<td>2339 runs</td>
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</tbody>
</table>

**** SLVTEST FAILURES (failures_slv.gms)
$call =gams slvtest lo=2 --prefix=aix --fail=failures_slv.gms --test=bchtlbas ul="ord(s)=286" --runall=no --c1=sbb --ftr

**** SLVTEST FAILURES DETAIL (slvtest.sum?)
25020 04/11/15 05:45:16 bchtlbas  MINLP  SBB  Bad Model SolveStat[13,13] minlp=sbb
**GAMS/CONVERT**

- Transforms a GAMS model instance into a scalar model into different formats: Models can then be passed on to others for investigation without confidentiality being lost
- A way of sharing GAMS test problems for use with other modeling systems or solvers
- More than 25 target formats

<table>
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<tbody>
<tr>
<td>All</td>
<td>Generates all supported file formats</td>
<td>LindoMPI</td>
<td>Generate Lindo MPI file</td>
</tr>
<tr>
<td>AlphaECP</td>
<td>Generates AlphaECP input file</td>
<td>Lingo</td>
<td>Generate Lingo input file</td>
</tr>
<tr>
<td>Ampi</td>
<td>Generates Ampi input file</td>
<td>LocalSolver</td>
<td>Generate LocalSolver input file (only with ConvertD)</td>
</tr>
<tr>
<td>AmpiNLC</td>
<td>Generate Ampi NLC compatible file</td>
<td>LSPSol</td>
<td>Generate Output function in LocalSolver input file (only with ConvertD)</td>
</tr>
<tr>
<td>Analyze</td>
<td>Generates three text files for rows columns and matrix</td>
<td>Memo</td>
<td>Generate a memo file containing model statistics and files created.</td>
</tr>
<tr>
<td>AnalyzeS</td>
<td>Generates short form of Analyze</td>
<td>Minopt</td>
<td>Generate Minopt input file</td>
</tr>
<tr>
<td>Baron</td>
<td>Generates Baron input file</td>
<td>NLP2dual</td>
<td>Generate the Wolfe dual of a smooth optimization model</td>
</tr>
<tr>
<td>CplexLP</td>
<td>Generate CPLEX LP format input file</td>
<td>NLP2MCP</td>
<td>Generates GAMS scalar MCP model</td>
</tr>
<tr>
<td>CplexMPS</td>
<td>Generate CPLEX MPS format input file</td>
<td>OSIL</td>
<td>Generates Optimization Services instance Language (OSIL) file</td>
</tr>
<tr>
<td>Dict</td>
<td>Generate Convert to GAMS Dictionary</td>
<td>Pyomo</td>
<td>Generates Pyomo Concrete scalar model</td>
</tr>
<tr>
<td>DictMap</td>
<td>Generate Convert to GAMS Dictionary Map</td>
<td>SFS</td>
<td>Generates Solver Foundation Services OML file</td>
</tr>
<tr>
<td>FileList</td>
<td>Generate file list of file formats generated</td>
<td>ViennaDag</td>
<td>Generate Vienna Dag input file</td>
</tr>
<tr>
<td>FixedMPS</td>
<td>Generate fixed format MPS file</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gams</td>
<td>Generate GAMS scalar model. This is the default conversion format used.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lgo</td>
<td>Generate an LGO Fortran file</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**GAMS/CONVERT - Example**

**GAMS Code**

```
Variables
  x(i,j) shipment quantities in cases
  z total transportation costs in thousands
Positive Variable x;
Equations
  cost define objective function
  supply(i) observe supply limit at plant i
  demand(j) satisfy demand at market j;
  cost .. z =e= sum((i,j), c(i,j)*x(i,j)) ;
  supply(i) .. sum(j, x(i,j)) =l= a(i) ;
  demand(j) .. sum(i, x(i,j)) =g= b(j) ;
Model transport /all/ ;
Solve transport using lp minimizing z ;
```

**Scalar Model**

```
Variables x1,x2,x3,x4,x5,x6,x7;
Positive Variables x1,x2,x3,x4,x5,x6;
Equations e1,e2,e3,e4,e5,e6;
e1 .. - 0.225*x1 - 0.153*x2 - 0.162*x3 - 0.225*x4 - 0.162*x5 - 0.126*x6 + x7 =E= 0;
e2 .. x1 + x2 + x3 =L= 350;
e3 .. x4 + x5 + x6 =L= 600;
e4 .. x1 + x4 =G= 325;
e5 .. x2 + x5 =G= 300;
e6 .. x3 + x6 =G= 275;
Model m /all/ ;
m.limrow=0; m.limcol=0;
Solve m using LP minimizing x7;
```
Paver 2 – GAMS Performance Tools

