



# HeuristicLab

A Paradigm-Independent and Extensible  
Environment for Heuristic Optimization

# Algorithm and Experiment Design with HeuristicLab

An Open Source Optimization Environment for  
Research and Education

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**HEAL**

Heuristic and Evolutionary  
Algorithms Laboratory



Heuristic  
Optimization in  
Production and  
Logistics

# Instructor Biographies

- Stefan Wagner
  - Full professor for complex software systems (since 2009)  
University of Applied Sciences Upper Austria
  - Co-founder of the HEAL research group
  - Project manager and chief architect of HeuristicLab
  - PhD in technical sciences (2009)  
Johannes Kepler University Linz, Austria
  - Associate professor (2005 – 2009)  
University of Applied Sciences Upper Austria
  - <http://heal.heuristiclab.com/team/wagner>
- Gabriel Kronberger
  - Full professor for business intelligence (since 2011)  
University of Applied Sciences Upper Austria
  - Member of the HEAL research group
  - Architect of HeuristicLab
  - PhD in technical sciences (2010)  
Johannes Kepler University Linz, Austria
  - Research assistant (2005 – 2011)  
University of Applied Sciences Upper Austria
  - <http://heal.heuristiclab.com/team/kronberger>



# Agenda

- Objectives of the Tutorial
- Introduction
- Where to get HeuristicLab?
- Plugin Infrastructure
- Graphical User Interface
- Available Algorithms & Problems
- **Demonstration Part I: Working with HeuristicLab**
- **Demonstration Part II: Data-based Modeling**
- Some Additional Features
- Planned Features
- Team
- Suggested Readings
- Bibliography
- Questions & Answers

# Objectives of the Tutorial

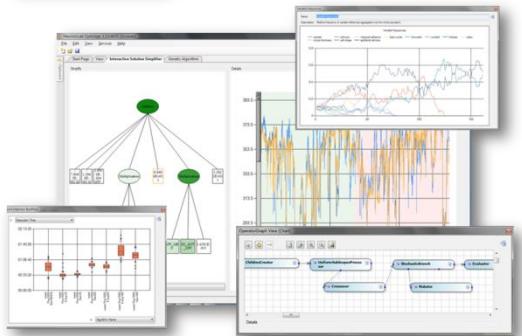
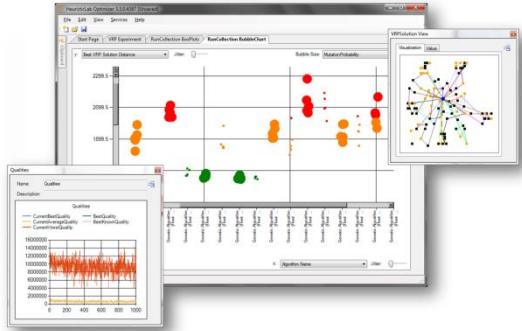


- Introduce general motivation and design principles of HeuristicLab
- Show where to get HeuristicLab
- Explain basic GUI usability concepts
- Demonstrate basic features
- Demonstrate editing and analysis of optimization experiments
- Demonstrate custom algorithms and graphical algorithm designer
- Demonstrate data-based modeling features
- Outline some additional features

# Introduction



- Motivation and Goals
  - graphical user interface
  - paradigm independence
  - multiple algorithms and problems
  - large scale experiments and analyses
  - parallelization
  - extensibility, flexibility and reusability
  - visual and interactive algorithm development
  - multiple layers of abstraction
  
- Facts
  - development of HeuristicLab started in 2002
  - based on Microsoft .NET and C#
  - used in research and education
  - second place at the *Microsoft Innovation Award 2009*
  - open source (GNU General Public License)
  - version 3.3.0 released on May 18th, 2010
  - latest version 3.3.11 “Beach Bar” released on February 13th, 2015



# Where to get HeuristicLab?



- Download binaries
  - deployed as ZIP archives
  - latest stable version 3.3.11 “Beach Bar”
    - released on February 13th, 2015
  - daily trunk builds
  - <http://dev.heuristiclab.com/download>
- Check out sources
  - SVN repository
  - HeuristicLab 3.3.11 tag
    - <http://svn.heuristiclab.com/svn/core/tags/3.3.11>
  - Stable development version
    - <http://svn.heuristiclab.com/svn/core/stable>
- License
  - GNU General Public License (Version 3)
- System requirements
  - Microsoft .NET Framework 4.5
  - enough RAM and CPU power ;-)

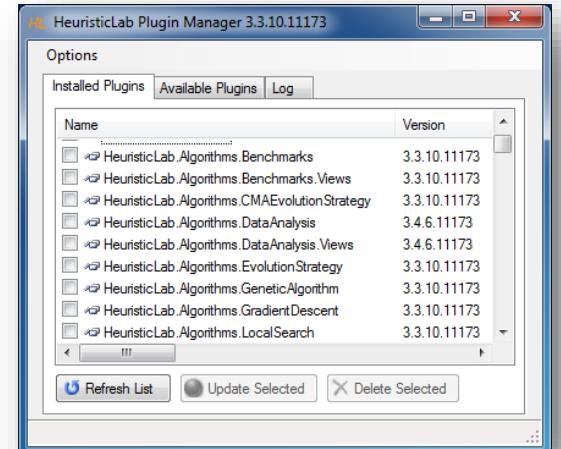
The screenshot shows the HeuristicLab website homepage. At the top right is a navigation bar with links for 'Login', 'Preferences', 'Home', 'News', 'Download', 'Features', 'Documentation', 'Support', 'Search', 'Start Page', 'Index', and 'History'. Below the navigation is a main content area with a heading 'HeuristicLab' and a sub-heading 'A Paradigm-Independent and Extensible Environment for Heuristic Optimization'. A 'WikiStart' link is also present. The central part of the page features a 'HeuristicLab Tour' section with a screenshot of the software interface showing a tree search and a graph. To the right of the tour is a list of features:

- Graphical User Interface
- Algorithm Prototyping
- Evolutionary Algorithms
- Genetic Programming
- Data Analysis
- Simulation-based Optimization
- Experiment Design and Analysis
- Plugin-based Architecture

A 'Download HeuristicLab 3.3' button is located below this list. On the left side of the main content area, there is a 'Research & Publications' section with a photo of a team, a 'License' section with the GPL logo, and a 'Contribute' section with a yellow stick figure icon. On the right side, there is a 'Join the discussion at the HeuristicLab group' section with an 'Email:' input field, a 'Subscribe' button, and a 'Visit group' button. At the bottom of the page, there is a 'Thank you!' message, a 'ReSharper' logo with a note of thanks to JetBrains, a 'Download in other formats:' section with 'Plain Text' and 'Last modified 6 weeks ago' links, and a note about the Trac open source project.

# Plugin Infrastructure

- HeuristicLab consists of many assemblies
  - 151 plugins in HeuristicLab 3.3.11
  - plugins can be loaded or unloaded at runtime
  - plugins can be updated via internet
  - application plugins provide GUI frontends
- Extensibility
  - developing and deploying new plugins is easy
  - dependencies are explicitly defined, automatically checked and resolved
  - automatic discovery of interface implementations (service locator pattern)
- Plugin Manager
  - GUI to check, install, update or delete plugins



# Plugin Architecture



Optimization

Unit Tests

Analysis

Encodings.\*

Problems.\*

Algorithms.\*

Random

Selection

Optimization.Operators

\*Engine

Scripting

Operators.\*

Optimization

Core

GraphVisualization

Optimizer

Core

Data

Parameters

Instances.\*

Base

Clients.Common

Collections

Tracing/Logging

Persistence

WindowsForms

CodeEditor

MainForm

ControlExtensions

Foundation

Common, Resources, External Libraries

PluginInfrastructure

Microsoft .NET 4.5

Models

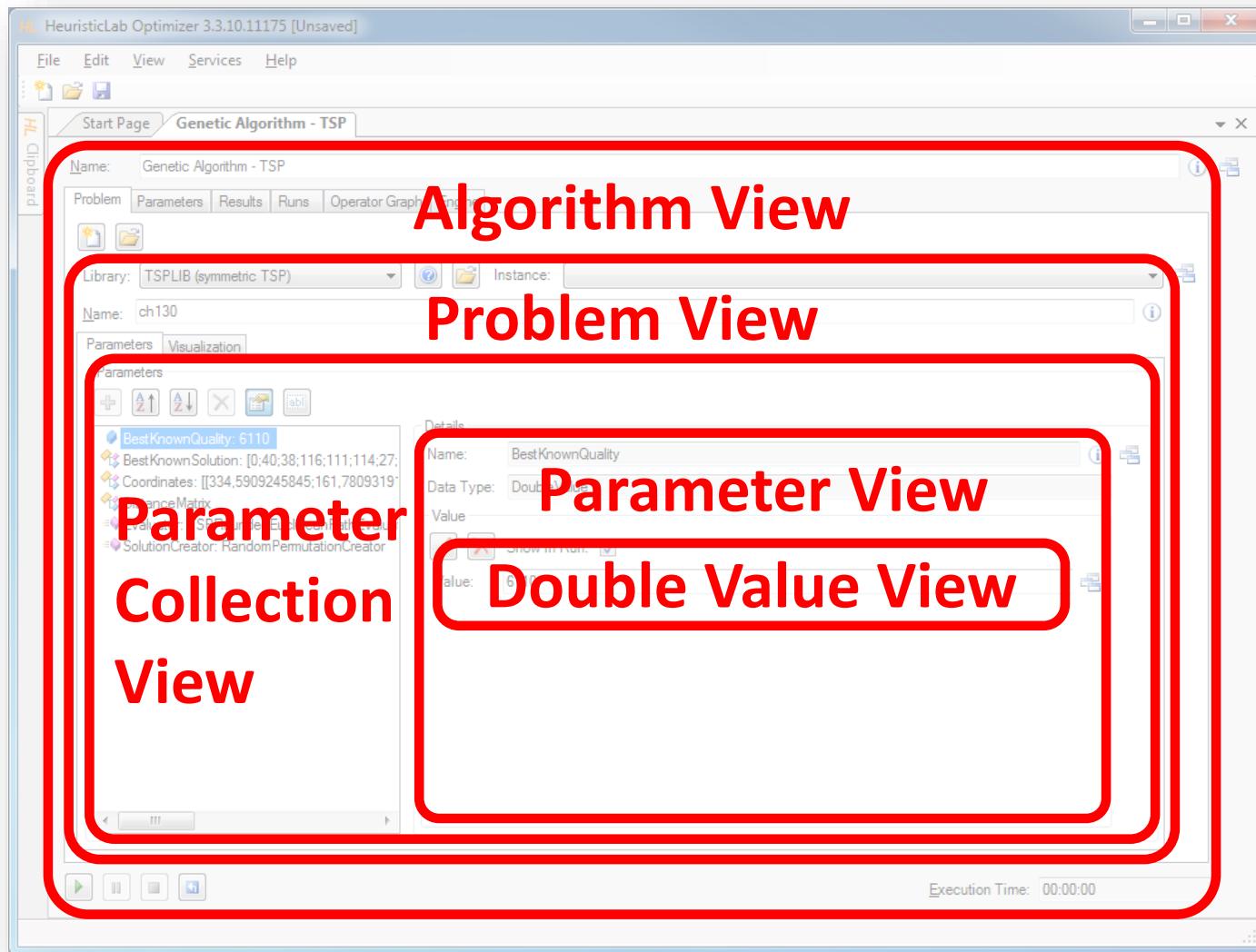
Views

# Graphical User Interface



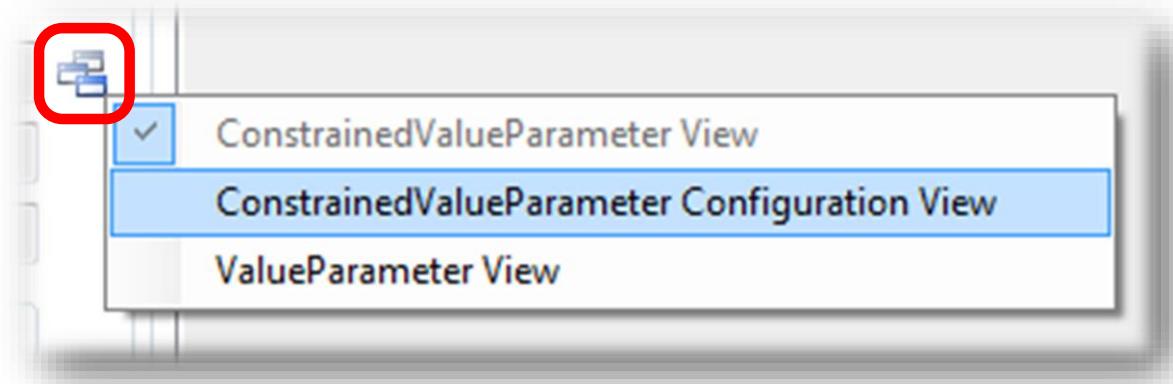
- HeuristicLab GUI is made up of views
  - views are visual representations of content objects
  - views are composed in the same way as their content
  - views and content objects are loosely coupled
  - multiple different views may exist for the same content
- Drag & Drop
  - views support drag & drop operations
  - content objects can be copied or moved (shift key)
  - enabled for collection items and content objects

# Graphical User Interface



# Graphical User Interface

- ViewHost
  - control which hosts views
  - right-click on windows icon to switch views
  - double-click on windows icon to open another view
  - drag & drop windows icon to copy contents



# Available Algorithms

## Population-based

- CMA-ES
- Evolution Strategy
- Genetic Algorithm
- Offspring Selection Genetic Algorithm
- Island Genetic Algorithm
- Island Offspring Selection Genetic Algorithm
- Parameter-less Population Pyramid (P3)
- SASEGASA
- Relevant Alleles Preserving GA (RAPGA)
- Genetic Programming
- NSGA-II
- Scatter Search
- Particle Swarm Optimization

## Trajectory-based

- Local Search
- Tabu Search
- Robust Taboo Search
- Variable Neighborhood Search
- Simulated Annealing

## Data Analysis

- Linear Discriminant Analysis
- Linear Regression
- Multinomial Logit Classification
- k-Nearest Neighbor
- k-Means
- Neighbourhood Component Analysis
- Artificial Neural Networks
- Random Forests
- Support Vector Machines
- Gaussian Processes

## Additional Algorithms

- User-defined Algorithm
- Performance Benchmarks
- Hungarian Algorithm
- Cross Validation
- LM-BFGS

# Available Problems

## Combinatorial Problems

- Traveling Salesman
- Vehicle Routing
- Knapsack
- Job Shop Scheduling
- Linear Assignment
- Quadratic Assignment
- OneMax
- Deceptive trap
- Deceptive trap step
- HIFF

## Additional Problems

- Single-Objective Test Function
- User-defined Problem
- Programmable Problem
- External Evaluation Problem  
(Anylogic, Scilab, MATLAB)
- Regression, Classification, Clustering
- Trading
- Grammatical Evolution

## Genetic Programming Problems

- Symbolic Classification
- Symbolic Regression
- Symbolic Time-Series Prognosis
- Artificial Ant
- Lawn Mower

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# Demonstration Part I: Working with HeuristicLab



- Create, Parameterize and Execute Algorithms
- Save and Load Items
- Create Batch Runs and Experiments
- Multi-core CPUs and Parallelization
- Analyze Runs
- Analyzers
- Building User-Defined Algorithms

# HeuristicLab Optimizer



The screenshot shows the HeuristicLab Optimizer 3.3.10.11175 application window. The left side features a toolbar with icons for file operations like Open, Save, and Import. Below the toolbar is a navigation bar with tabs: Start Page (selected), Problem, Parameters, Results, and Help. The main content area displays the "Start Page" with the title "HeuristicLab Optimizer 3.3.10.11175". It includes instructions for starting work, a numbered list of steps for algorithm management, and a section for predefined algorithms. A red box highlights the "Samples" section on the right, which lists various optimization problems and scripts. Red text overlaid on this section reads "double-click to open sample algorithms and problems".

HL HeuristicLab Optimizer 3.3.10.11175

File Edit View Services Help

Start Page

## HeuristicLab Optimizer 3.3.10.11175

Follow these steps to start working with HeuristicLab Optimizer:

1. Open an algorithm
  - click (New Item) in the toolbar and select an algorithm or click (Open File) in the toolbar and load an algorithm from a file
2. Open a problem in the algorithm
  - in the Problem tab of the algorithm click (New Problem) and select a problem or click (Open Problem) and load a problem from a file
3. Set parameters
  - set problem parameters in the Problem tab of the algorithm
  - set algorithm parameters in the Parameters tab of the algorithm
4. Run the algorithm
  - click (Start/Resume Algorithm) to execute the algorithm (if the button is grayed out some parameters of the algorithm or the problem still have to be set)
  - wait for the algorithm to terminate or click (Pause Algorithm) to interrupt its execution or click (Stop Algorithm) to stop its execution
5. Check results
  - check the results on the Results tab of the algorithm
  - click (Start/Resume Algorithm) to continue the algorithm or click (Reset Algorithm) to prepare a new run

Looking for predefined algorithms which can be executed immediately?

- check out the **sample algorithms** below

Any feedback, questions, problems or requests for new features?

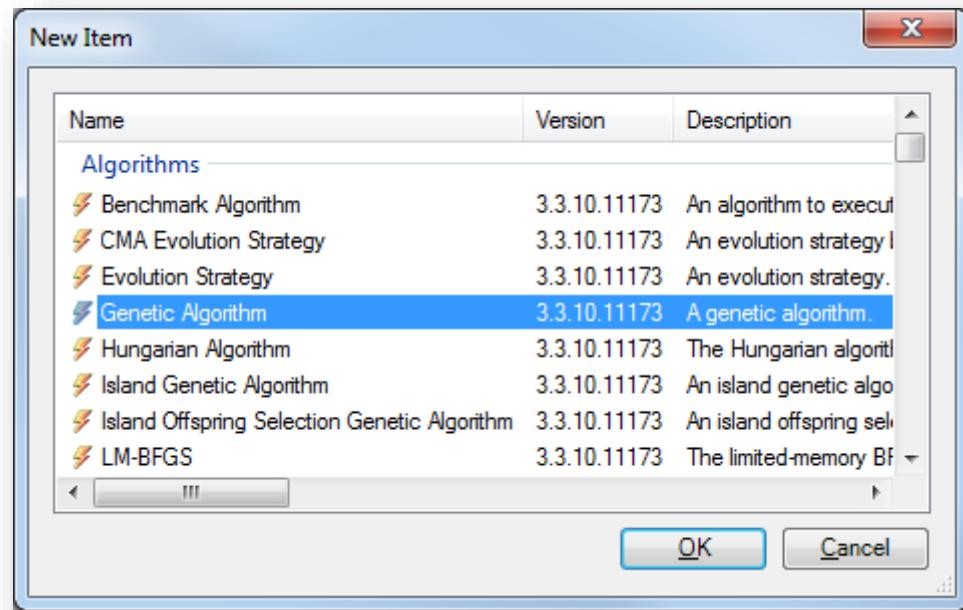
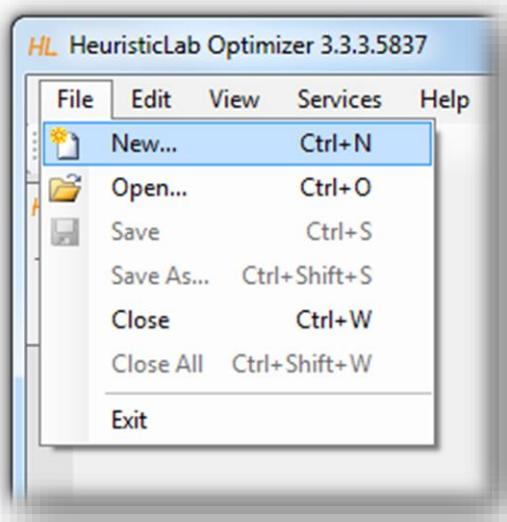
- visit the HeuristicLab trac at <http://dev.heuristiclab.com>
- watch the HeuristicLab video tutorials at <http://www.youtube.com/heuristiclab>
- join the HeuristicLab mailing list <mailto:heuristiclab@googlegroups.com>
- visit the HeuristicLab facebook site at <http://www.facebook.com/heuristiclab>
- write an e-mail to <mailto:support@heuristiclab.com> to contact the HeuristicLab

Show Start Page on Startup

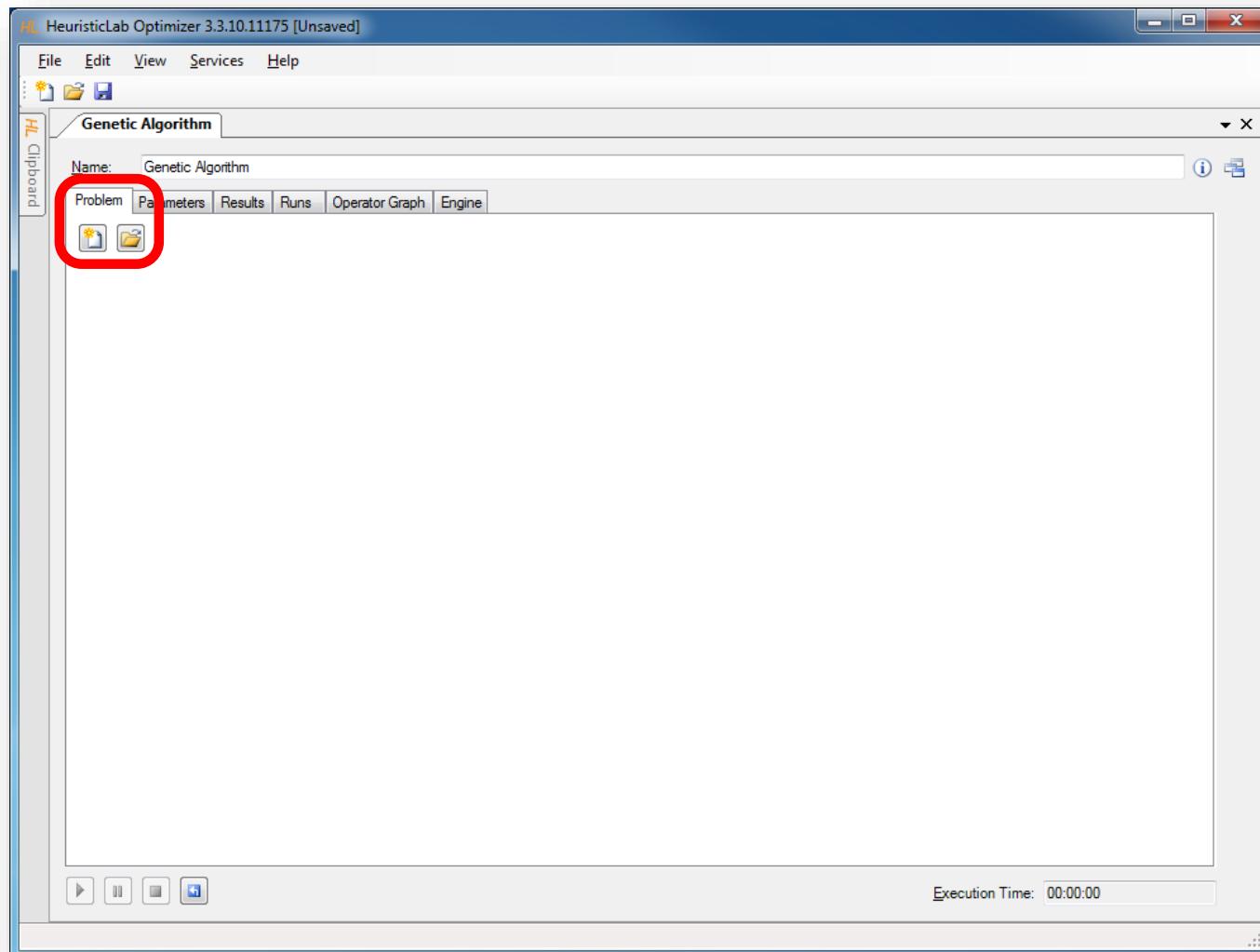
Samples

Name	Description
Standard Problems	
Evolution Strategy - Griewank	An evolution strat
Genetic Algorithm - TSP	A genetic algorith
Genetic Algorithm - VRP	A genetic algorith
Genetic Programming - Artificial Ant	A standard geneti
Genetic Programming - Multiplexer 11 problem	A genetic program
Grammatical Evolution - Artificial Ant (SantaFe)	Grammatical evoluti
Island Genetic Algorithm - TSP	An island genetic
Local Search - Knapsack	A local search alg
Particle Swarm Optimization - Schwefel	A particle swarm o
Particle Swarm Optimization - Rastrigin	A particle swarm o
Scatter Search - TSP	A scatter search alg
Simulated Annealing - Rastrigin	A simulated anneal
Taillard Benchmark Problem	A taillard search alg
Taillard Benchmark Problem	A taillard search alg
Variable Neighborhood Search - TSP	A variable neighb
Data Analysis	
Gaussian Process Regression	A Gaussian proce
Genetic Programming - Symbolic Classification	A standard geneti
Genetic Programming - Symbolic Regression	A standard geneti
Genetic Programming - Time Series Prediction (Mackey-Glass-17)	A genetic program
Grammatical Evolution - Symbolic Regression (Poly-10)	Grammatical evoluti
Scripts	
Genetic Algorithm Script - QAP	A scripted genetic
GUI Automation Script	A script that runs
Offspring Selection Genetic Algorithm Script - Rastrigin	A scripted offsprin

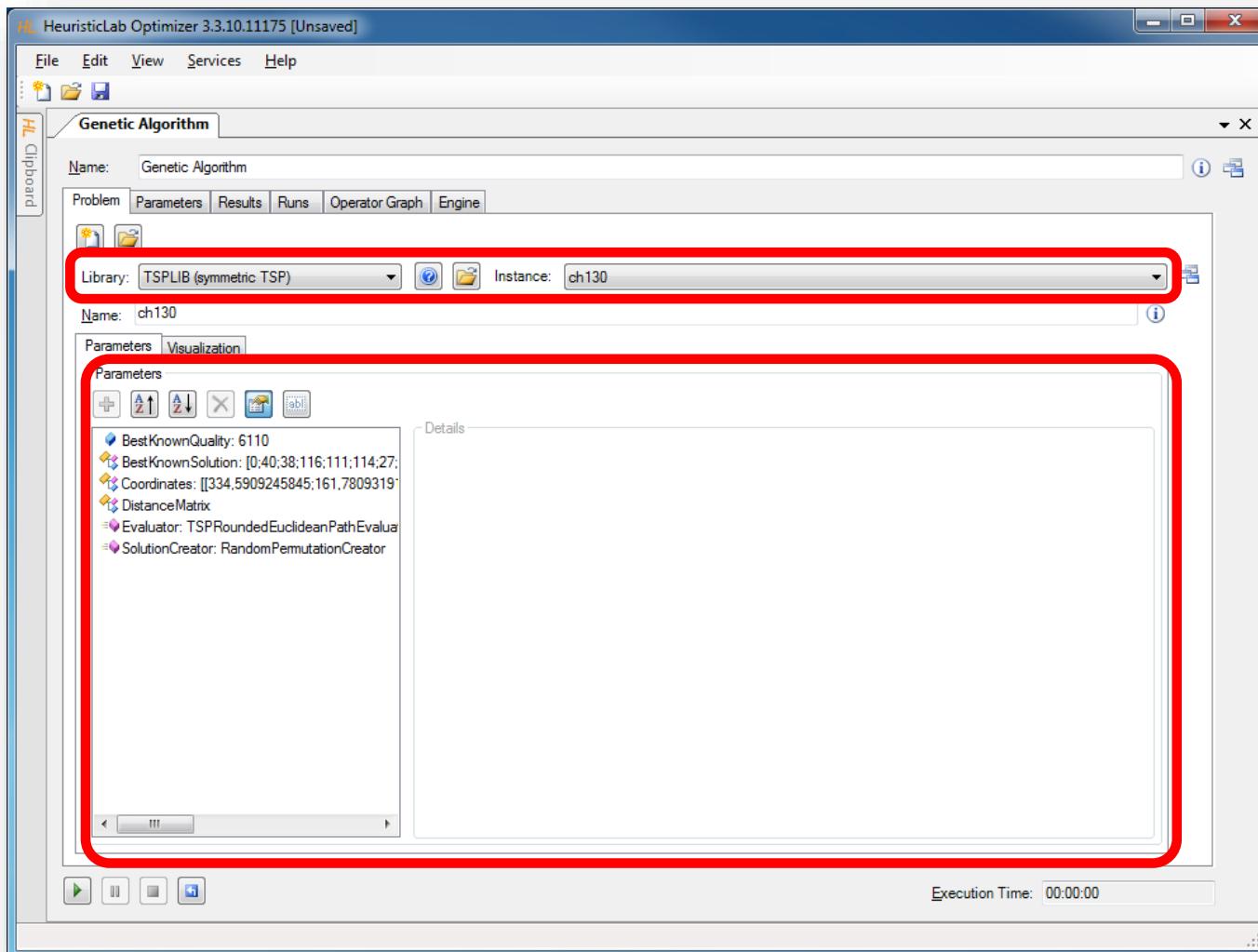
# Create Algorithm



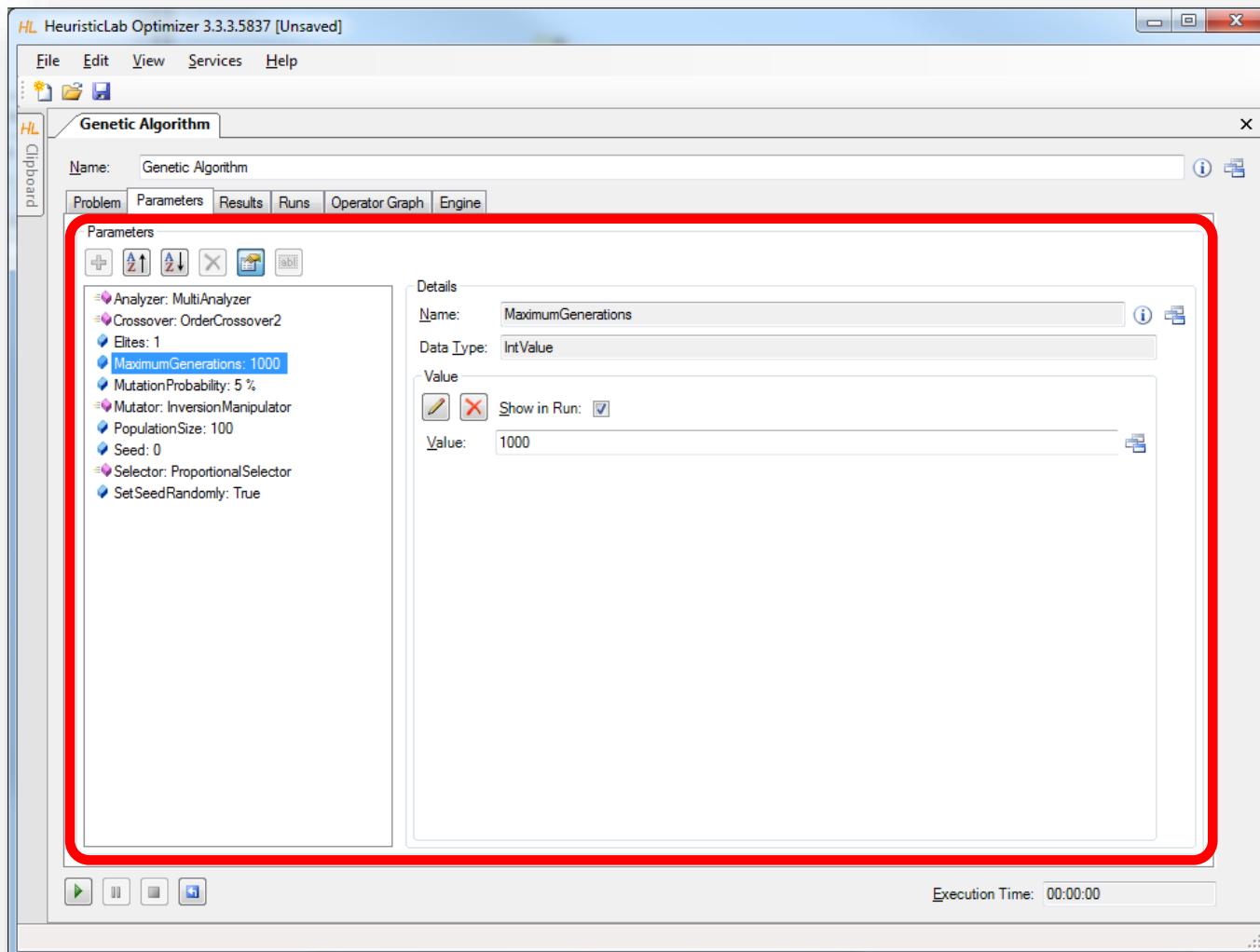
# Create or Load Problem



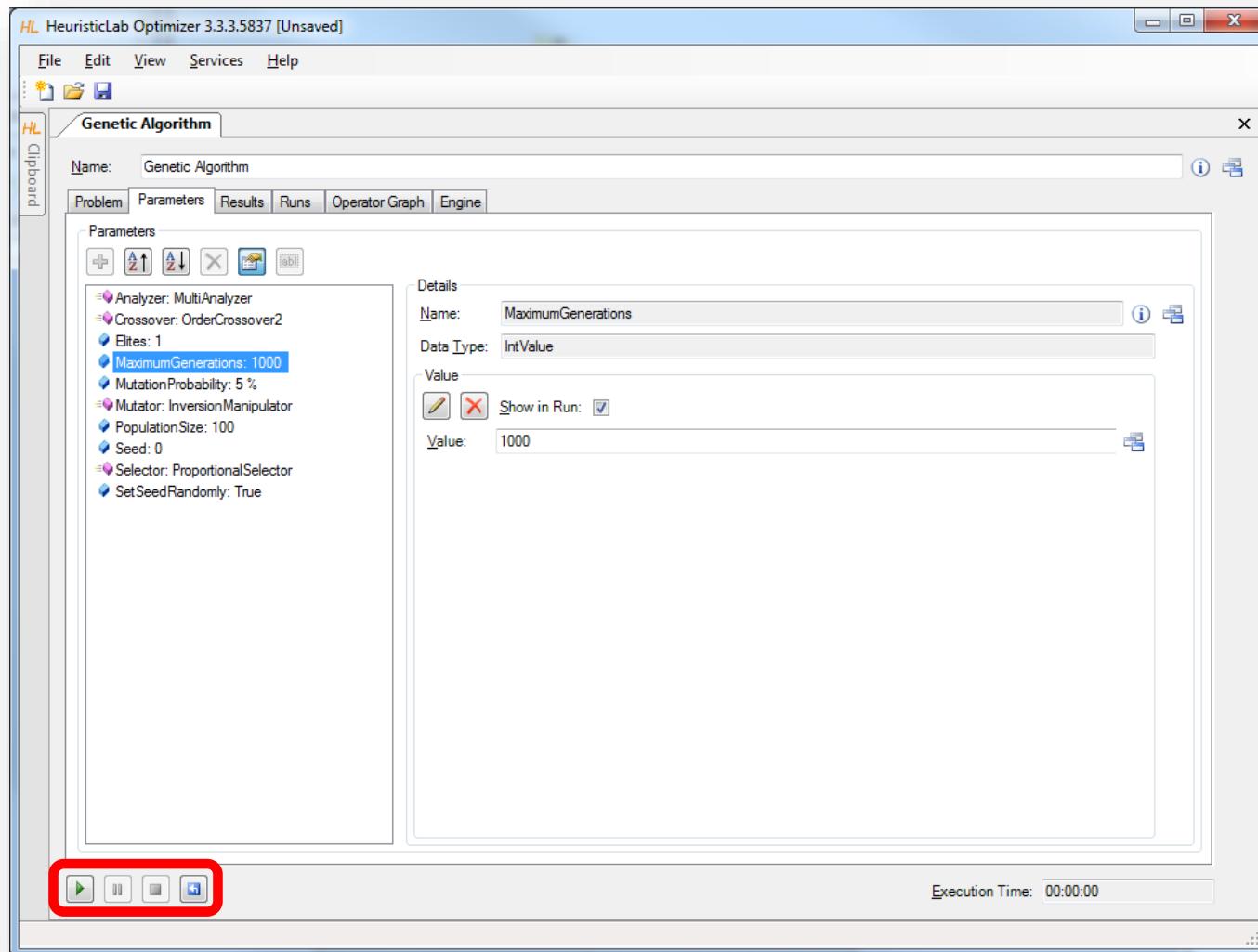
# Import or Parameterize Problem Data



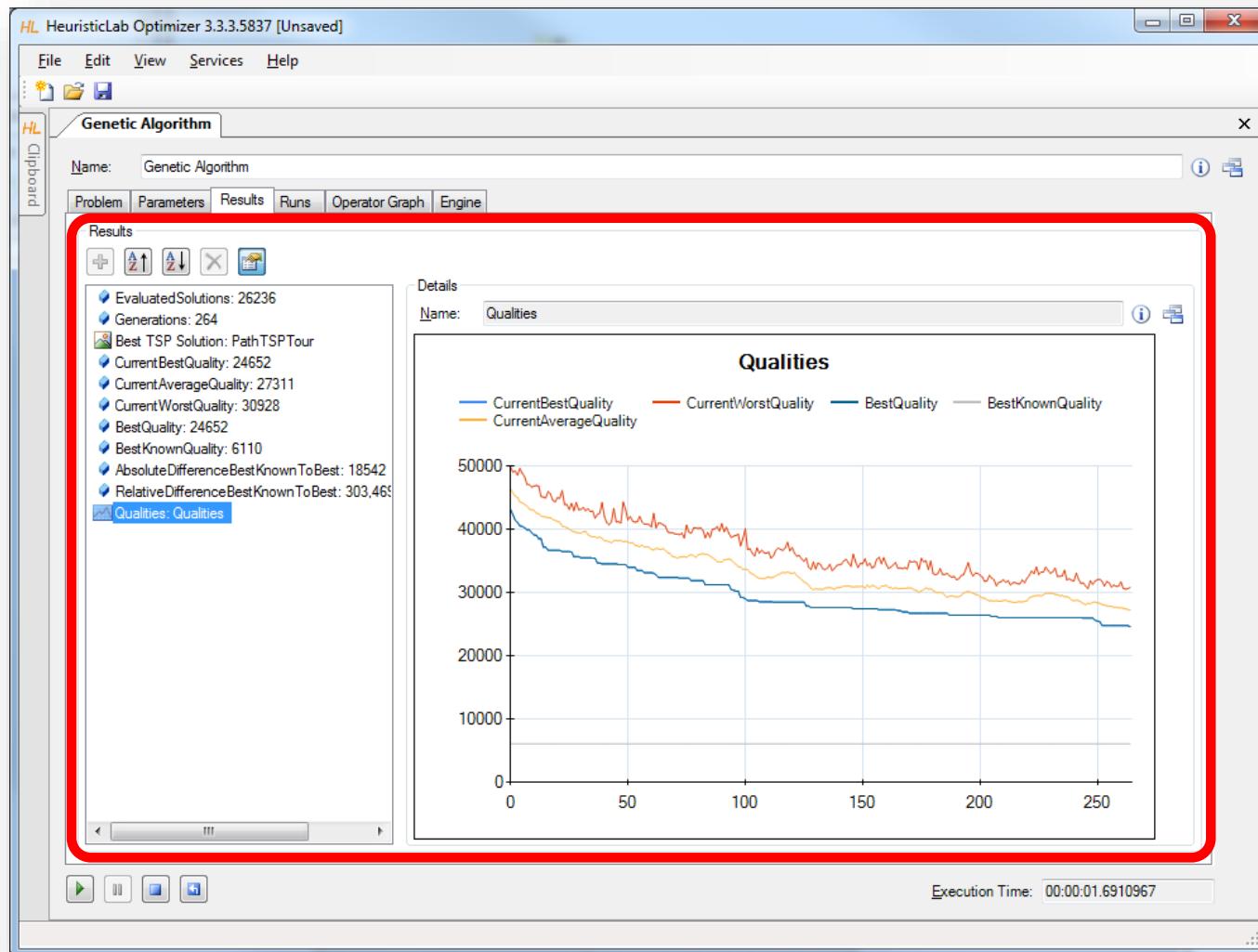
# Parameterize Algorithm



# Start, Pause, Resume, Stop and Reset

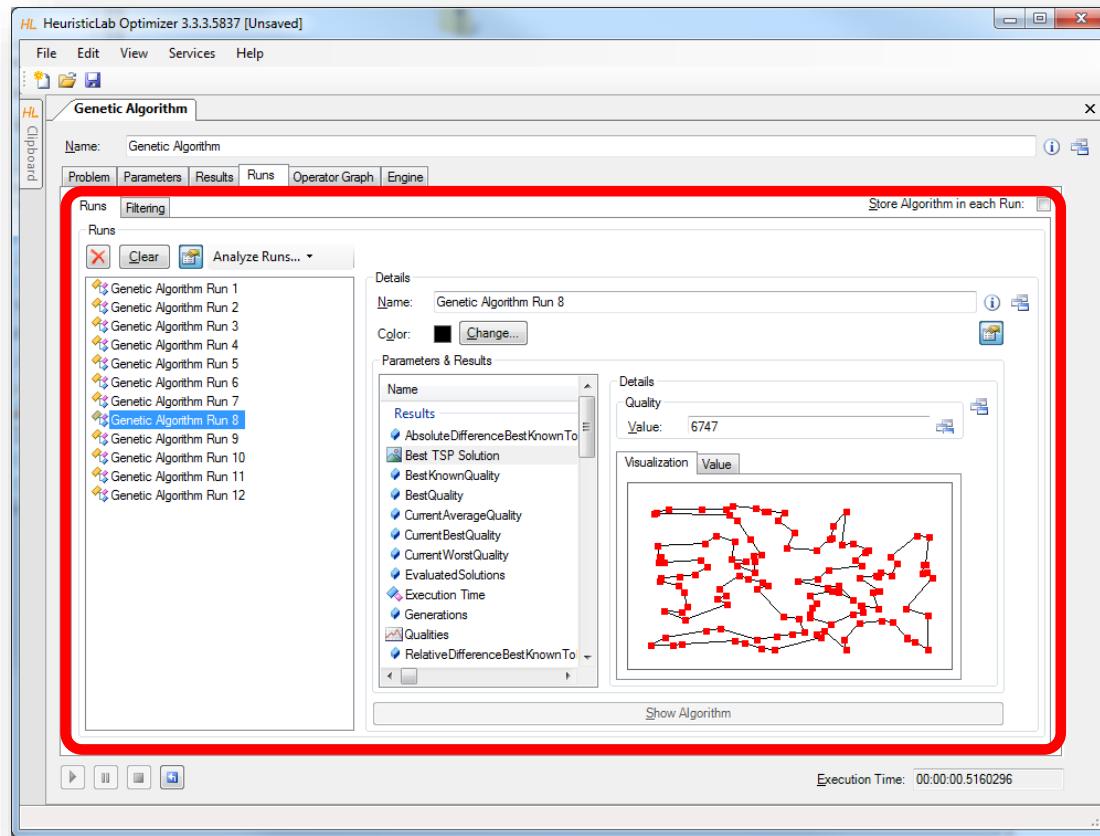


# Inspect Results



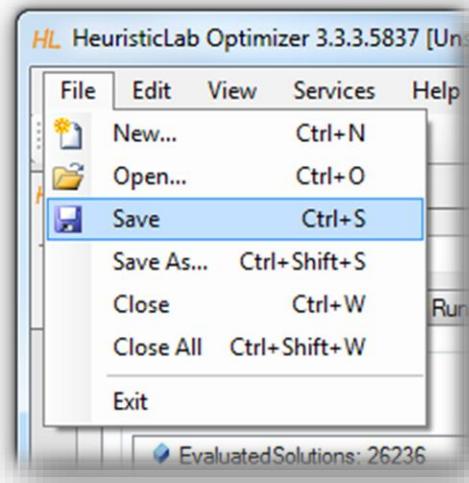
# Compare Runs

- A run is created each time when the algorithm is stopped
  - runs contain all results and parameter settings
  - previous results are not forgotten and can be compared