- Automates the analysis and comparison of solver performance data
- Easy customization of performance metrics
- Computation and visualization of performance statistics
- Platform independent, simple use, high performance, and flexibility, open source
- Give the tools in the hand of the user: Make your own benchmarks!

http://www.gamsworld.org/performance/paver2/
What else is **new**?

### GAMS Distribution 24.4

**Distribution History**

- **24.4.2** (Maintenance release) March 15, 2015
- **24.4.1** (Major release) December 20, 2014

**GAMS Major Release 24.4.1 - December 20, 2014**

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  - External Function libraries
  - Documentation
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  - BENCH
  - CBC
  - Couenne
  - CONOPT
  - CPLEX
  - DICOPT
  - GUROBI
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  - Lindo/LindoGlobal
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  - GAMS Model Library
  - GAMS Test Library

Agenda

- GAMS – Elements, Enhancements, and Examples
- Enhancements around GAMS
- Some Case Studies
- Past – Presence – Future
Three Case Studies

1. General Dynamics – efficient frontiers of multi-objective design optimization problems

2. xyz Energy Company – solving many difficult MIP models in parallel on the Amazon cloud

3. EMS-EDM Prophet – an Energy and Energy Data Management System
Set s /s*s10/;
Parameter
   A_s(s,i,j) "scenario data",
   xlo_s(s,i,j) "scenario lower bound for x.l",
   em_s(s,i) "scenario solution for e.m";
Loop(s,
   A(i,j) = A_s(s,i,j);
   x.lo(j)=xlo_s(s,j);
   solver mymodel min z using lp;
   xl_s(s,j) = x.l(j);
   em_s(s,i) = e.m(i);
);
Solving Scenarios

transport.gms (LP) solved 500 times with CPLEX:

```gams
Loop(s,
    d(i,j) = dd(s,i,j);
    f = ff(s);
    solve transport using lp minimizing z;
    rep(s) = transport.objval;
);
```

<table>
<thead>
<tr>
<th>Setting</th>
<th>Solve time (secs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solvelink=%Solvelink.ChainScript%</td>
<td>52.221</td>
</tr>
<tr>
<td>Solvelink=%Solvelink.CallModule%</td>
<td>37.366</td>
</tr>
<tr>
<td>Solvelink=%Solvelink.LoadLibrary%</td>
<td>03.252</td>
</tr>
</tbody>
</table>
Scenario Solver

- Generates model once and updates the algebraic model keeping the model "hot" inside the solver
- Platform independent, works with all solvers
- Performance close to native solver API

Set s /s*s10/;

Parameter
  A_s(s,i,j) "scenario data",
  xlo_s(s,i,j) "scenario lower bound for x.l",
  em_s(s,i) "scenario solution for e.m;

Set dict / s. scenario. ",
  A. param. A_s,
  x. lower. xlo_s,
  x. level. xl_s,
  e. marginal. em_s /;
solve mymodel min z using lp scenario dict;
**Performance**

Example: Stochastic model with 66,320 linear problems

<table>
<thead>
<tr>
<th>Setting</th>
<th>Solve time (secs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loop: Solvelink=%Solvelink.Chainscript (default)</td>
<td>7,204</td>
</tr>
<tr>
<td>Loop: Solvelink=%Solvelink.LoadLibrary%</td>
<td>2,481</td>
</tr>
<tr>
<td>GAMS Scenario Solver</td>
<td>392</td>
</tr>
<tr>
<td>Cplex Concert Technology</td>
<td>210</td>
</tr>
</tbody>
</table>
Solving Independent Models

1. Small Ratio of solver time / GAMS time → Scenario Solver
2. Large ratio i.e. only solver time is relevant (pre/post processing not critical) → Grid Computing Facility, Cplex Remote Object or Gurobi Compute Server
3. If entire model run including pre processing/MP solve/post processing is costly → Parallel execution of entire model in the cloud
ACSOM

- Advanced Collaborative System Optimization Modeler
- Configuration of (expensive) military vehicles
- Project partners:
  - General Dynamics Land Systems (GDLS)
  - Industrial & Systems Engineering, Wayne State University
  - GAMS Development Corp
  - Amsterdam Optimization Group
Considers All to Make the Whole
Full Spectrum

Numerous Subsystems with a multitude of options for each

- Force Protection Approach?
- Two, Three, Four Crew Members?
- Auto loader?
  - Configuration/Approach?
- Hull Material?
  - Aluminum?
  - Steel?
  - Titanium?
- Which Core Data Network?
- Hull Design?