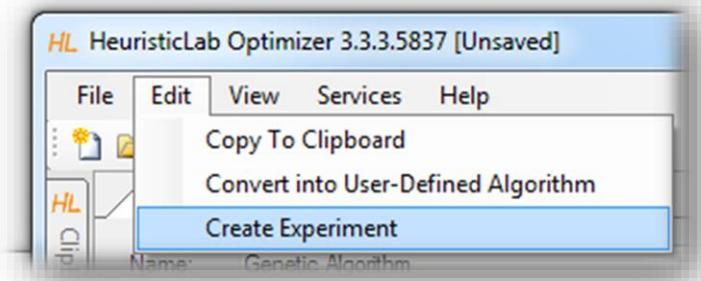
# Save and Load

- Save to and load from disk
  - HeuristicLab items (i.e., algorithms, problems, experiments, ...) can be saved to and loaded from a file
  - algorithms can be paused, saved, loaded and resumed
  - data format is custom compressed XML
  - saving and loading files might take several minutes
  - saving and loading large experiments requires some memory

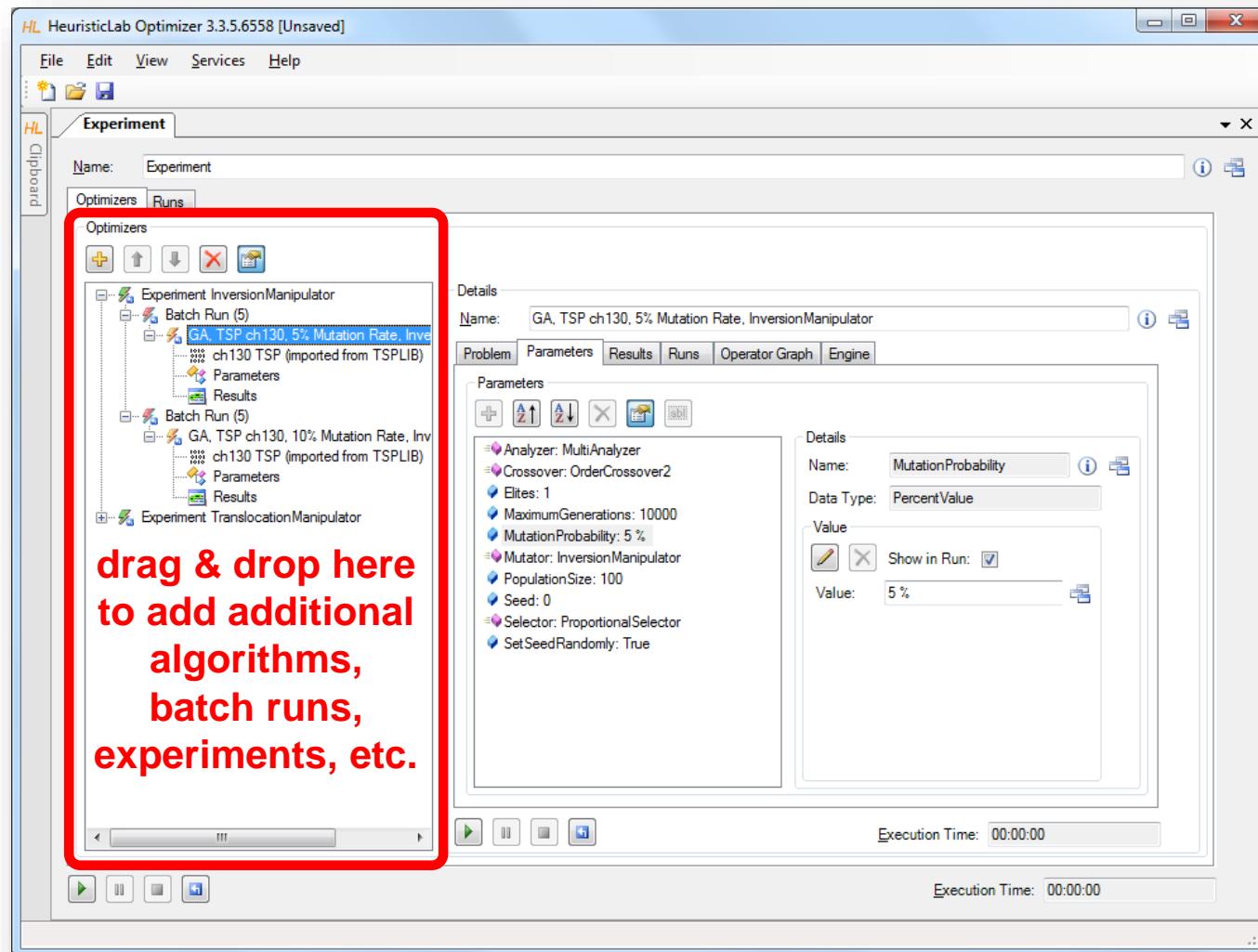


# Create Batch Runs and Experiments

- Batch runs
  - execute the same optimizer (e.g. algorithm, batch run, experiment) several times
- Experiments
  - execute different optimizers
  - suitable for large scale algorithm comparison and analysis
- Experiments and batch runs can be nested
- Generated runs can be compared afterwards

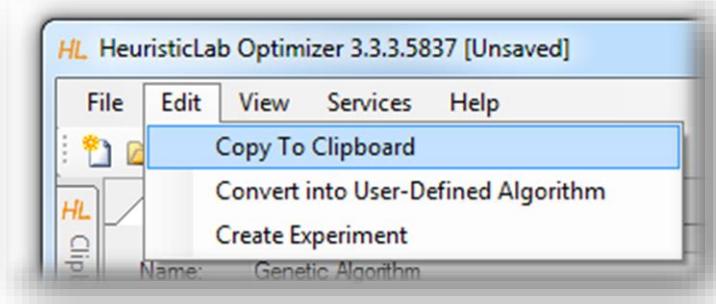


# Create Batch Runs and Experiments



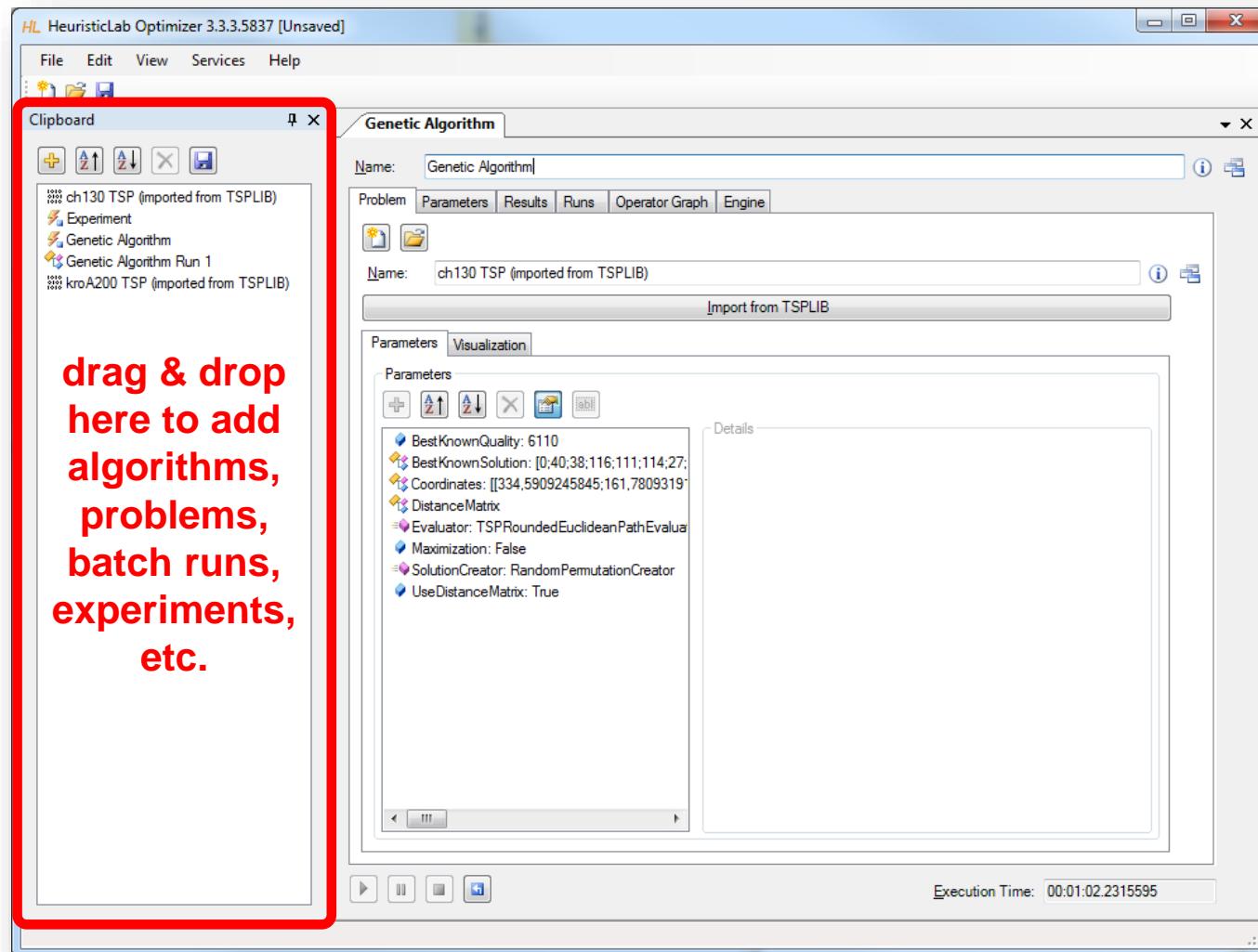
# Clipboard

- Store items
  - click on the buttons to add or remove items
  - drag & drop items on the clipboard
  - use the menu to add a copy of a shown item to the clipboard

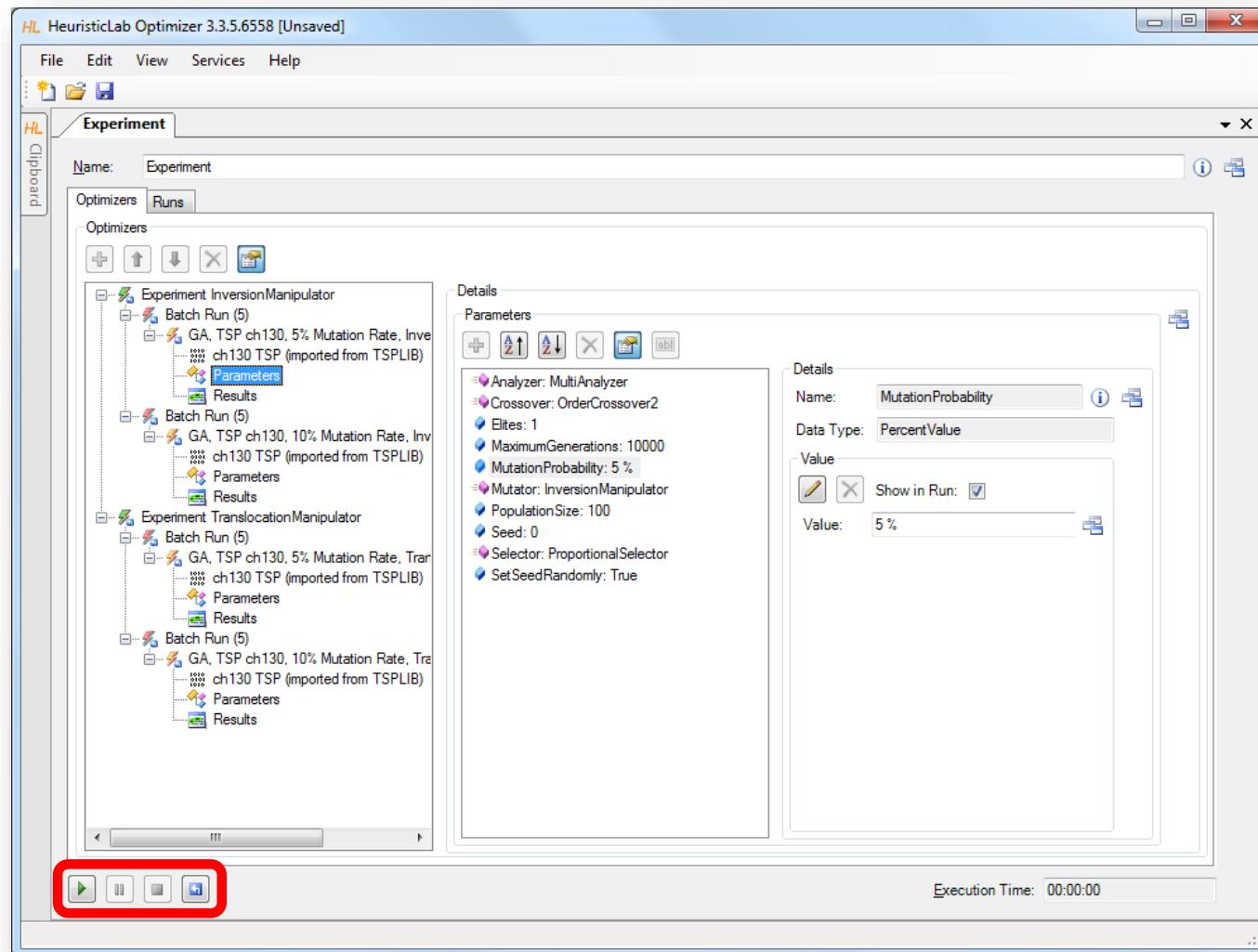


- Show items
  - double-click on an item in the clipboard to show its view
- Save and restore clipboard content
  - click on the save button to write the clipboard content to disk
  - clipboard is automatically restored when HeuristicLab is started the next time

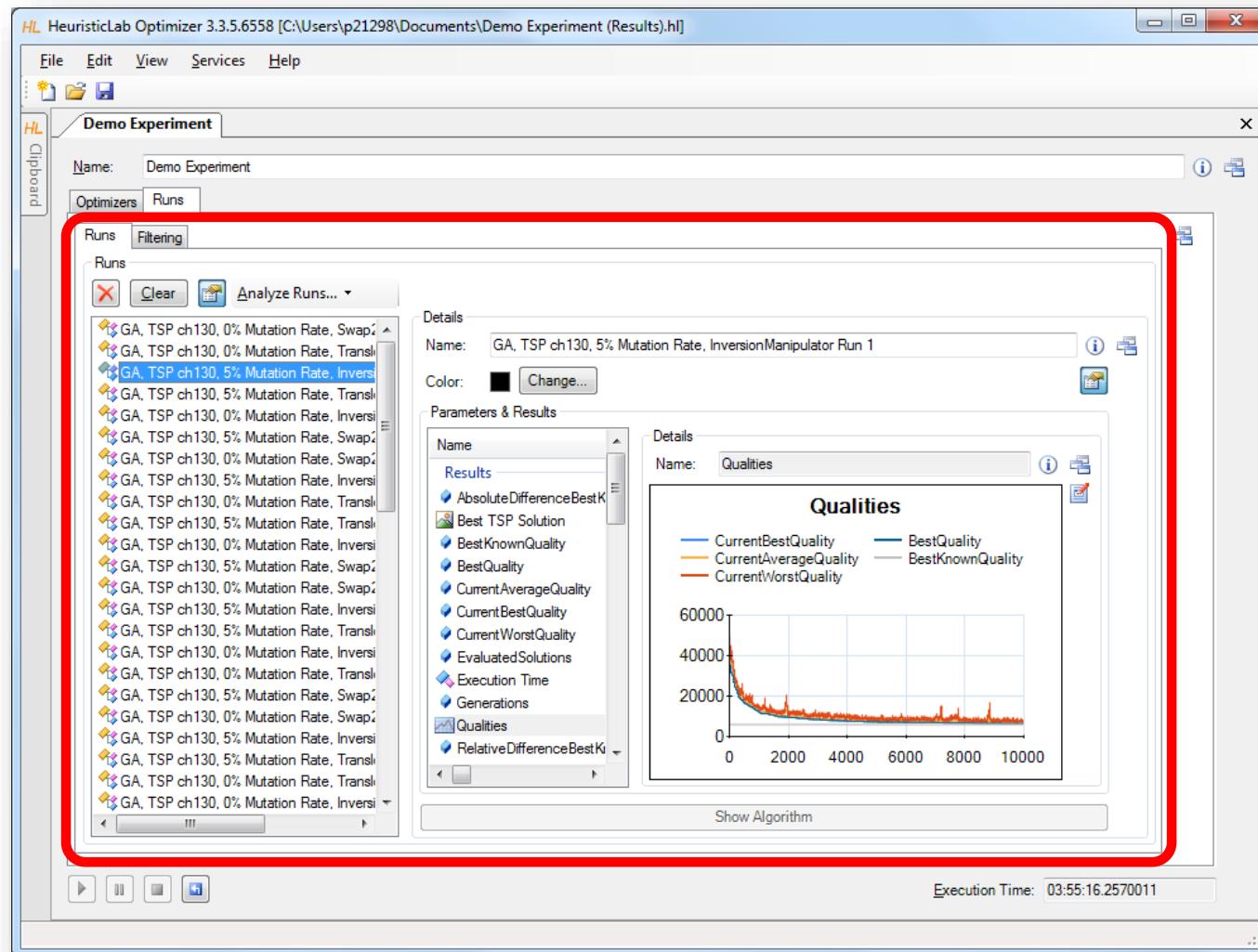
# Clipboard



# Start, Pause, Resume, Stop, Reset

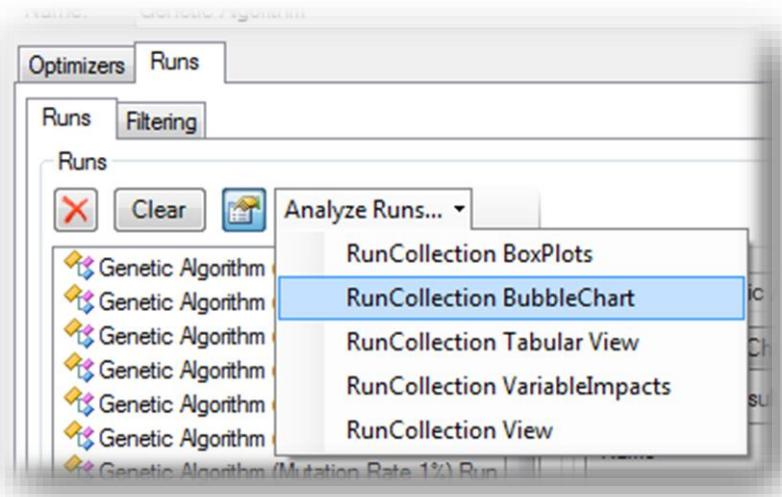


# Compare Runs



# Analyze Runs

- HeuristicLab provides interactive views to analyze and compare all runs of a run collection
  - textual analysis
    - RunCollection Tabular View
  - graphical analysis
    - RunCollection BubbleChart
    - RunCollection BoxPlots
- Filtering is automatically applied to all open run collection views



# Runs – Tabular View

HL HeuristicLab Optimizer 3.3.3.5837 [Unsaved]

File Edit View Services Help

Genetic Algorithm RunCollection Tabular View

Rows: 30 Columns: 48

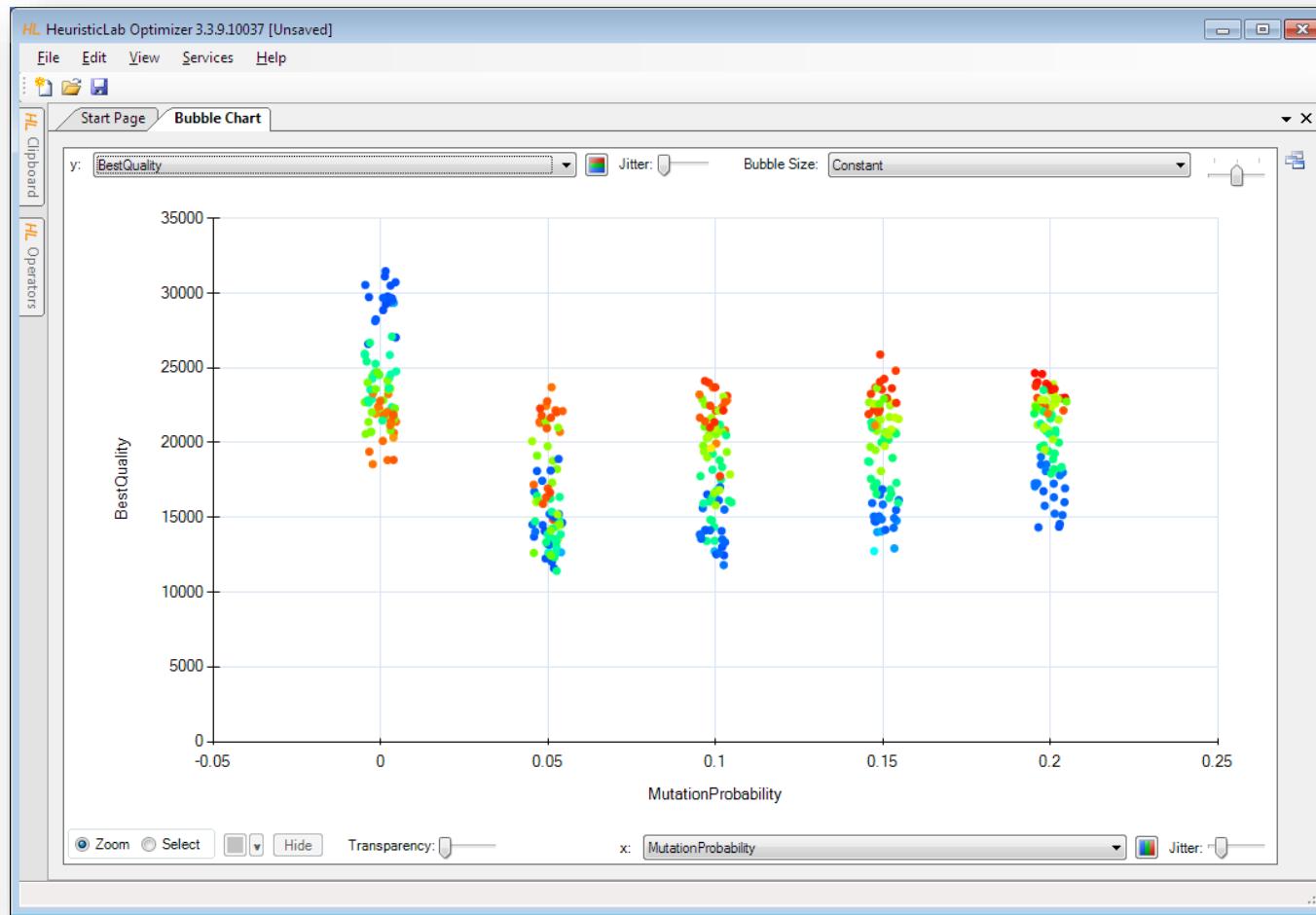
	BestKnownQuality	Best Known Solution	BestQuality	Coordinates	Crossover	CurrentAverageQuality
▶ Genetic Algorithm (Mutation Rate 1%) Run 13	5110	[0;40;38;116;111;114;...]	16405	[[334,5909245...]	OrderCrosso...	16543,13
Genetic Algorithm (Mutation Rate 1%) Run 14	5110	[0;40;38;116;111;114;...]	14783	[[334,5909245...]	OrderCrosso...	15029,02
Genetic Algorithm (Mutation Rate 1%) Run 15	5110	[0;40;38;116;111;114;...]	14252	[[334,5909245...]	OrderCrosso...	14282,89
Genetic Algorithm (Mutation Rate 1%) Run 16	5110	[0;40;38;116;111;114;...]	13243	[[334,5909245...]	OrderCrosso...	13245,95
Genetic Algorithm (Mutation Rate 1%) Run 17	5110	[0;40;38;116;111;114;...]	13703	[[334,5909245...]	OrderCrosso...	13749,98
Genetic Algorithm (Mutation Rate 1%) Run 18	5110	[0;40;38;116;111;114;...]	13564	[[334,5909245...]	OrderCrosso...	13951,09
Genetic Algorithm (Mutation Rate 1%) Run 19	5110	[0;40;38;116;111;114;...]	15421	[[334,5909245...]	OrderCrosso...	15431,74
Genetic Algorithm (Mutation Rate 1%) Run 20	5110	[0;40;38;116;111;114;...]	14409	[[334,5909245...]	OrderCrosso...	15147
Genetic Algorithm (Mutation Rate 1%) Run 21	5110	[0;40;38;116;111;114;...]	13771	[[334,5909245...]	OrderCrosso...	13954,56
Genetic Algorithm (Mutation Rate 1%) Run 22	5110	[0;40;38;116;111;114;...]	14529	[[334,5909245...]	OrderCrosso...	14532,3
Genetic Algorithm (Mutation Rate 5%) Run 13	5110	[0;40;38;116;111;114;...]	13095	[[334,5909245...]	OrderCrosso...	13642,7
Genetic Algorithm (Mutation Rate 5%) Run 14	5110	[0;40;38;116;111;114;...]	12403	[[334,5909245...]	OrderCrosso...	12818,09
Genetic Algorithm (Mutation Rate 5%) Run 15	5110	[0;40;38;116;111;114;...]	14091	[[334,5909245...]	OrderCrosso...	14653,98
Genetic Algorithm (Mutation Rate 5%) Run 16	5110	[0;40;38;116;111;114;...]	12595	[[334,5909245...]	OrderCrosso...	13297,99
Genetic Algorithm (Mutation Rate 5%) Run 17	5110	[0;40;38;116;111;114;...]	12792	[[334,5909245...]	OrderCrosso...	13264,38
Genetic Algorithm (Mutation Rate 5%) Run 18	5110	[0;40;38;116;111;114;...]	12711	[[334,5909245...]	OrderCrosso...	13151,19
Genetic Algorithm (Mutation Rate 5%) Run 19	5110	[0;40;38;116;111;114;...]	12326	[[334,5909245...]	OrderCrosso...	12625,78
Genetic Algorithm (Mutation Rate 5%) Run 20	5110	[0;40;38;116;111;114;...]	13346	[[334,5909245...]	OrderCrosso...	13777,85
Genetic Algorithm (Mutation Rate 5%) Run 21	5110	[0;40;38;116;111;114;...]	12807	[[334,5909245...]	OrderCrosso...	13284,81
Genetic Algorithm (Mutation Rate 5%) Run 22	5110	[0;40;38;116;111;114;...]	12741	[[334,5909245...]	OrderCrosso...	13113,18
Genetic Algorithm (Mutation Rate 10%) Run 13	5110	[0;40;38;116;111;114;...]	15921	[[334,5909245...]	OrderCrosso...	18084,04
Genetic Algorithm (Mutation Rate 10%) Run 14	5110	[0;40;38;116;111;114;...]	16384	[[334,5909245...]	OrderCrosso...	19609,36

# Runs – Tabular View



- Sort columns
  - click on column header to sort column
  - Ctrl-click on column header to sort multiple columns
- Show or hide columns
  - right-click on table to open dialog to show or hide columns
- Compute statistical values
  - select multiple numerical values to see count, sum, minimum, maximum, average and standard deviation
- Select, copy and paste into other applications

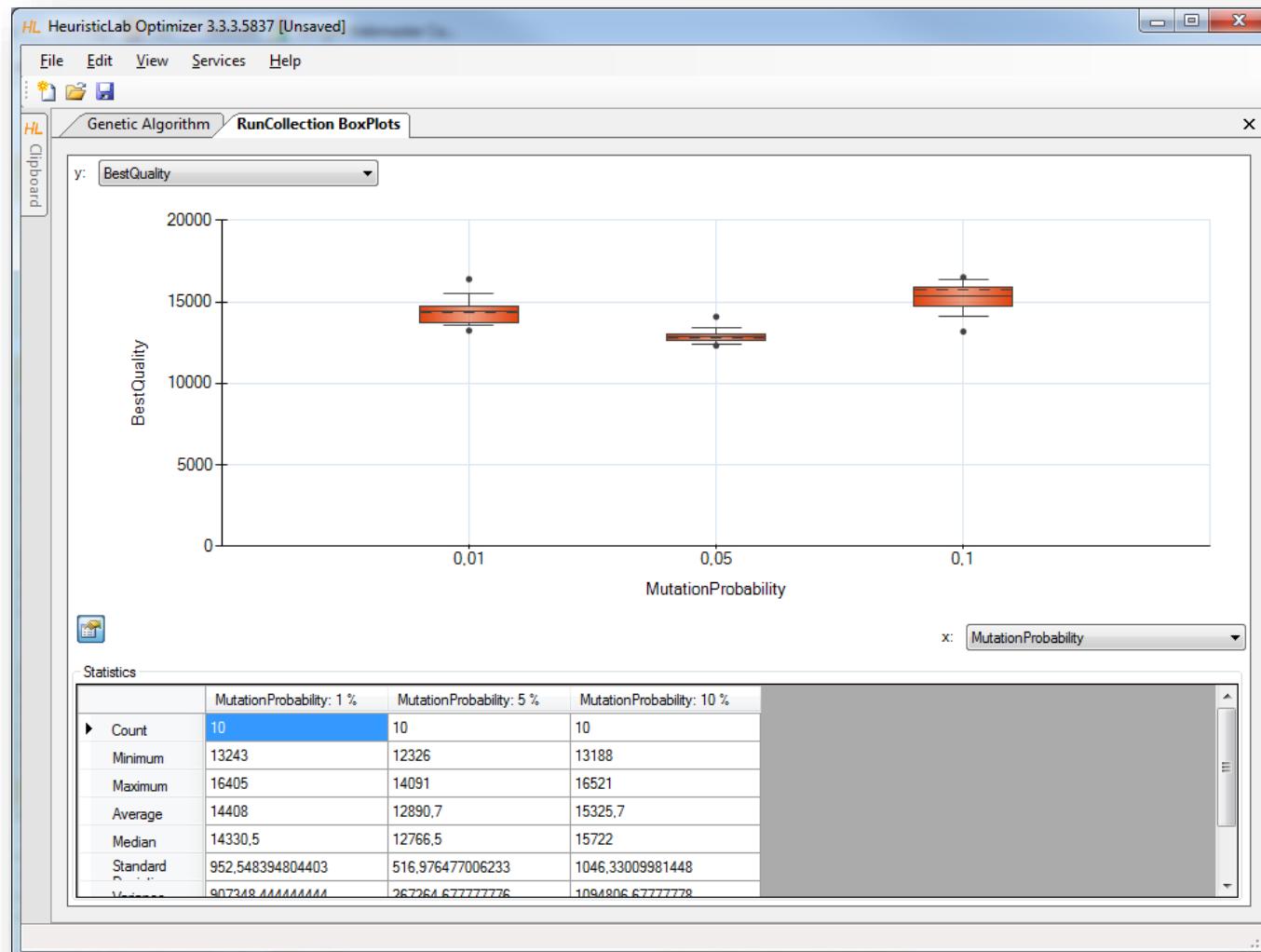
# Runs – BubbleChart



# Runs – BubbleChart

- Choose values to plot
  - choose which values to show on the x-axis, the y-axis and as bubble size
  - possible values are all parameter settings and results
- Add jitter
  - add jitter to separate overlapping bubbles
- Zoom in and out
  - click on Zoom and click and drag in the chart area to zoom in
  - double click on the chart area background or on the circle buttons beside the scroll bars to zoom out
- Color bubbles
  - click on Select, choose a color and click and drag in the chart area to select and color bubbles
  - apply coloring automatically by clicking on the axis coloring buttons
- Show runs
  - double click on a bubble to open its run
- Export image
  - right-click to open context menu to copy or save image
  - save image as pixel (BMP, JPG, PNG, GIF, TIF) or vector graphics (EMF)
- Show box plots
  - right-click to open context menu to show box plots view

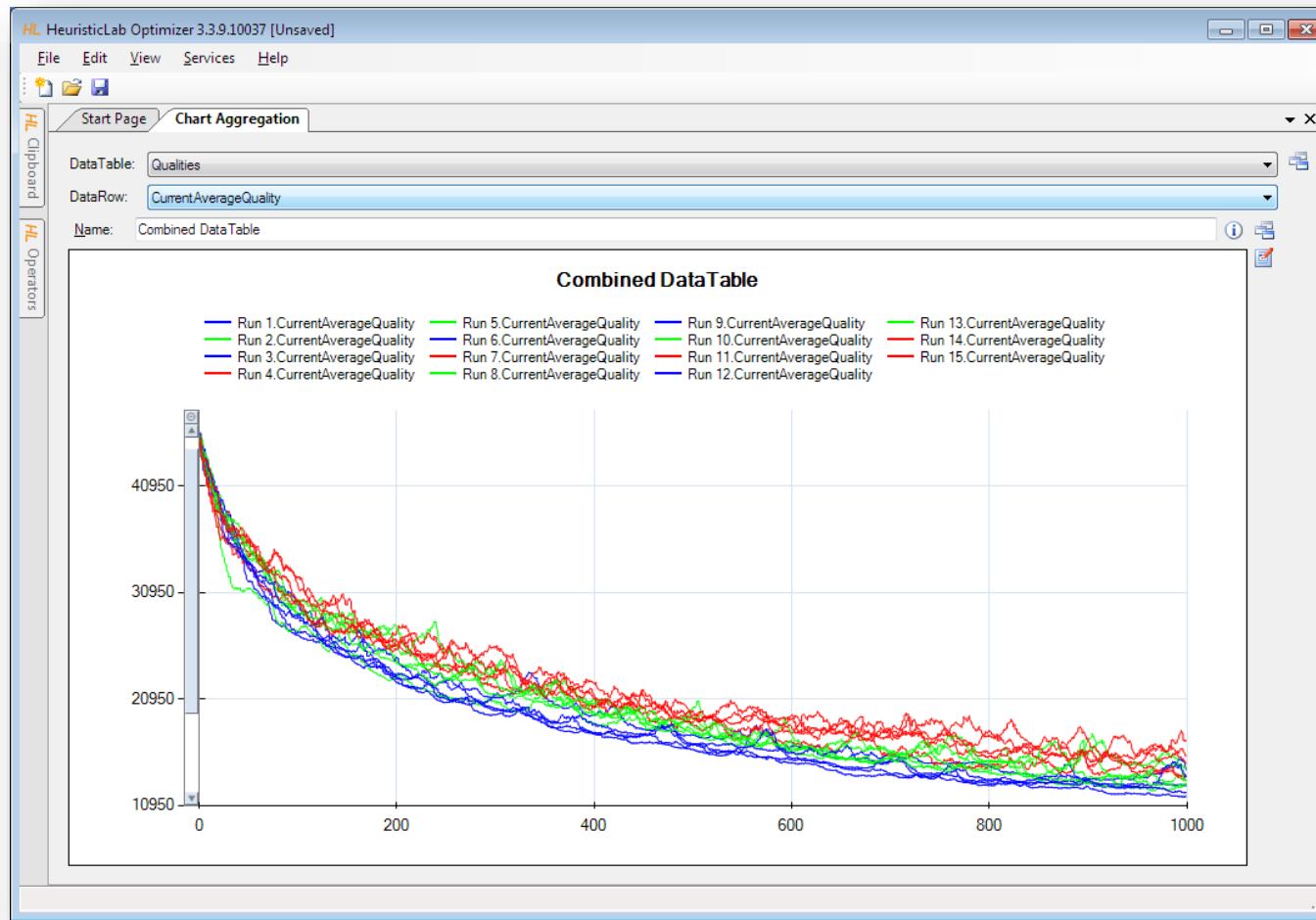
# Runs – BoxPlots



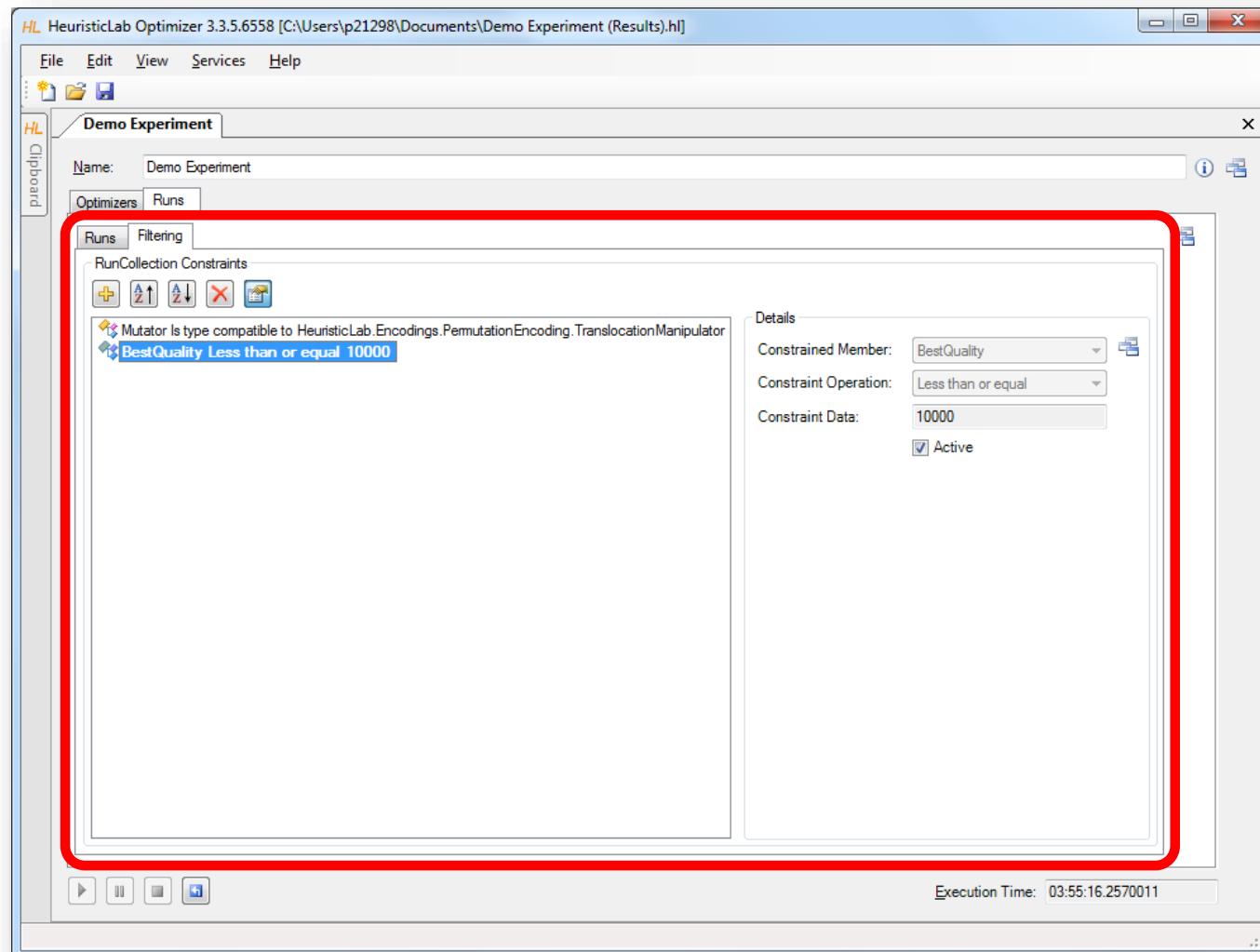
# Runs – BoxPlots

- Choose values to plot
  - choose which values to show on the x-axis and y-axis
  - possible values are all parameter settings and results
- Zoom in and out
  - click on Zoom and click and drag in the chart area to zoom in
  - double click on the chart area background or on the circle buttons beside the scroll bars to zoom out
- Show or hide statistical values
  - click on the lower left button to show or hide statistical values
- Export image
  - right-click to open context menu to copy or save image
  - save image as pixel (BMP, JPG, PNG, GIF, TIF) or vector graphics (EMF)