Power?
- What Type of Engine?
- What Type Transmission?

What Type of Suspension System?
- Torsion bars?
- HSUs?
- Passive?
- Track?
- Fully Active?

Which Servo Motor Controller Architecture?

Approved for Public Release, Distribution Unlimited, GDLS approved, log 2008-09, dated 03/19/08 6
The Whole-system Design Problem

21 SUBSYSTEMS

<table>
<thead>
<tr>
<th>Options per subsystem</th>
<th>Theoretically Possible Subsystem Combinations</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2,092,152</td>
</tr>
<tr>
<td>3</td>
<td>10,460,353,203</td>
</tr>
</tbody>
</table>

Approved for Public Release, Distribution Unlimited. GDLS approved, log 2008-09, dated 03/19/08
Project **Scope**

**Generation of Efficient Frontiers**

**Significant performance improvements**

- Use multiple cores:
  - For current setup (laptops)
  - For high-performance machines
- Prepare for advancing technologies (distributed)
## Scenario Solver and Parallel Combined

<table>
<thead>
<tr>
<th>Implementation</th>
<th>Number of MIP models</th>
<th>Solve time (sec)</th>
<th>Rest of algorithm (sec)</th>
<th>Total time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional GAMS loop</td>
<td>100,000</td>
<td>1068</td>
<td>169</td>
<td>1237</td>
</tr>
<tr>
<td>Scenario Solver</td>
<td>100,000</td>
<td>293</td>
<td>166</td>
<td>459</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Implementation</th>
<th>Number of MIP models</th>
<th>Worker Threads</th>
<th>Parallel sub-problem time (sec)</th>
<th>Rest of algorithm (serial)</th>
<th>Total time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallel + Scenario Solver</td>
<td>100,000</td>
<td>4</td>
<td>116</td>
<td>67</td>
<td>183</td>
</tr>
</tbody>
</table>

## Retooling of an Application

### Old System
- VB.Net
- MPL (single point)
- CPLEX
- SQL throughout

### New System
- GAMS (complete algorithm; streamlined design)
- GAMS .NET API for ACE algorithm
- CPLEX
- Bulk SQL just once

### Performance Improvements
On the same hardware:
- From hours and even days for large problems
- To minutes, up to an hour
xyz Energy Company

Massive Parallel for Large Scale MIP

• Failures with Stochastic and Robust Optimization
• Scenario Analysis worked!
• Task: Solve 1,000 scenarios (MIPs, ~1 hour per scenario) every week overnight in parallel
• Post processing of results outside GAMS
• Issues:
  • Automation
  • Licensing
  • Security in the cloud
Protecting IP and Sensitive Data

- Obfuscate or hide sensitive information
  - Extrinsic function libraries
  - External Equations
  - Secure work files
  - Encrypted source files
- **Obfuscated files**: change all the names and other documentation related to a specific model run
Normal

Reduced LP has 5 rows, 6 columns, and 12 nonzeros.
Presolve time = 0.00 sec. (0.00 ticks)

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Dual Objective</th>
<th>In Variable</th>
<th>Out Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>73.125000</td>
<td>x(seattle.new-york)</td>
<td>demand(new-york)</td>
</tr>
<tr>
<td>2</td>
<td>119.025000</td>
<td>x(seattle.chicago)</td>
<td>demand(chicago)</td>
</tr>
<tr>
<td>3</td>
<td>153.675000</td>
<td>x(san-diego.topeka)</td>
<td>demand(topeka)</td>
</tr>
<tr>
<td>4</td>
<td>153.675000</td>
<td>x(san-diego.new-york)</td>
<td>supply(seattle)</td>
</tr>
</tbody>
</table>

LP status(1): optimal

Obfuscated

Reduced LP has 5 rows, 6 columns, and 12 nonzeros.
Presolve time = 0.00 sec. (0.00 ticks)