# Runs – Multi-Line Chart



# Filter Runs

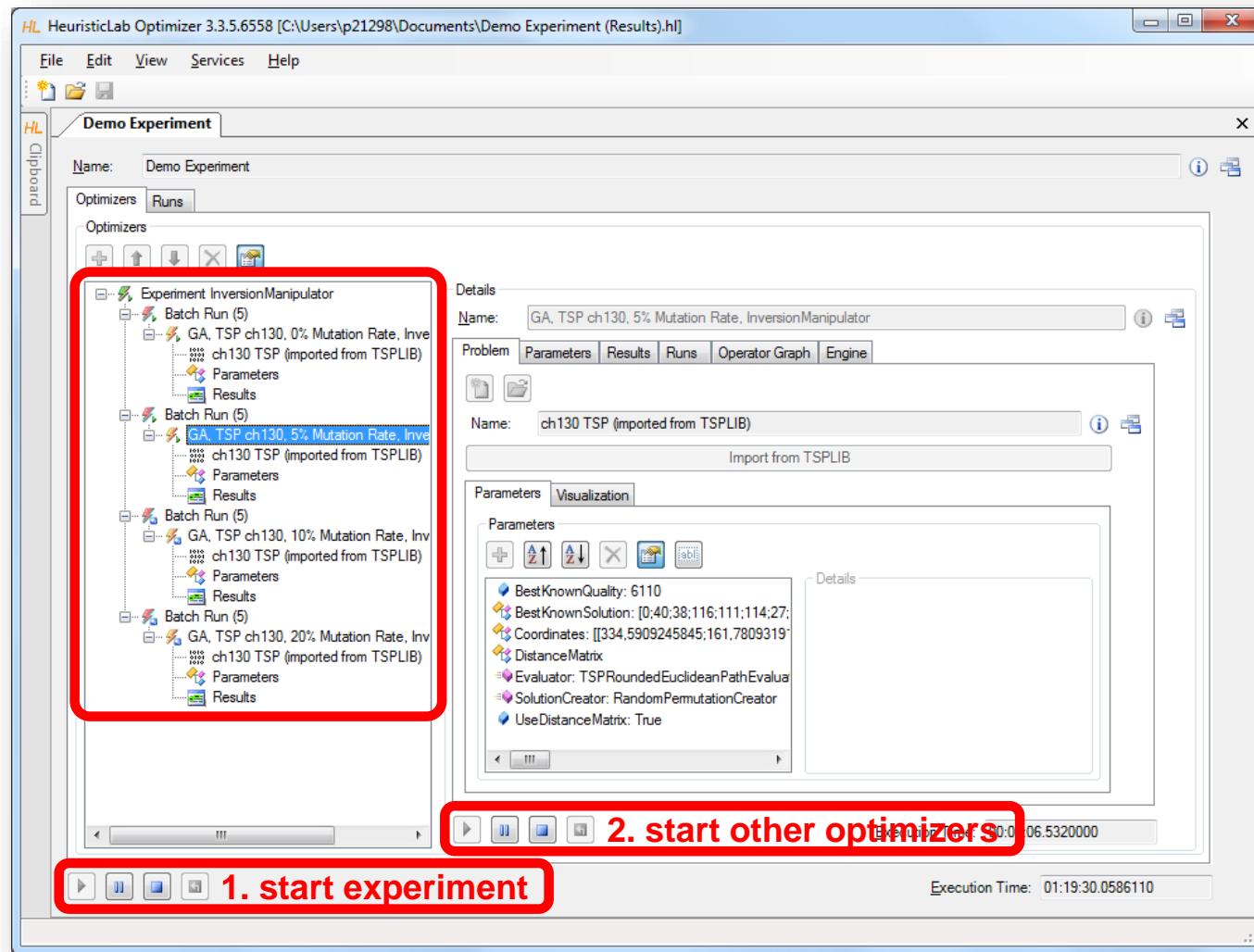


# Multi-core CPUs and Parallelization

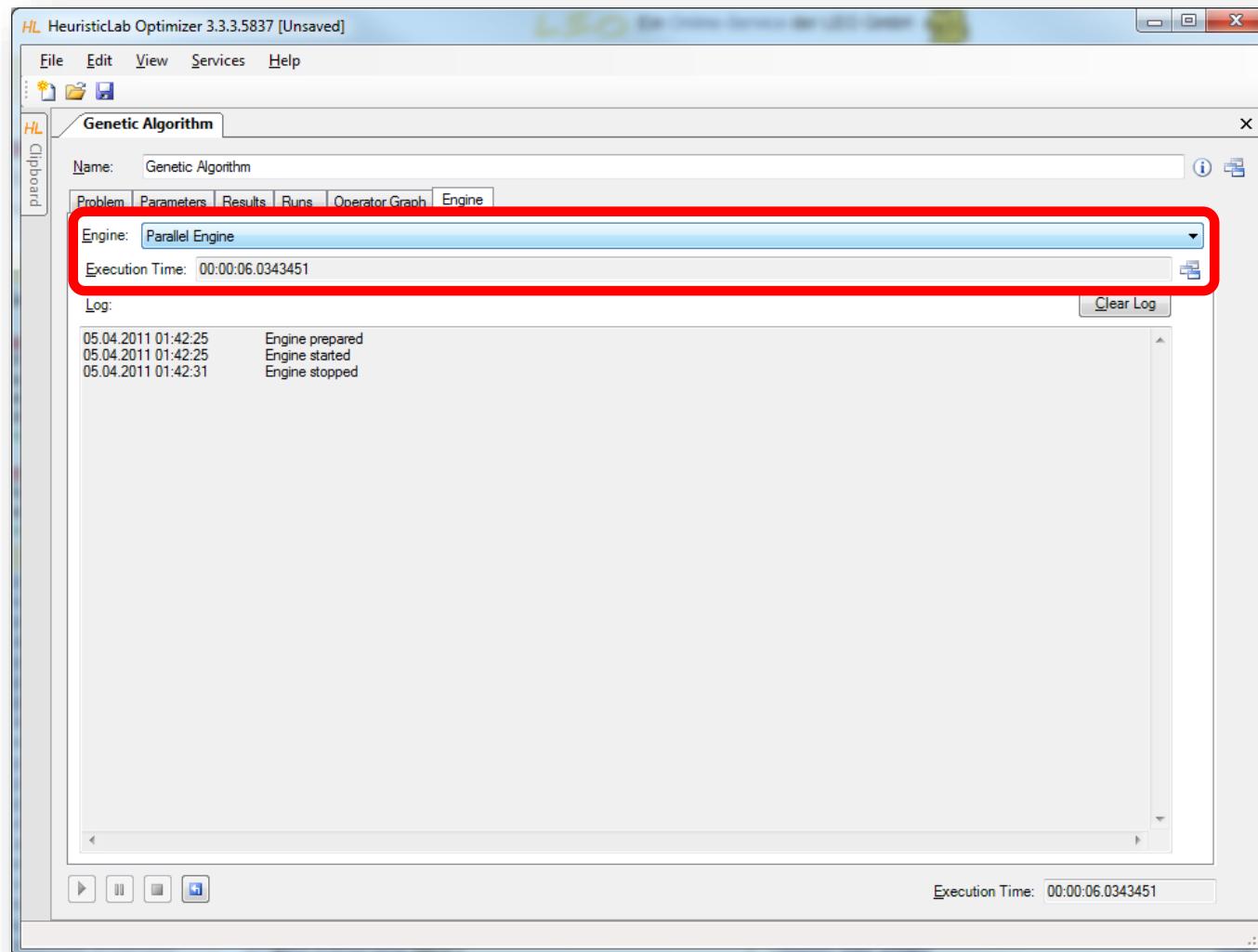


- Parallel execution of optimizers in experiments
  - optimizers in an experiment are executed sequentially from top to bottom per default
  - experiments support parallel execution of their optimizers
  - select a not yet executed optimizer and start it manually to utilize another core
  - execution of one of the next optimizers is started automatically after an optimizer is finished
- Parallel execution of algorithms
  - HeuristicLab provides special operators for parallelization
  - engines decide how to execute parallel operations
  - sequential engine executes everything sequentially
  - parallel engine executes parallel operations on multiple cores
  - Hive engine (under development) executes parallel operations on multiple computers
  - all implemented algorithms support parallel solution evaluation

# Parallel Execution of Experiments



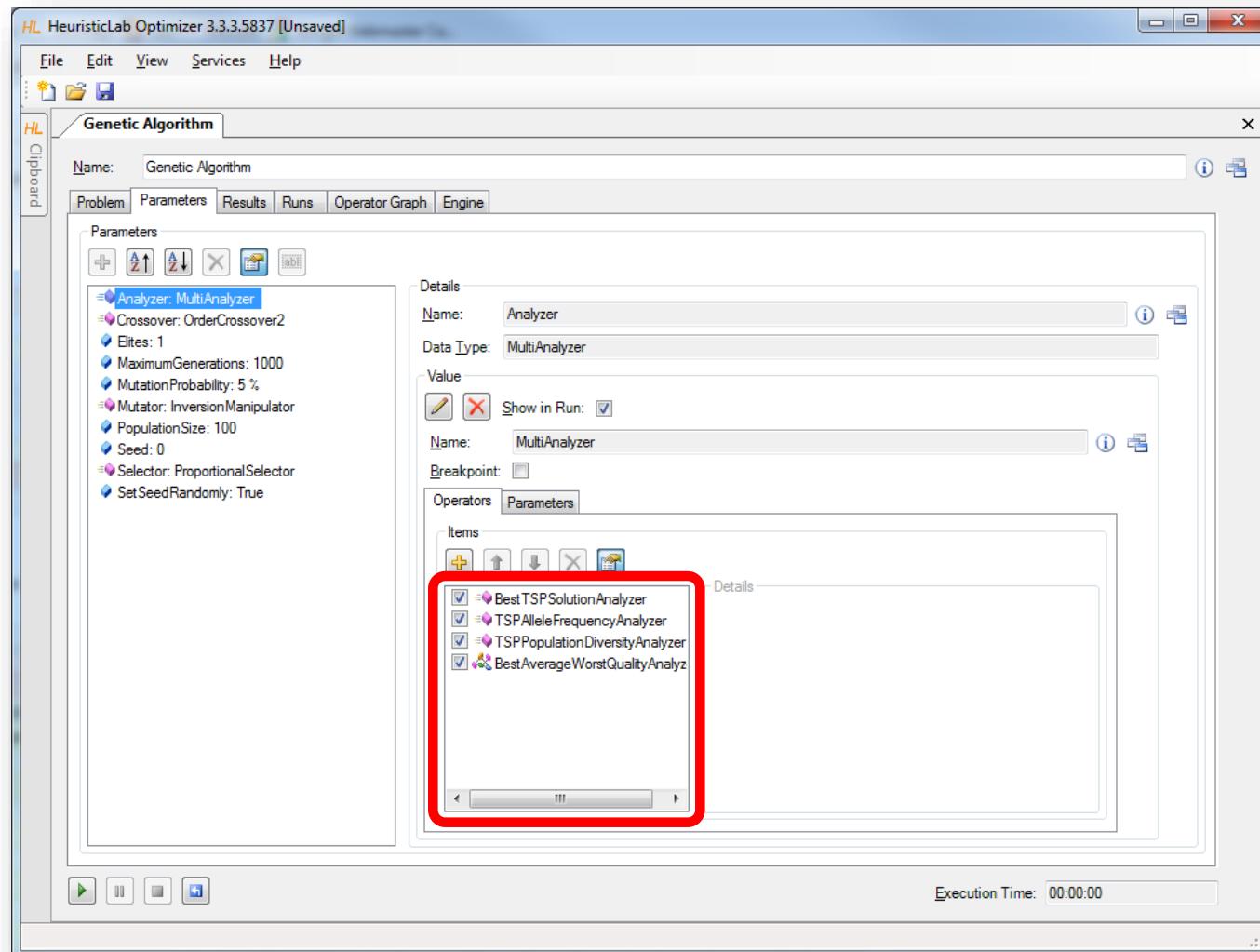
# Parallel Execution of Algorithms



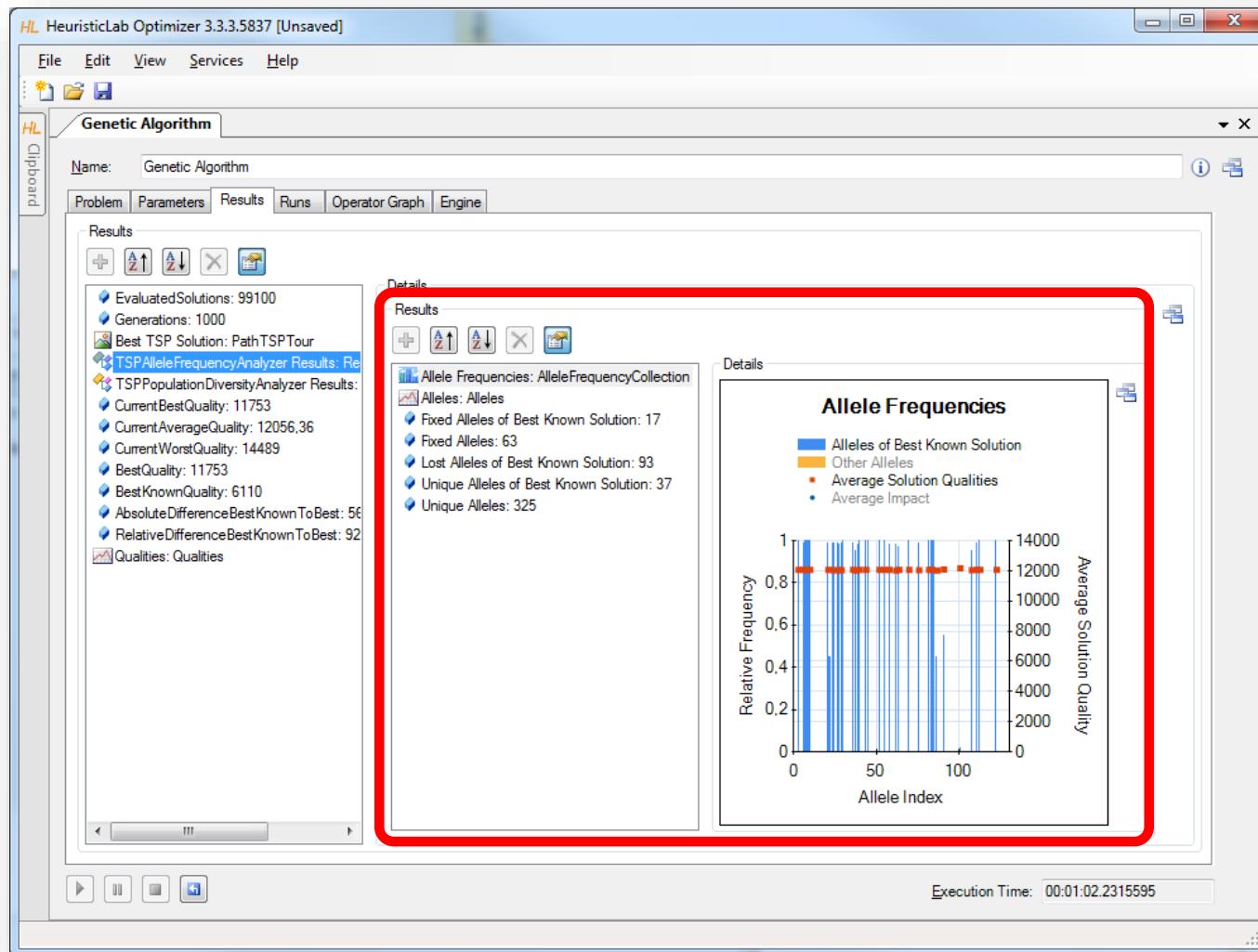
# Analyzers

- Special operators for analysis purposes
  - are executed after each iteration
  - serve as general purpose extension points of algorithms
  - can be selected and parameterized in the algorithm
  - perform algorithm-specific and/or problem-specific tasks
  - some analyzers are quite costly regarding runtime and memory
  - implementing and adding custom analyzers is easy
- Examples
  - TSPAlleleFrequencyAnalyzer
  - TSPPopulationDiversityAnalyzer
  - SuccessfulOffspringAnalyzer
  - SymbolicDataAnalysisVariableFrequencyAnalyzer
  - SymbolicRegressionSingleObjectiveTrainingBestSolutionAnalyzer
  - ...

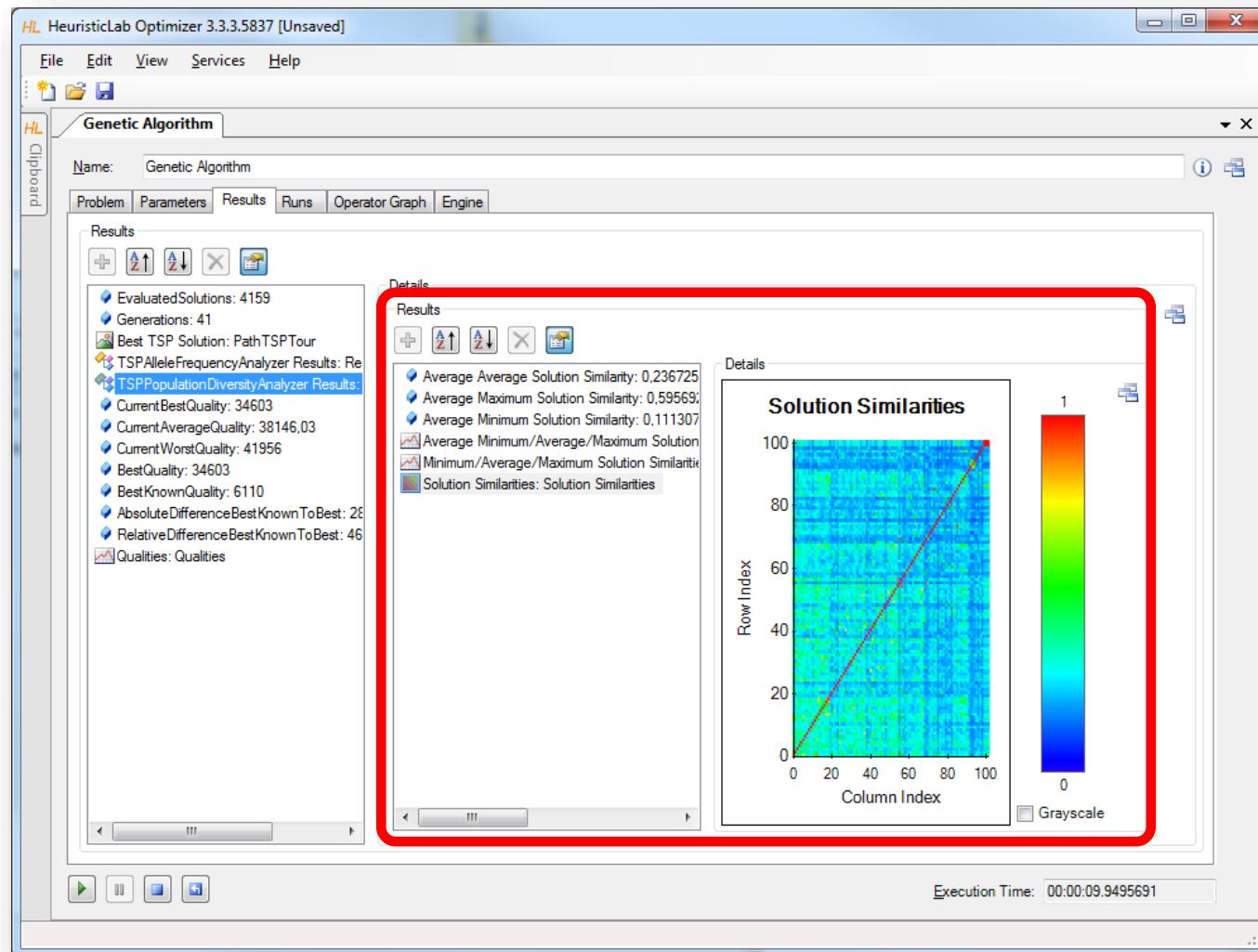
# Analyzers



# TSPAlleleFrequencyAnalyzer



# TSPPopulationDiversityAnalyzer



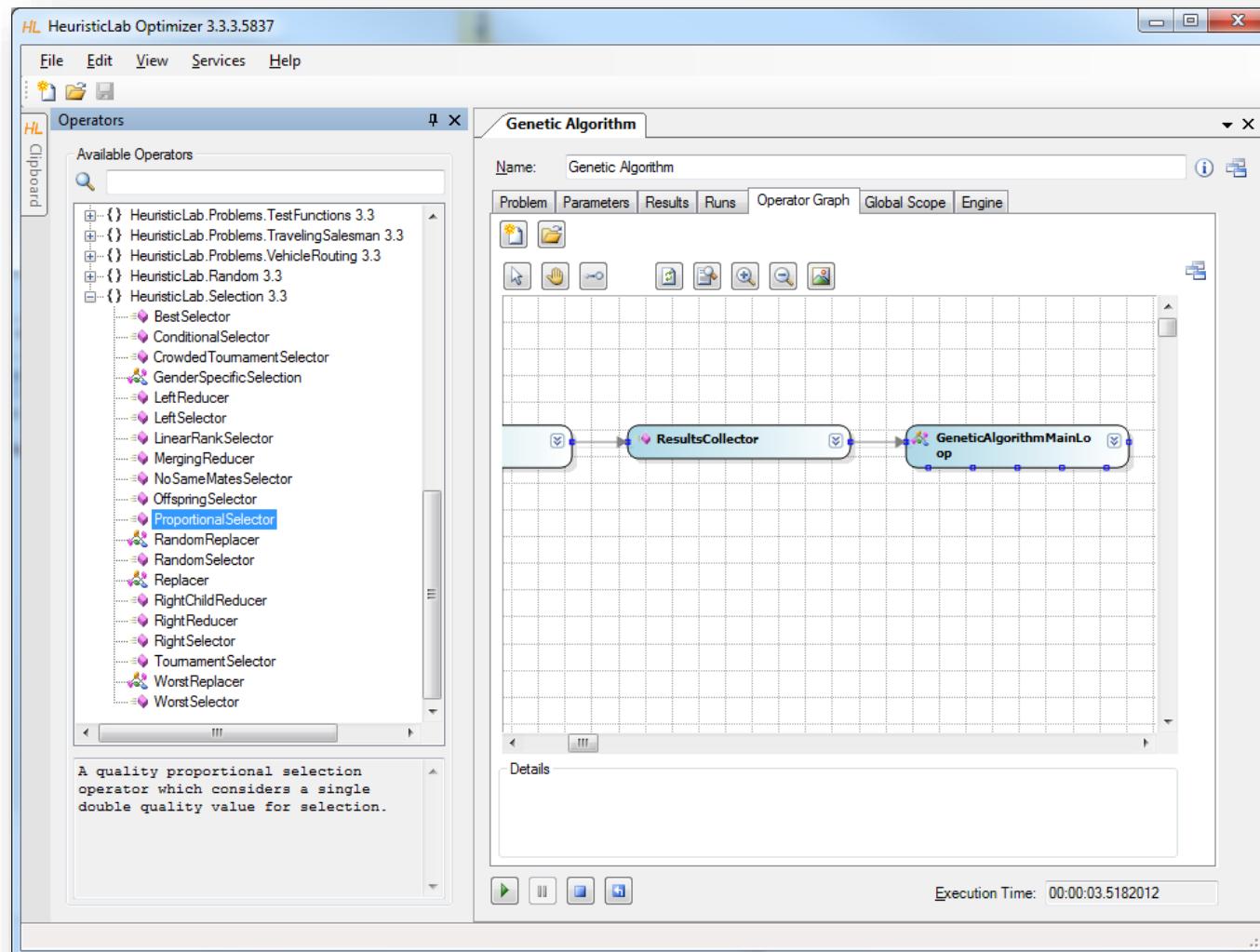
# Building User-Defined Algorithms

- Operator graphs
  - algorithms are represented as operator graphs
  - operator graphs of user-defined algorithms can be changed
  - algorithms can be defined in the graphical algorithm designer
  - use the menu to convert a standard algorithm into a user-defined algorithm

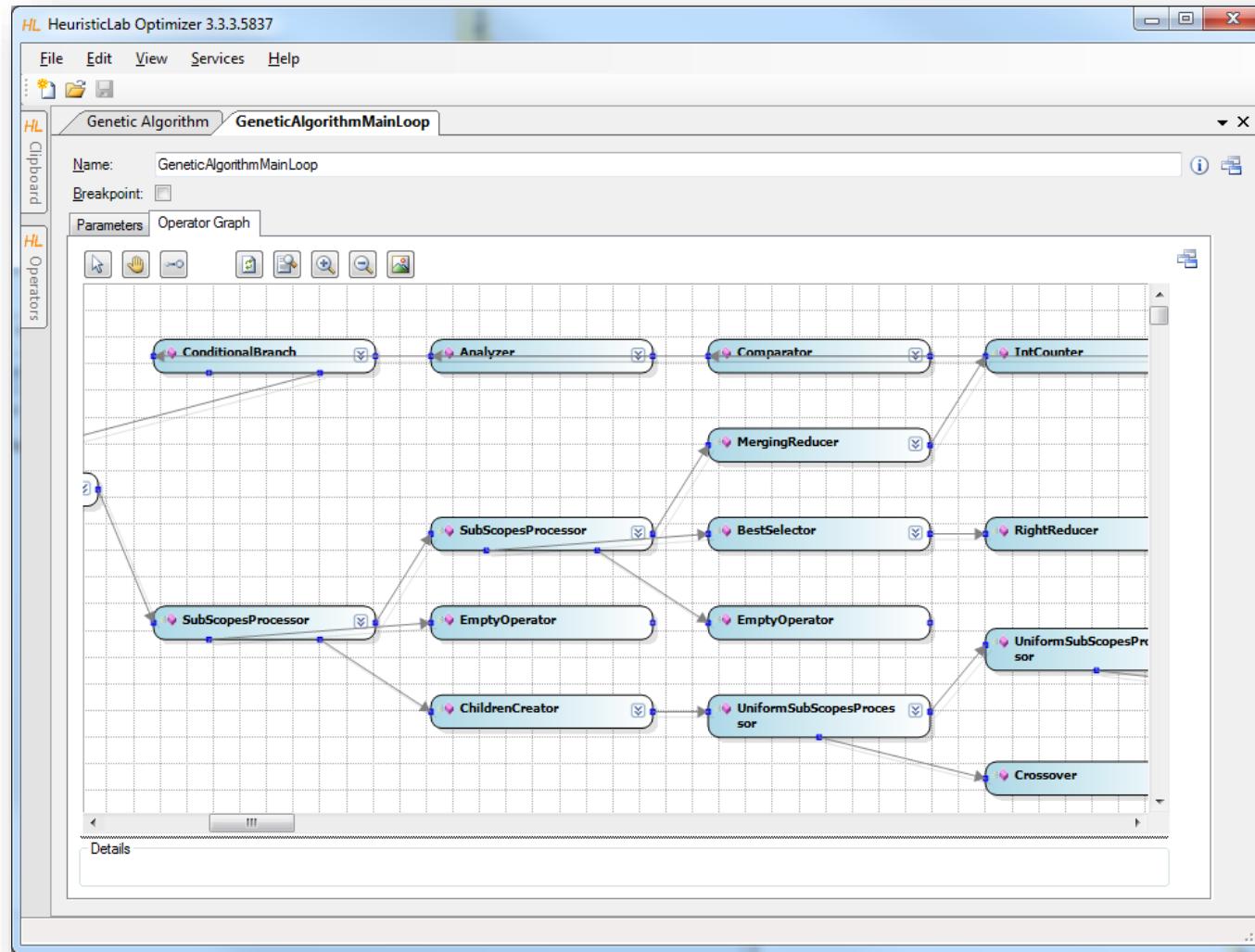


- Operators sidebar
  - drag & drop operators into an operator graph
- Programmable operators
  - add programmable operators in order to implement custom logic in an algorithm
  - no additional development environment needed
- Debug algorithms
  - use the debug engine to obtain detailed information during algorithm execution

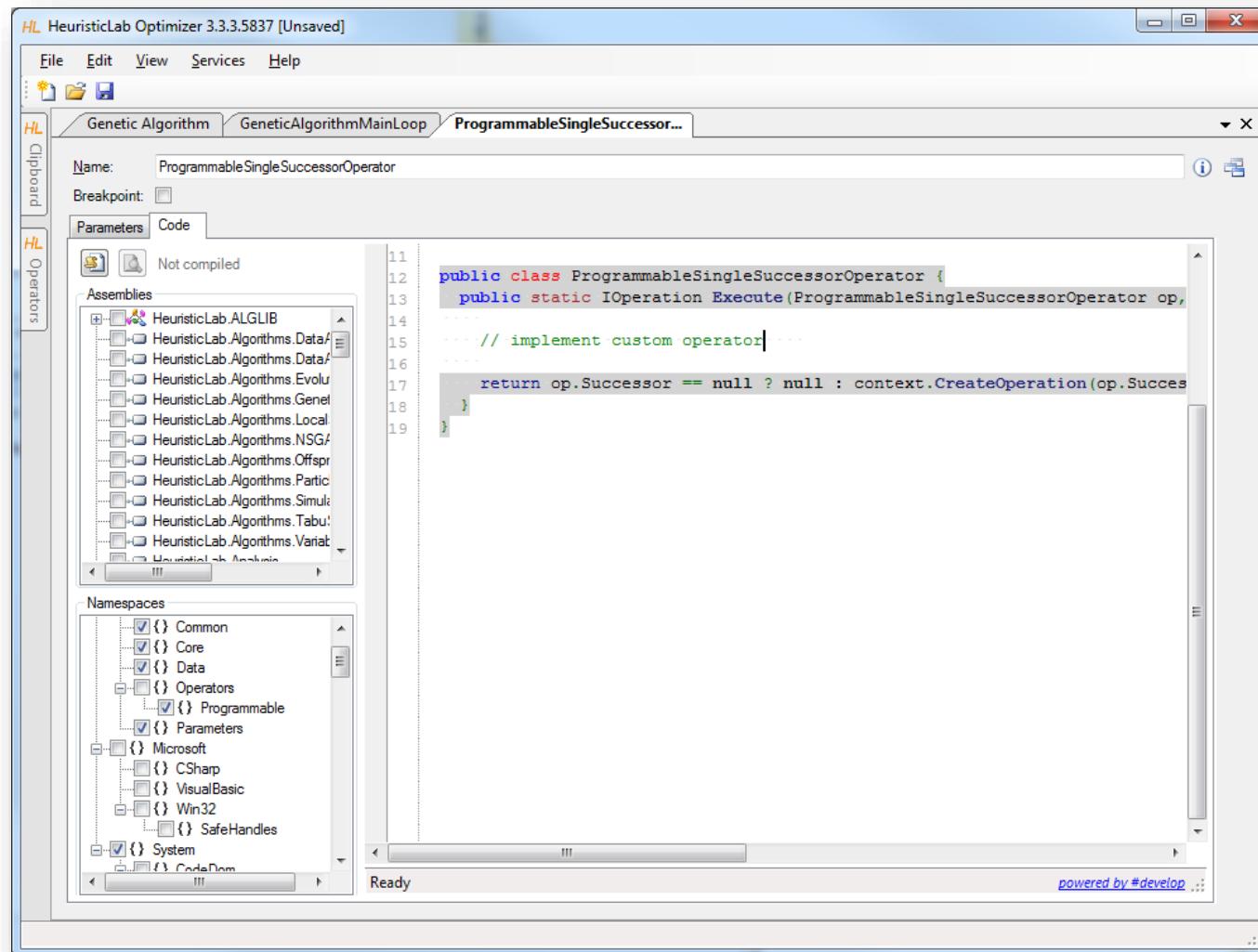
# Building User-Defined Algorithms



# Building User-Defined Algorithms



# Programmable Operators



# Scripts

HeuristicLab Optimizer 3.3.10.11175 [Unsaved]

Name: Genetic Algorithm Script - QAP

Compilation successful

```
38
39     for (int g = 0; g < generations; g++) {
40         var parents = population.SampleProportional(random, 2 * popSize, qualities);
41         for (int i = 0; i < popSize; i++) {
42             nextGen[i] = PartiallyMatchedCrossover.Apply(random, parents[i * 2], i);
43             if (random.NextDouble() < mutationRate) Swap2Manipulator.Apply(random,
44                 nextQual[i] = QAPEvaluator.Apply(nextGen[i], qap.Weights, qap.Distances));
45             if (nextQual[i] < bestQuality) {
46                 bestQuality = nextQual[i];
47                 bestQualityGeneration = g;
48             }
49         }
50         qualityRow.Values.Add(bestQuality);
51         Array.Copy(nextGen, population, popSize);
52         Array.Copy(nextQual, qualities, popSize);
53     }
54
55     vars.elapsed = new TimeSpanValue(DateTime.UtcNow - start);
56     vars.bestQuality = bestQuality;
57     vars.bestQualityFoundAt = bestQualityGeneration;
58 }
59 }
```

Variables

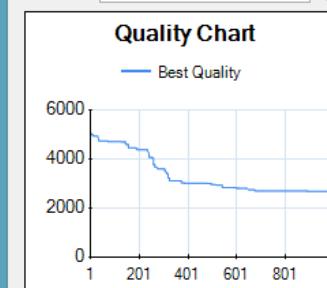
Name	Value
qap	dre56
qualityChart	Quality Chart
elapsed	00:00:09.6073
bestQuality	2670
bestQualityFoundAt	889

Quality Chart

Name: Quality Chart

Quality Chart

Best Quality



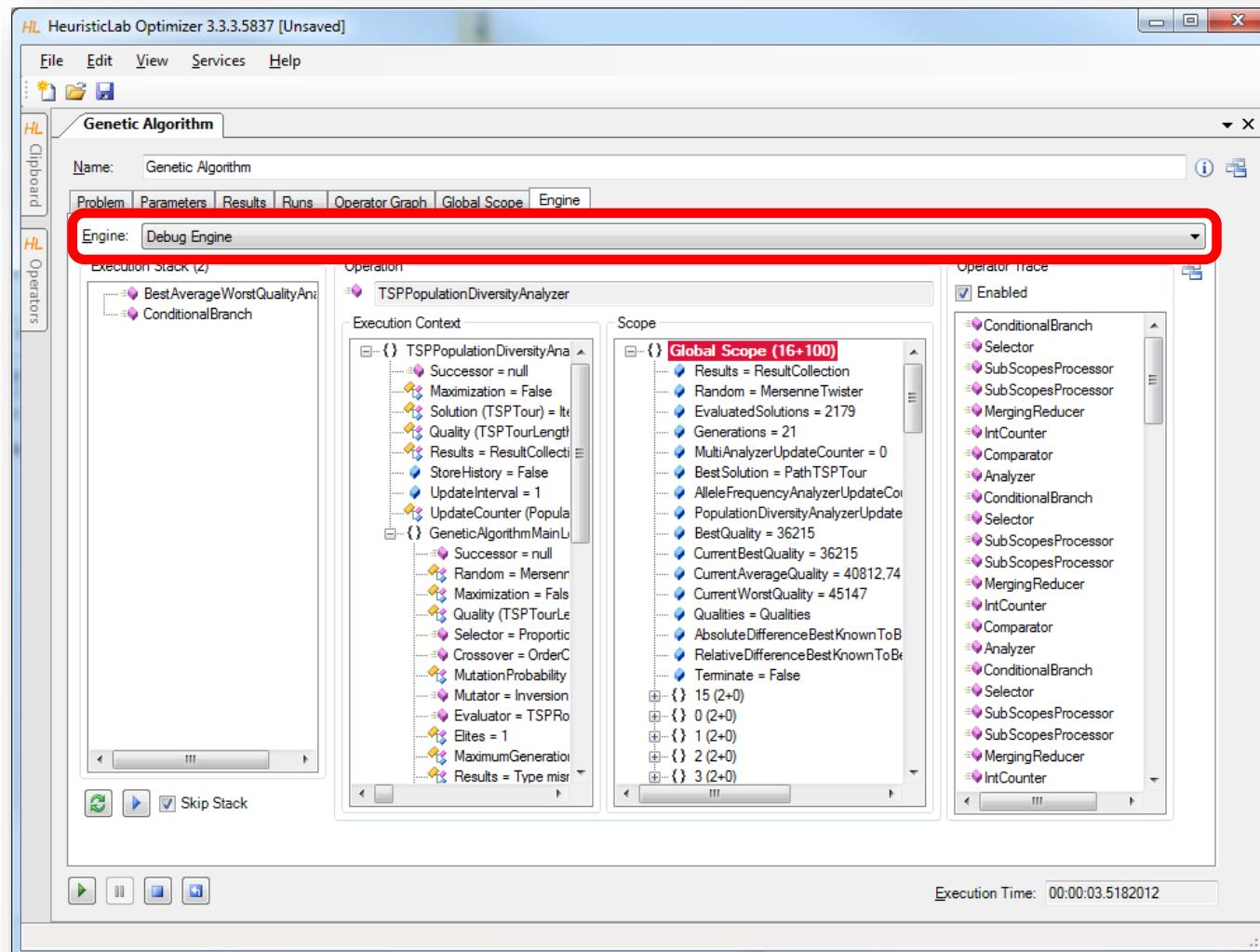
Generation	Best Quality
1	5500
201	4000
401	3000
601	2500
801	2500

Ready

Output Error List

Compiling ... Compilation succeeded.

# Debugging Algorithms



# Agenda

- Objectives of the Tutorial
- Introduction
- Where to get HeuristicLab?
- Plugin Infrastructure
- Graphical User Interface
- Available Algorithms & Problems
- **Demonstration Part I: Working with HeuristicLab**
- **Demonstration Part II: Data-based Modeling**
- Some Additional Features
- Planned Features
- Team
- Suggested Readings
- Bibliography
- Questions & Answers

# Demonstration Part II: Data-based Modeling



- Introduction
- Regression with HeuristicLab
- Model simplification and export
- Variable relevance analysis
- Classification with HeuristicLab

# Introduction to Data-based Modeling



- Dataset: Matrix  $(x_{i,j})_{i=1..N, j=1..K}$ 
  - N observations of K input variables
  - $x_{i,j}$  = i-th observation of j-th variable
  - Additionally: Vector of labels  $(y_1 \dots y_N)^T$
- Goal: learn association of input variable values to labels

# Data Analysis in HeuristicLab



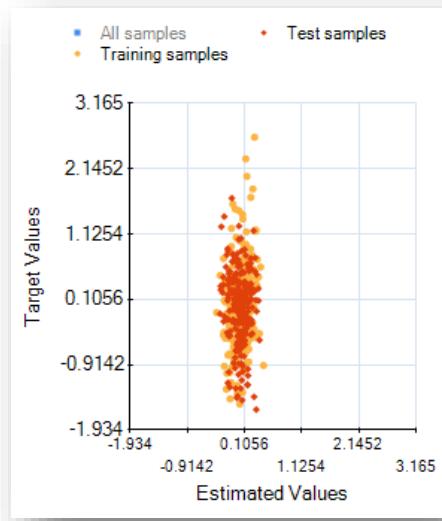
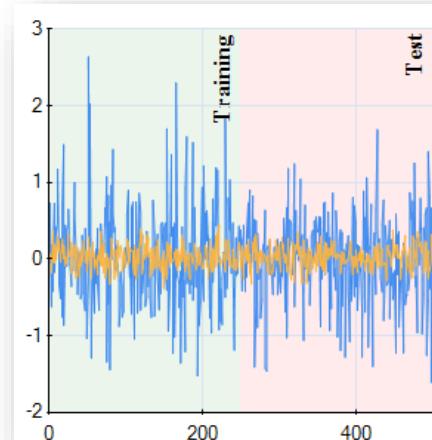
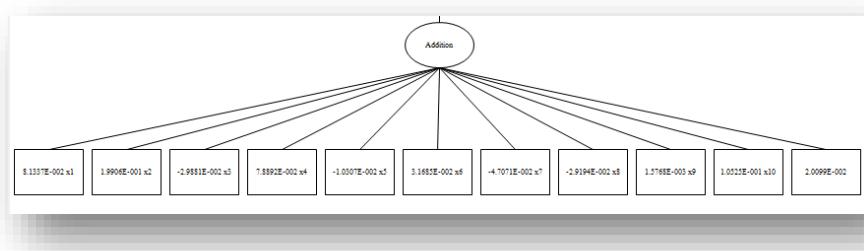
- Symbolic regression and classification using genetic programming
- External Libraries:
  - Linear Regression, Logistic Regression,
  - k-Nearest Neighbours, k-Means,
  - Random Forest, Support Vector Machines, Neural Networks, Gaussian Processes

# Case Study: Regression

- Poly-10 benchmark problem dataset
  - 10 input variables  $x_1 \dots x_{10}$
  - $y = x_1x_2 + x_3x_4 + x_5x_6 + x_1x_7x_9 + x_3x_6x_{10}$
  - non-linear modeling approach necessary
  - frequently used in GP literature
  - available as benchmark problem instance in HeuristicLab

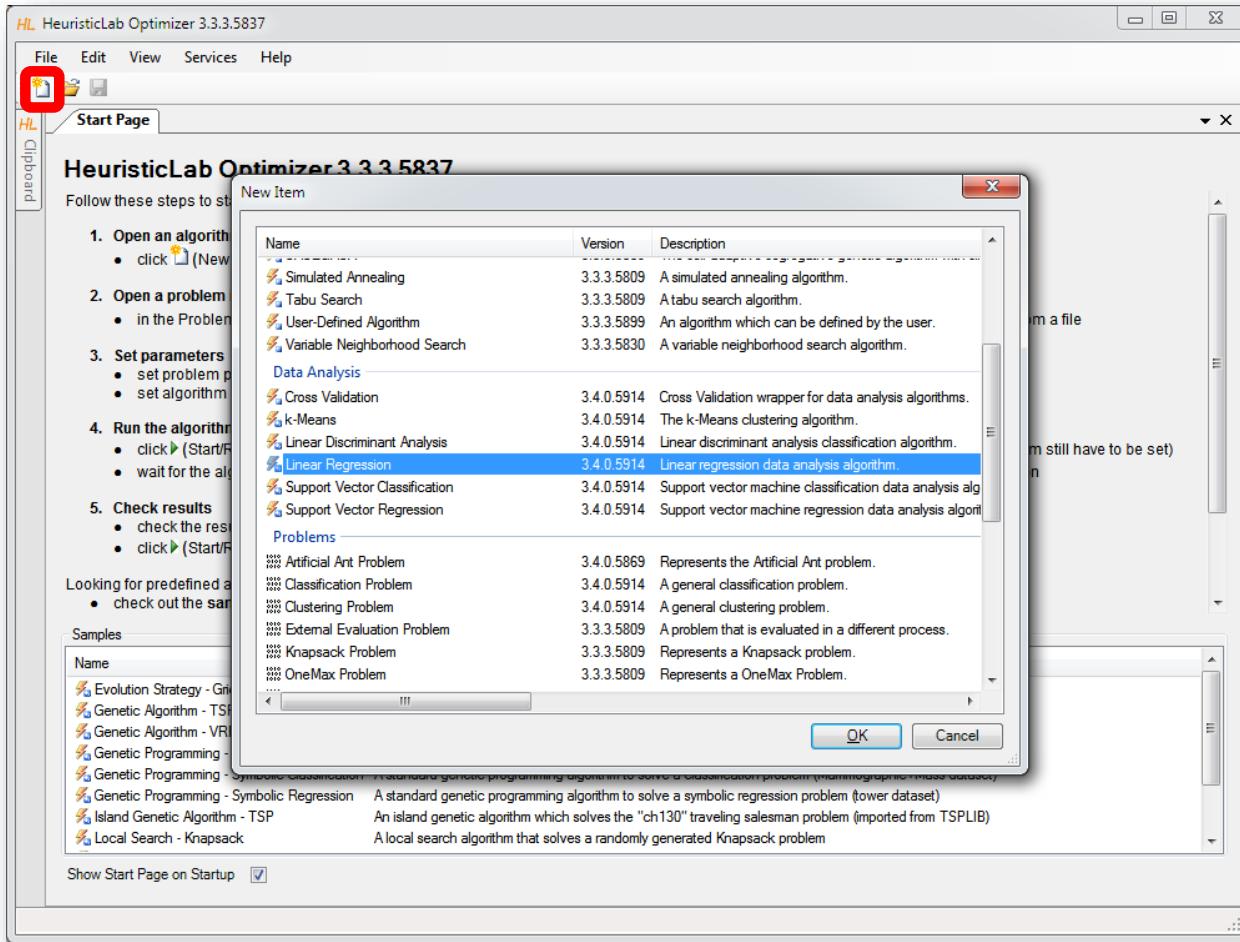
# Demonstration

- problem configuration
  - data import
  - target and input variables
  - data partitions (training and test)
- algorithm configuration
- analysis of results
  - accuracy metrics
  - visualization of model output