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Dual Objective</th>
<th>In Variable</th>
<th>Out Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>73.125000H(&quot;!&quot;!&quot;!&quot;!&quot;!&quot;!&quot;&quot;)A00002(&quot;!&quot;!&quot;!&quot;!&quot;!&quot;&quot;) slack</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>119.025000 H(&quot;!&quot;!&quot;!&quot;!&quot;!&quot;!&quot;&quot;)A00002(&quot;!&quot;!&quot;!&quot;!&quot;!&quot;&quot;) slack</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>153.675000H(&quot;!&quot;!&quot;!&quot;!&quot;!&quot;!&quot;&quot;)A00002(&quot;!&quot;!&quot;!&quot;!&quot;!&quot;&quot;) slack</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>153.675000H(&quot;!&quot;!&quot;!&quot;!&quot;!&quot;!&quot;&quot;)A00001(&quot;!&quot;!&quot;!&quot;!&quot;&quot;) slack</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

LP status(1): optimal
### Obfuscated Save/Restart File

#### Looking at Results

#### Normal

<table>
<thead>
<tr>
<th>Demand</th>
<th>Equ</th>
<th>Level</th>
<th>Marginal</th>
</tr>
</thead>
<tbody>
<tr>
<td>seattle</td>
<td>new-york</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>chicago</td>
<td>300</td>
<td></td>
<td></td>
</tr>
<tr>
<td>topeka</td>
<td>0.036</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Supply</th>
<th>Equ</th>
<th>Level</th>
<th>Marginal</th>
</tr>
</thead>
<tbody>
<tr>
<td>san-diego</td>
<td>new-york</td>
<td>275</td>
<td></td>
</tr>
<tr>
<td>chicago</td>
<td>0.00900000000000001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>topeka</td>
<td>275</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Obfuscated

<table>
<thead>
<tr>
<th>C</th>
<th>Par</th>
<th>Level</th>
<th>Marginal</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 D</td>
<td>Par</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>3 E</td>
<td>Par</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>6 F</td>
<td>Par</td>
<td>0.036</td>
<td></td>
</tr>
</tbody>
</table>

| H | Var | 275 | |
|---|-----|-----|
Massive Parallel in the Cloud

- Deployment environment: „Cloud“ (Amazon EC2)
- Up to 1,000 parallel instances (workers)
- Automated setup, including
  - Start instances
  - Prepare & Submit GAMS jobs
  - Collect results
  - Stop instances
- Python
  - Boto: Python interface to Amazon webservices
  - Setup and control of instances (Workers)
  - GAMS OO API (Python): Control of GAMS jobs
AWS Cloud Setup at xyz Company

**Local Machine**
- Client
- Storage (S3)

**Server (EC 2)**
- Master
- Worker 1
- Worker 2
- Worker n

**Configured AWS Instances**
- Python
- GAMS

**Tasks**
- Preparation of obfuscated binary model file
- Preparation of data for every worker
- Mapping of results into original namespace
- Control of instances
- Submission of model and scenario data to workers
- Collection and merge of results
Energy Systems

EMS-EDM PROPHET
Energy and Energy Data Management

Fraunhofer IOSB
Institutsteil Angewandte Systemtechnik AST
EMS-EDM PROPHET® – Modules 2015

Resource Planning System – RPS
- LP & MIP optimization
- Deterministic & Stochastic
- High Performance Solver
- Short, medium & long term
- Archiving (Oracle)
EMS-EDM PROPHET® – Customers

© 2014 Fraunhofer IOSB-AST
Optimization of power plant utilization

Technical constraints

Reserve provision: secondary reserve
[MW, normalized]

Positive SR

Negative SR

Reserve provision: tertiary reserve
(minutes reserve) [MW, normalized]

Positive MR

Negative MR

Reserve provision: hours reserve
[MW, normalized]

Positive HR

Negative HR

Reserve provision: hot standby reserve
[MW, normalized]

Load coverage: Demand [MW, normalized]
Optimization of multi-utility operation
RPS — Graphical Modeling