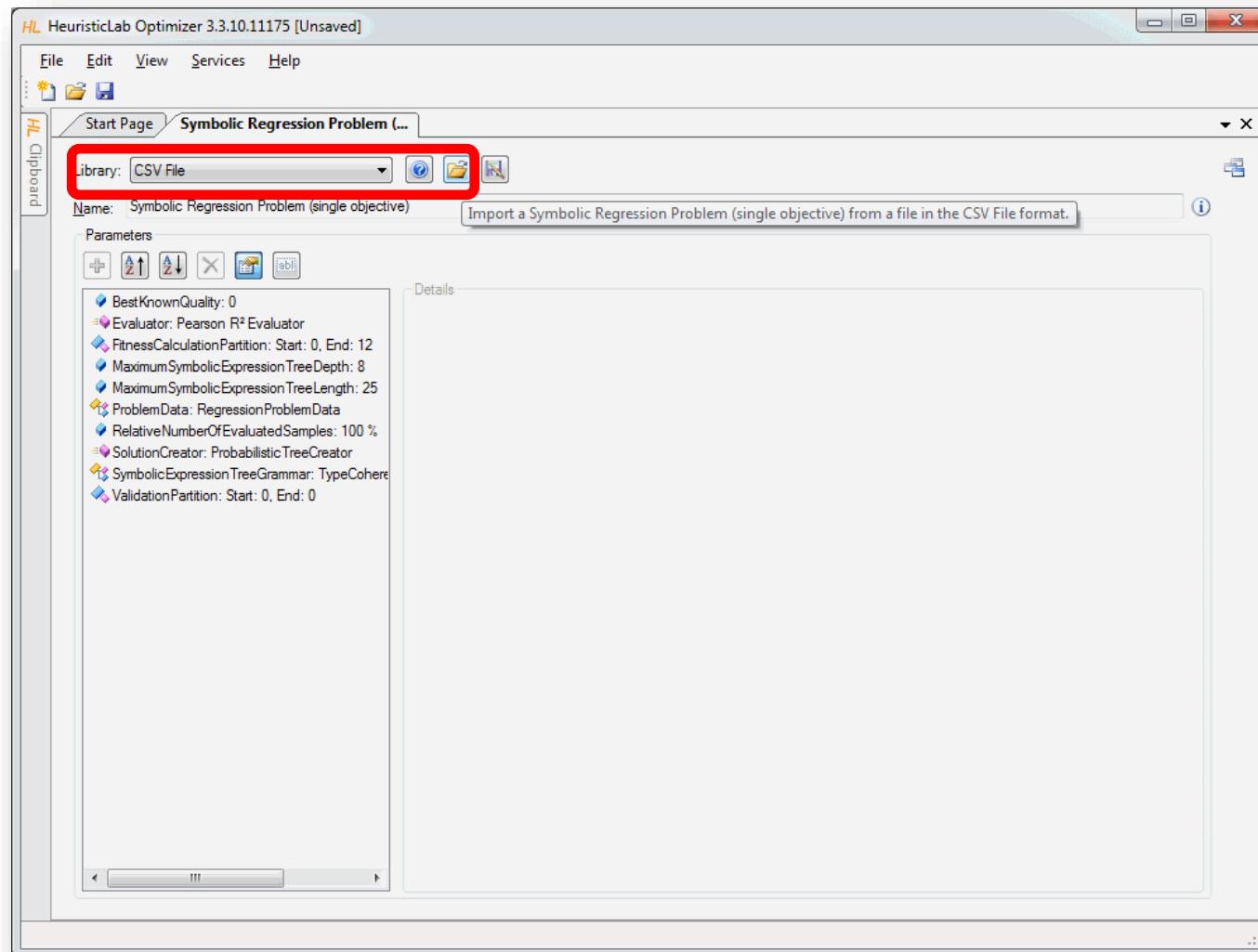


# Linear Regression

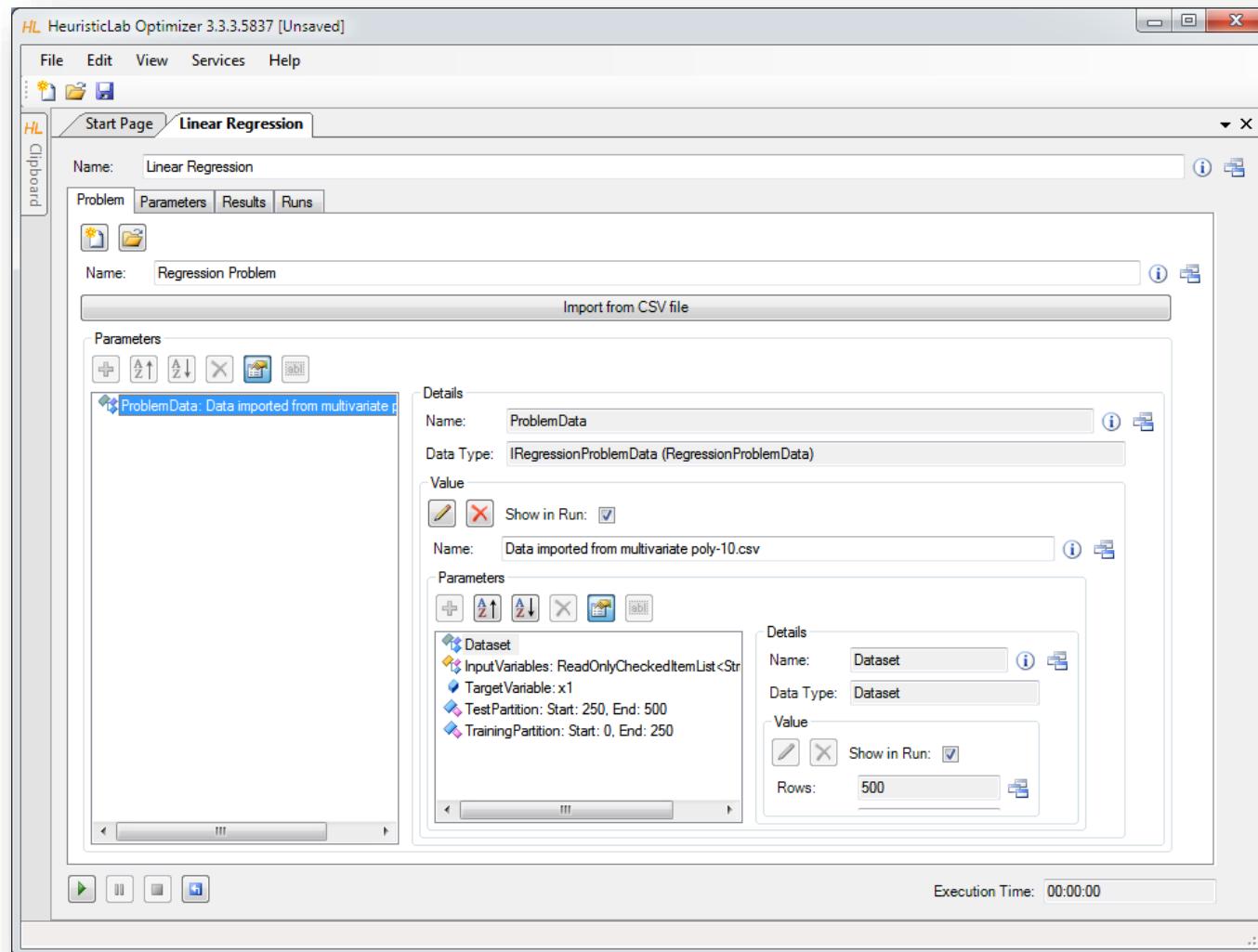
- Create new algorithm



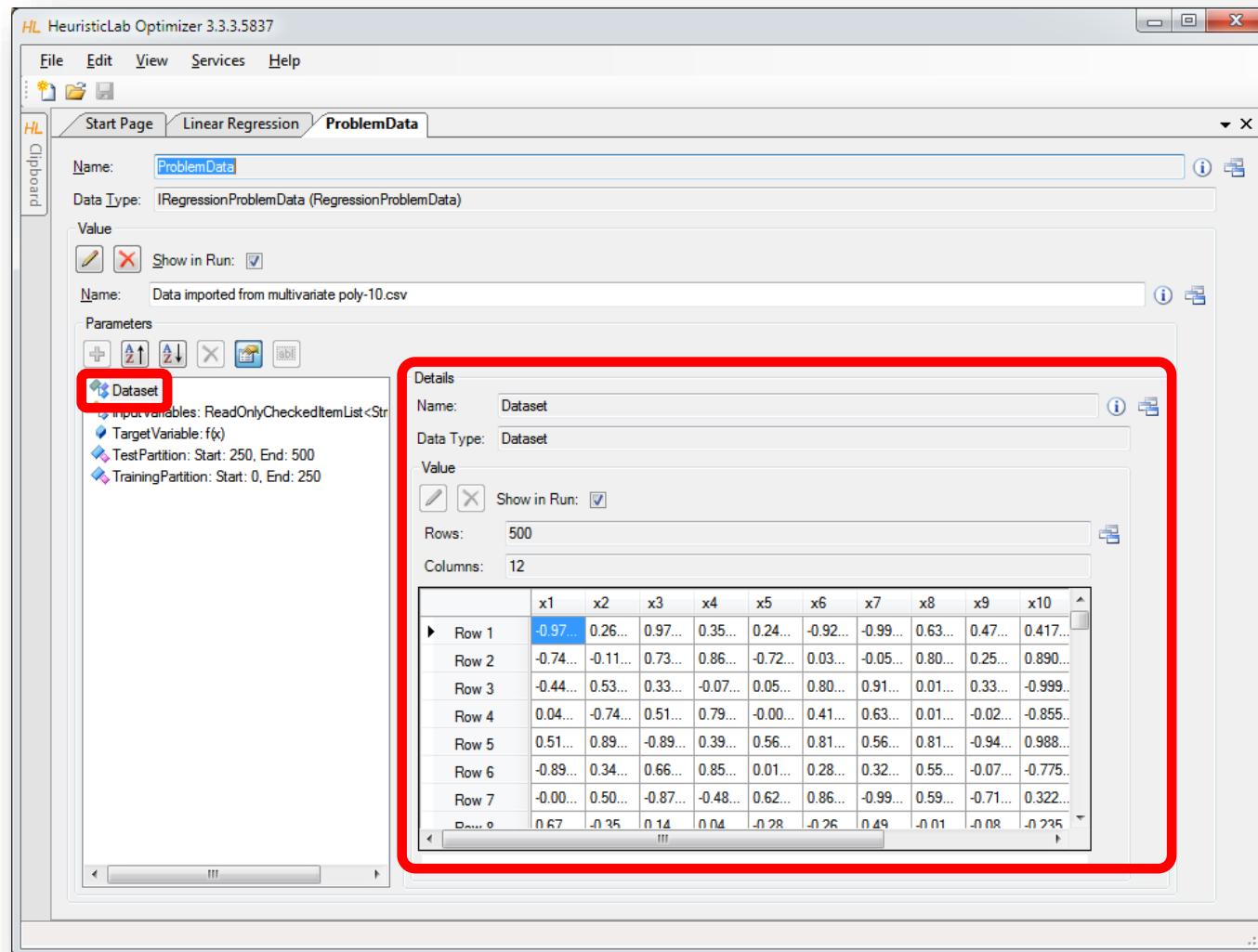
# Import Data from CSV-File



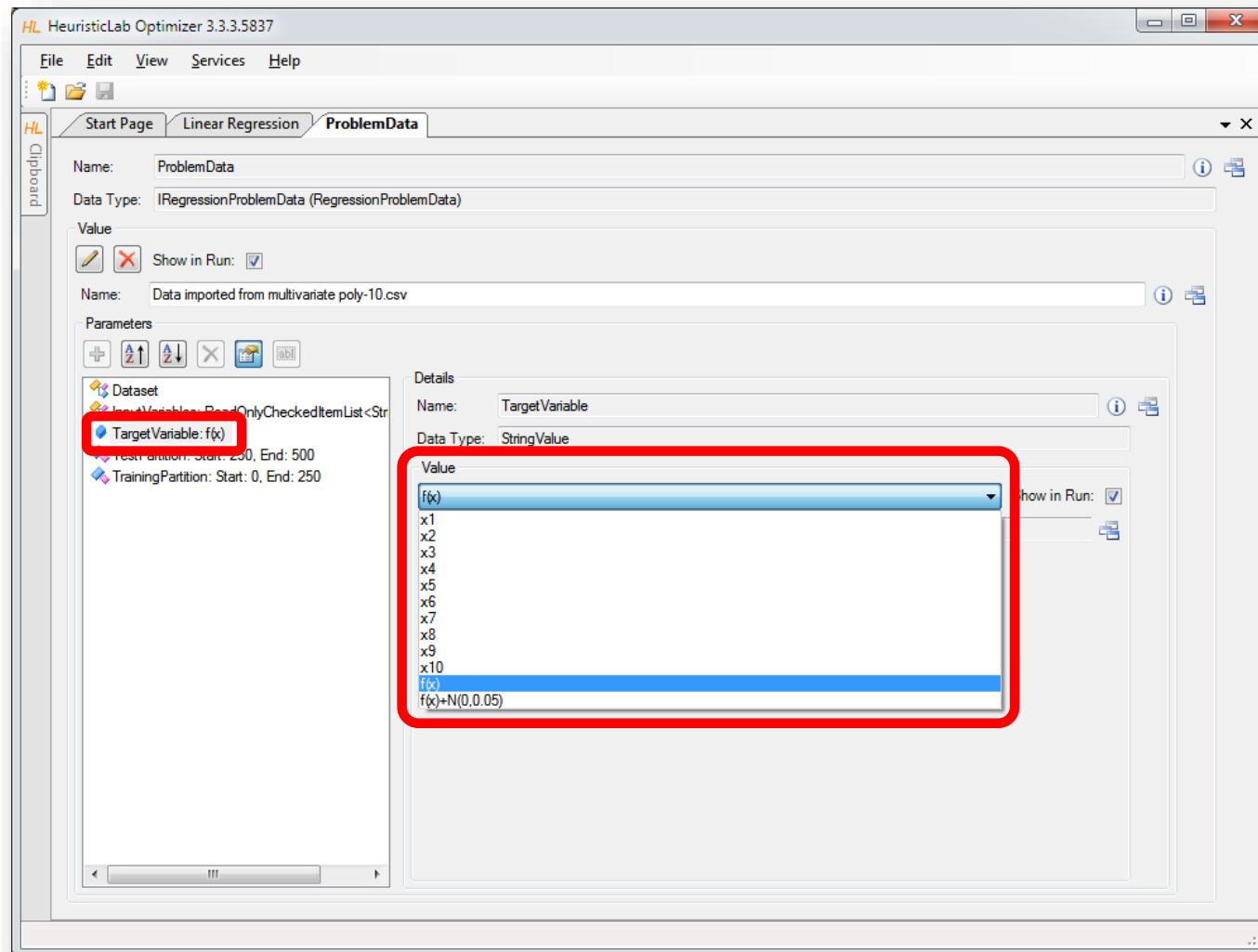
# Inspect and Configure Dataset



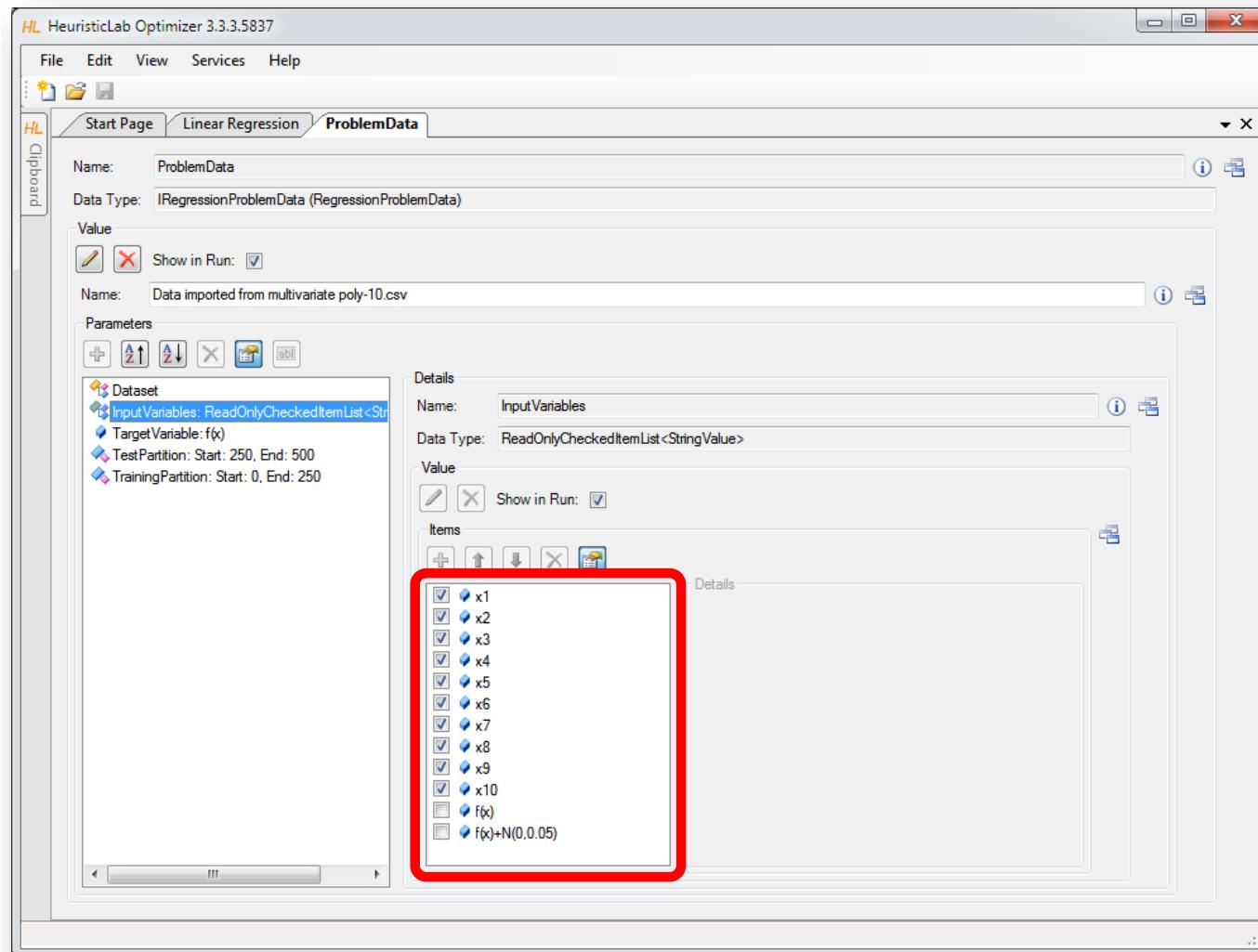
# Inspect Imported Data



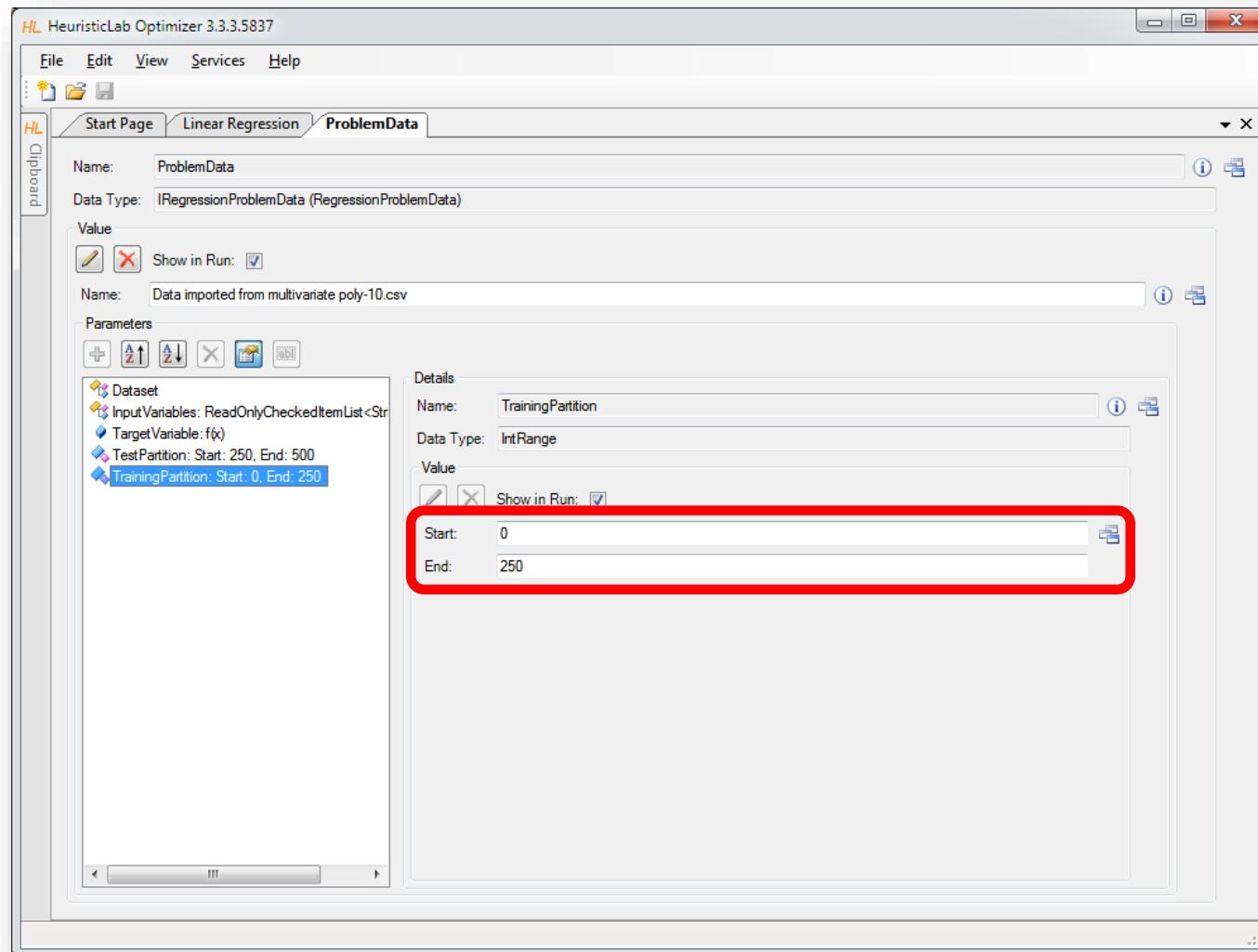
# Set Target Variable



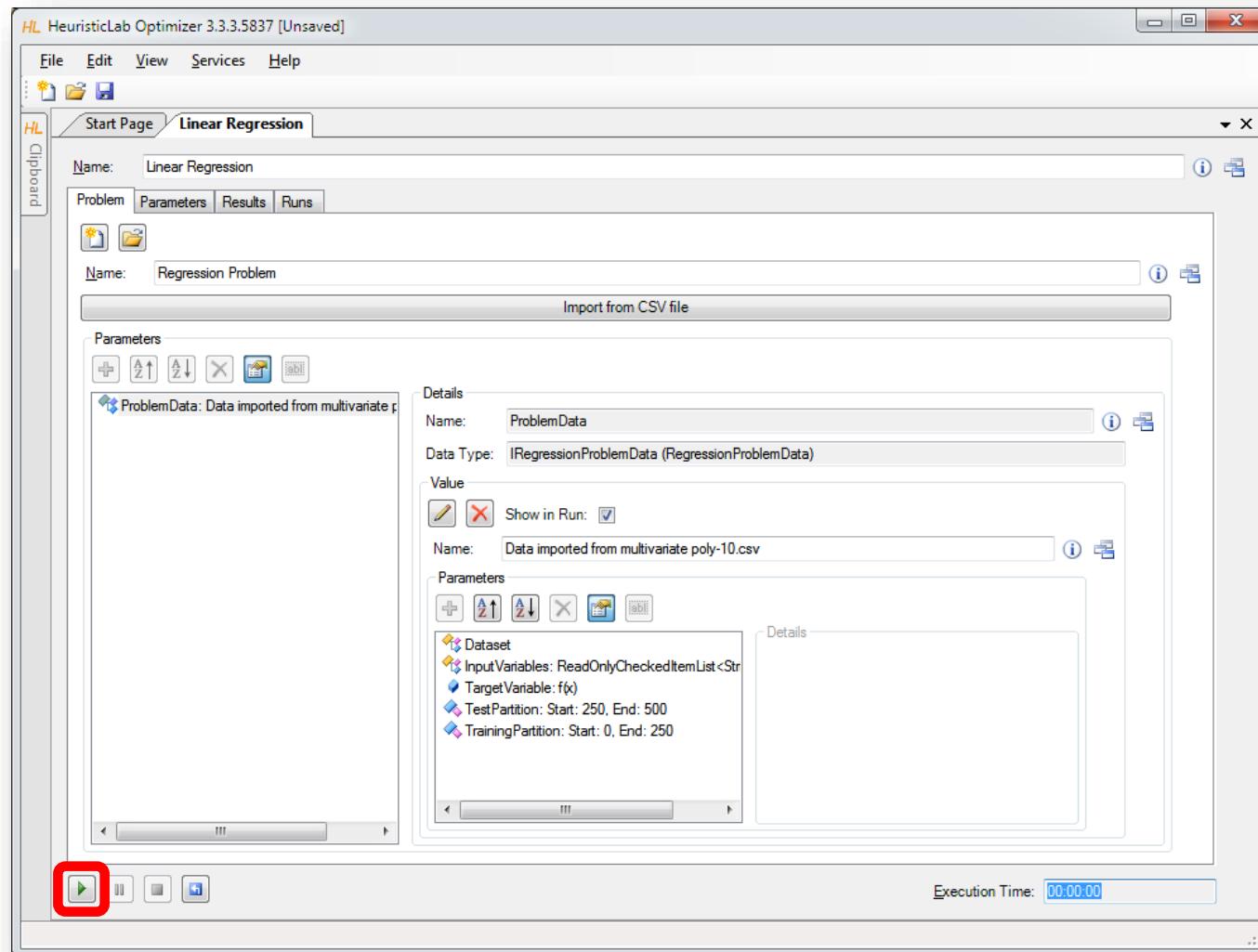
# Select Input Variables



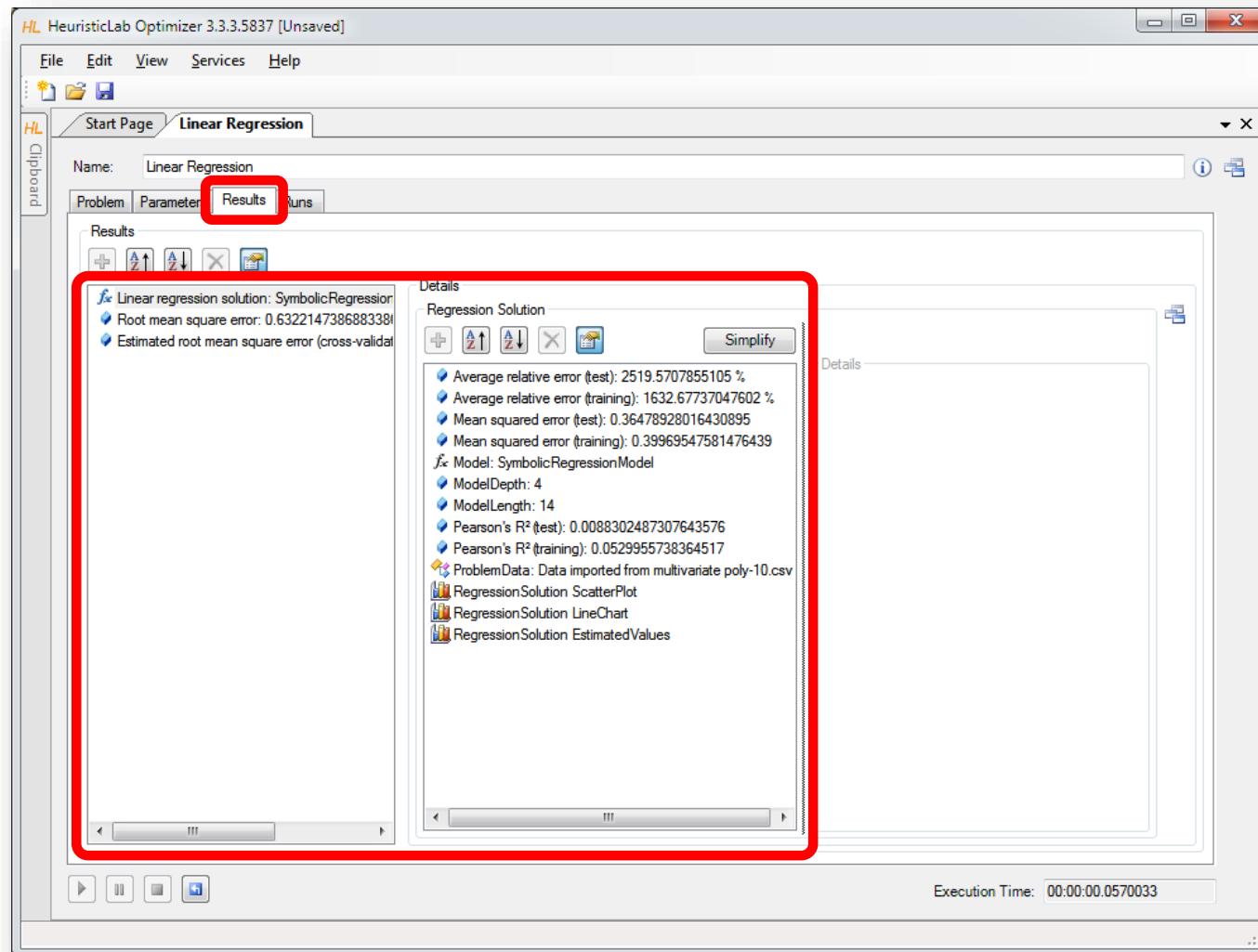
# Configure Training and Test Partitions



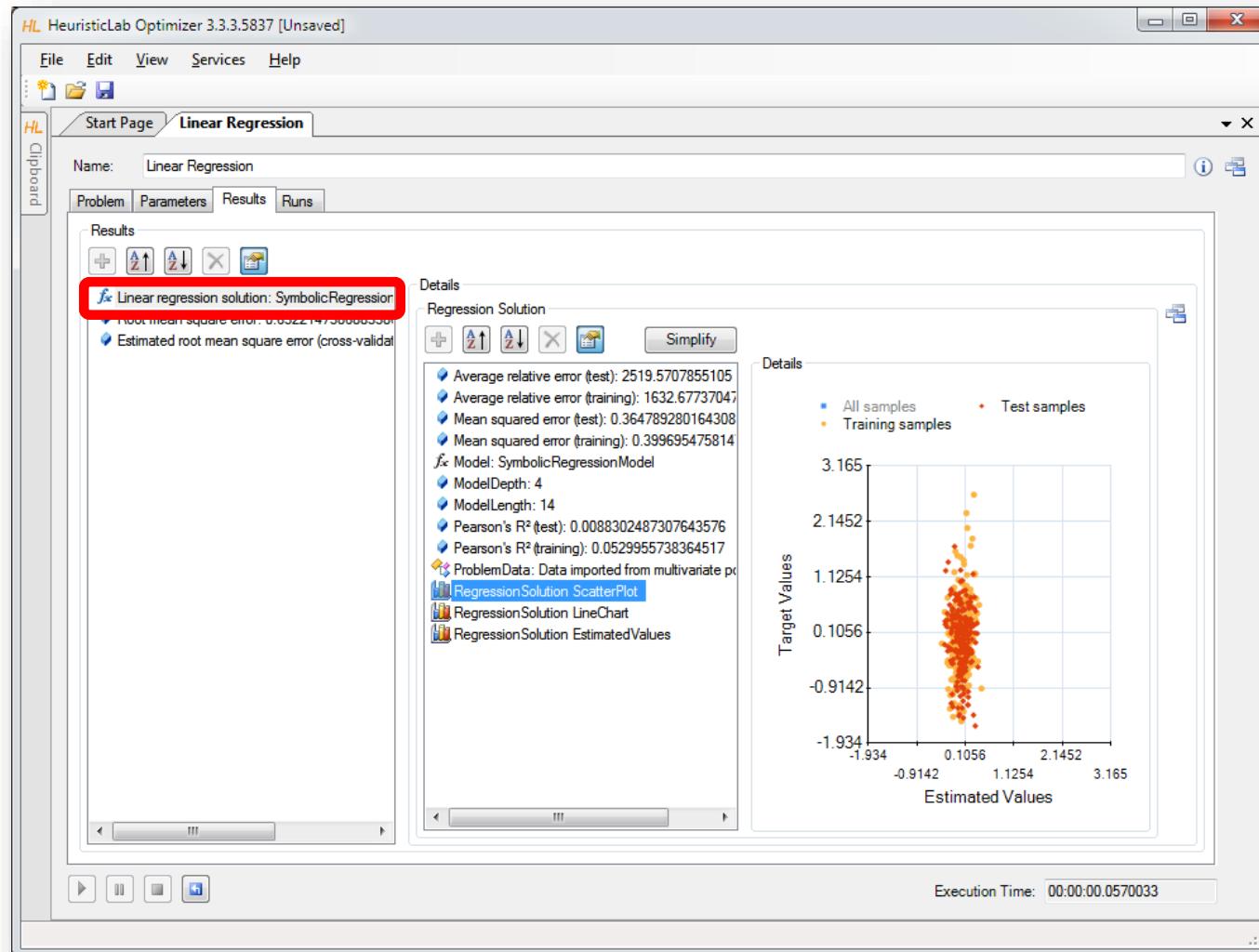
# Run Linear Regression



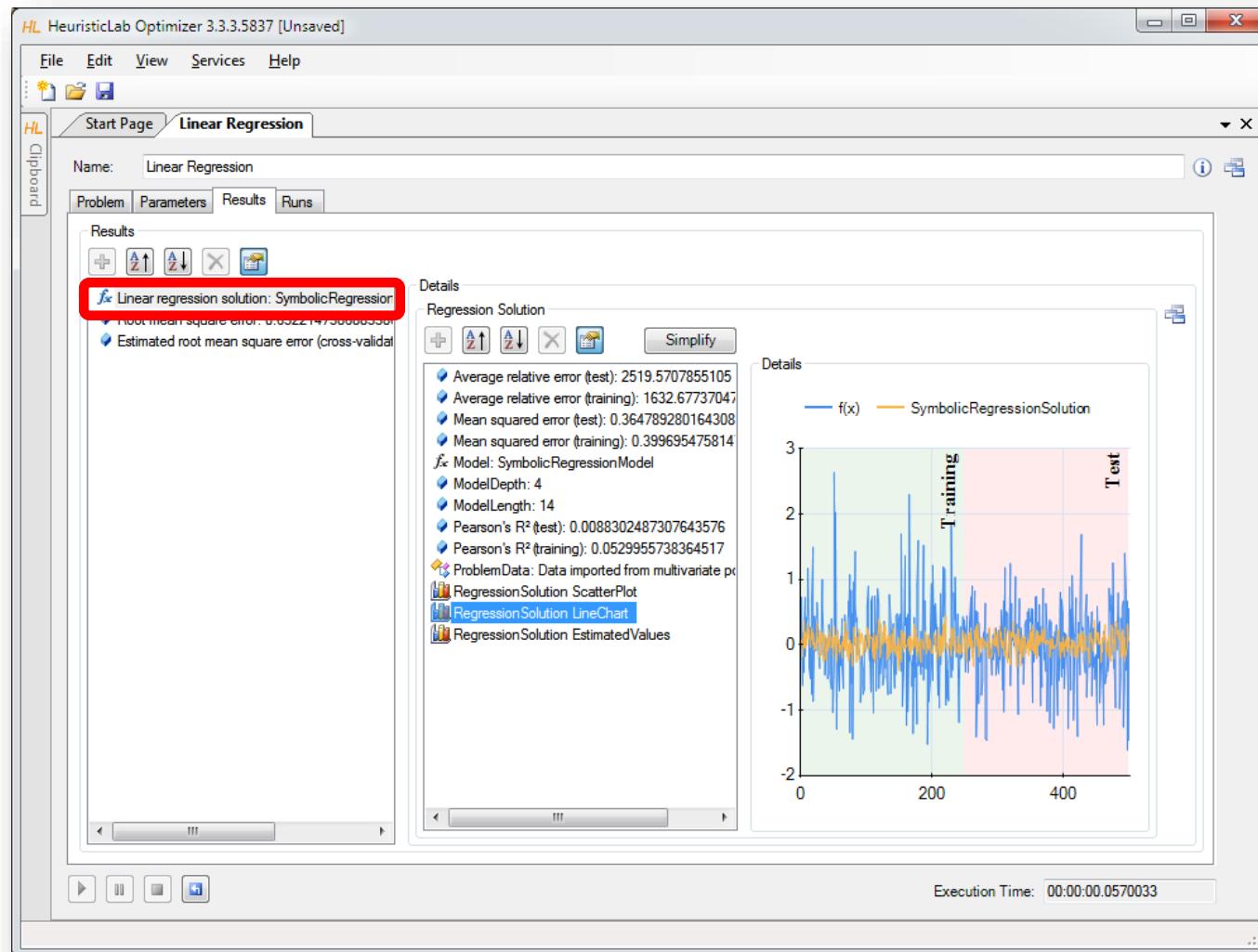
# Inspect Results



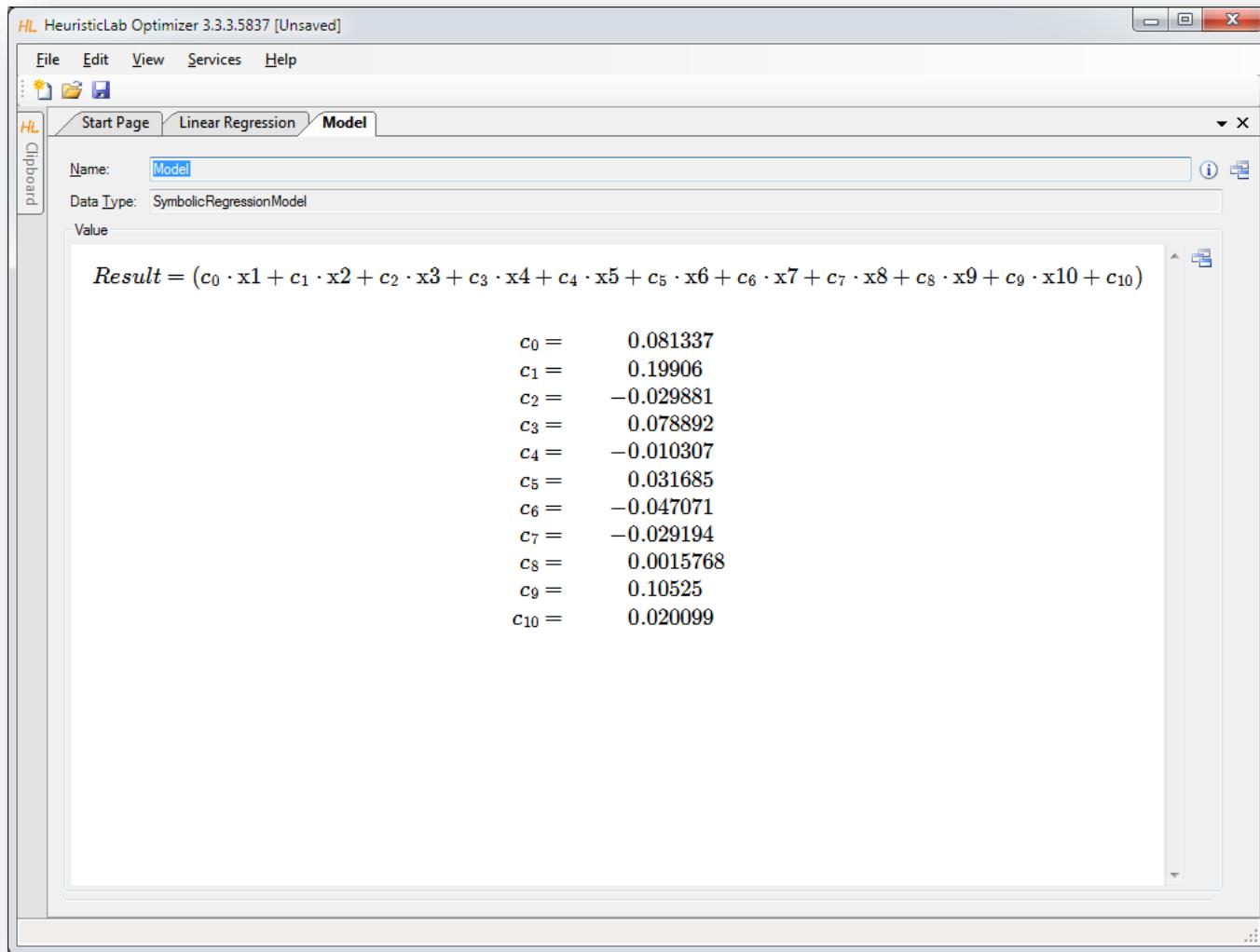
# Inspect Scatterplot of Predicted and Target Values



# Inspect Linechart



# Inspect the Model



The screenshot shows the HeuristicLab Optimizer