Graphical modeling of optimization problems

Drag ´n Drop

Power plant

© 2014 Fraunhofer IOSB-AST
RPS – Interaction with GAMS

Lade Optimierungs-DLL
Operation abgeschlossen 00:00
Lade Zeitbasis
Operation abgeschlossen: 00:00
Erzeuge Projektverzeichnis und entferne temporäre Dateien
Operation abgeschlossen: 00:00
Erzeuge GAMS-Datei ...
schreibe Komponentendeklarationen
schreibe GDX-Daten
schreibe Instanzwerte
schreibe Set-Datenwerte
schreibe Set-Datenwerte für die Startbedingungen
schreibe Tabellen
schreibe Tabelle "Startzustandstabelle [NW_BK_034]"

... Zeitbedarf GDX-Datei-Erzeugung [hh:mm:ss]: 00:00:09
schreibe Modelldaten
schreibe Instanzgleichungen
schreibe Bilanzgleichungen
schreibe Untermodellgleichungen
schreibe Objektfunktion
Schreiben der Deklarationsdatenwerte
Schreiben der Deklarationswerte abgeschlossen
Erzeuge Optionsdatei (OptFile)
Zeitbedarf GAMS-Datei-Erzeugung [hh:mm:ss]: 00:02:34

... Durchführung der Optimierung ...
[19.03.2014 01:00 - 23.03.2014 00:00]
Datei: "C:\GAMS\win64\24.3\gams.exe"
Parameter: "C:\EMS-EDM PROPHET\system\Rps-
Some Lessons Learned

- For successful applications know more than math/modeling or work with domain specific experts
- Applications (may) evolve over time: Appetite comes with eating..
- Be aware of non-technical constraints, e.g. legal requirements
Agenda

GAMS – Elements, Enhancements, and Examples

Enhancements around GAMS

Some Case Studies

Past – Presence – Future
1976 - A World Bank Slide

The Vision

RESULT:
- Limited drain of resources
- Same representation of models for humans and machines
- Model representation is also model documentation
2012 INFORMS Impact Prize

Originators of Algebraic Modeling Languages

36 Years later
**Change in Focus: Past**

### Computation
- Hardware / Algorithm
- Limits application
- Users left out
Change in Focus: **Now**

```gams
repeat
    rhs(kml) = sum(grid(kml,g)$(nwng(g)=posg(kml)), gridrhs(kml,g));
    solve mod_epsmethod maximizing a_objval using mip;
    iter-=iter+l;
    if (mod_epsmethod.modelstat<>%Mode1Stat.Optimal% and
        mod_epsmethod.modelstat<>%Mode1Stat.Integer Solution%,
        infeas=infeas+l; // not optimal is in this case infeasible
        put iter:5:0, ' infeasible' /
          lastZero = O; loop(km1$(posg(km1)>0 and lastZero=O), lastZero=numk(kml));
        posg(km1)$(numk(kml)<=lastZero) = maxg(kml); // skip all solves for more demanding
    else
        put iter:5:0;
        loop(k, put z.l(k):12:2);
        jump(kml)=l;
        * find the first off max (obj function that hasn't reach the final grid point).
        * If this obj.fun is k then assign jump for the 1..k-th objective functions
        * The jump is calculated for the innermost objective function (km=1)
          jump(kml)$(numk(kml)=1)=l+floor(sl.L(kml)/step(kml));
          loop(kml$ jump(kml)>1), put ' jump');
        put ;
    );
* Proceed forward in the grid
  firstOffMax = 0;
  loop(kml$(posg(kml)<maxg(kml) and firstOffMax=0),
    posg(kml)=min((posg(kml)+jump(kml)),maxg(kml)); firstOffMax=numk(kml));
  posg(kml)$>maxg(kml)firstOffMax = 0;
until sum
```

**Computation**
- Hardware / Algorithm
- Limits application
- Users left out

**Model**
- Modeling skill limits
- Applications
- Users involved
Progress in LP: 1988—2004

- Algorithms (*machine independent*):
  - Primal *versus* best of Primal/Dual/Barrier: \(3,300x\)
- Machines (workstations \(\rightarrow\) PCs):
  \(1,600x\)
- NET: Algorithm \(*\) Machine: \(5,300,000x\)
  (2 months/5300000 \(\approx\) 1 second)

Robert E. Bixby
Gurobi Optimization & Rice University
Change in **Focus: Now**

**Mathematical Optimization**
- Computation
- Well defined (narrow) application area
- Small set of methods (LP, MIP, NLP, ...)
- Small amounts of (structured) data
- Visualization?
- Niche market

**Business Analytics**
- Application
- Broad application area
- Wide range of methods
- Huge amounts of data
- Visualization crucial
- Big market

**Application**
- Embedded Models
- User hardly aware of model
Change in **Focus: Future**

“*I never predict. I just look out the window and see what is visible – but not yet seen*”  
(Peter Drucker)
Algebraic Problem Representation

Model as a communication device

- Helps defining the problem
- Gives structure for efficient (inter-team) communication
- Provides (data) contract between different parts of the application
- Executable description of the problem

Effort for model development is often small compared to the effort required for the rest of application
Evolving Solver-Links

GAMS provides uniform interface to all major solvers

Often new and interesting algorithmic features driven by implementation choices

But: Using solver specific features prevents easy exchange of solvers
Evolving **Solver-Links**

Challenge: Find a concept that combines the essentials of new features independent of the particular implementation choices. Examples:

- **Logical Constraints:** \( If \ y = 1 \Rightarrow x_1 + x_2 + x_3 = 0; \)
- **BigM-Formulation**
  \[ \text{constr01}.. \ x_1 + x_2 + x_3 = M*(1-y); y \in \{0,1\}; \]
- **Indicator Constraints (CPLEX, XPRESS, SCIP):**
  \[ \text{constr01}.. \ x_1 + x_2 + x_3 = 0; \text{indic} \ \text{constr01}$y1 \]
- **Alternative: SOS1 (GUROBI):**
  \[ \text{constr01}.. \ x_1 + x_2 + x_3 = M; \text{SOS1:}(y, M); \]
- **(Generalized) Disjunctive Programming (Grossmann)**

- **Stochastic Programming** - supported solvers through EMP/SP
Stochastic Programming EMP/SP

- Simple interface to add uncertainty to existing deterministic models
- (EMP) Keywords to describe uncertainty include: discrete and parametric random variables, stages, chance constraints, Value at Risk, ...
- Available solution methods:
  - Automatic generation of Deterministic Equivalent (can be solved with any solver)
  - Specialized commercial algorithms (DECIS, LINDO)
Open architecture and interfaces

Frequently optimization models only (important) element of larger system

GAMS provides environment to build robust and fail safe systems, because optimization

• May take longer than one is willing to wait
• Will eventually fail
Open architecture and interfaces

Don’t lock developers and users into a certain environment. Adjust for:

- Advancing hardware and computer paradigms (e.g. cloud computing)
- New solver technology and solution methods
- New graphical user interfaces and deployment environments
Small Community:
- 2010 ~ 64k OR Analytic Professionals in the US
- INFORMS 10-12k members
GENERAL ALGEBRAIC MODELING SYSTEM

to Application Building

- Software Architecture, Object Oriented Design
- Components, Encapsulation, Classes, Data Access Layer,
- Agile Programming, Mesh,

Huge Community:
- 2006 ~ 3.3 Mill. IT Professionals in the US
- Rapidly changing IT environments
(Some of the) **Issues**

- Role of Optimization within Application
- **Generalist** (domain expert and modeling expert and IT expert) versus **Team of Specialists**
- Quality of Data
- **Standalone** Application or **Integration**
- Lifecycle of Application
Example: All in One – **Top Down**

**Monolithic Application**

- Established Application Interface
- AML
- Analytical Software
- Solver

- Add “AML” to existing analytical software system
- “large” user base, e.g. MATLAB, or SAS
Example: All in One – **Bottom Up**

- Integrate GUI-builder into AML
- “small” user base, e.g. AIMMS (Pro) or FICO Xpress-Insight
Example: **Composite Application**

- "Construction Kit" with different connected elements
- Use existing frameworks to build applications, e.g. Oracle Application Express, MS .NET, IBM ODME, ....
- OO API to connect to framework
Summary

GAMS – Elements, Enhancements, and Examples

- Simple, but powerful language
- Designed to interact
- Evolution through more than 25 years of R&D and user feedback
- Maturity through experience and rigorous testing

Striving for Innovation and Compatibility

- Increase productivity
- Provide cutting edge technology
- Don’t lock developers and users into a certain environment
- Protect investments of users
• Steve Dirkse, GAMS Development
• An Introduction to Model Development with GAMS
• Monday, 1:50-2:40 pm
• Room: Goldenwest
Thank You

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