interface. The window title is "HL HeuristicLab Optimizer 3.3.3.5837 [Unsaved]". The menu bar includes File, Edit, View, Services, and Help. The toolbar has icons for New, Open, Save, and Run. The navigation bar shows Start Page, Linear Regression, and Model (which is selected). On the left, there's a clipboard icon. The main area displays the following information:

Name: Model  
Data Type: SymbolicRegressionModel

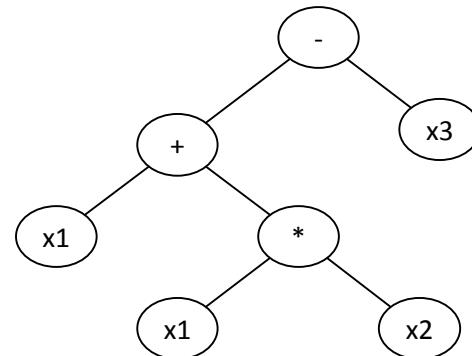
Value

$Result = (c_0 \cdot x_1 + c_1 \cdot x_2 + c_2 \cdot x_3 + c_3 \cdot x_4 + c_4 \cdot x_5 + c_5 \cdot x_6 + c_6 \cdot x_7 + c_7 \cdot x_8 + c_8 \cdot x_9 + c_9 \cdot x_{10} + c_{10})$

$c_0 =$	0.081337
$c_1 =$	0.19906
$c_2 =$	-0.029881
$c_3 =$	0.078892
$c_4 =$	-0.010307
$c_5 =$	0.031685
$c_6 =$	-0.047071
$c_7 =$	-0.029194
$c_8 =$	0.0015768
$c_9 =$	0.10525
$c_{10} =$	0.020099

# Symbolic Regression with HeuristicLab

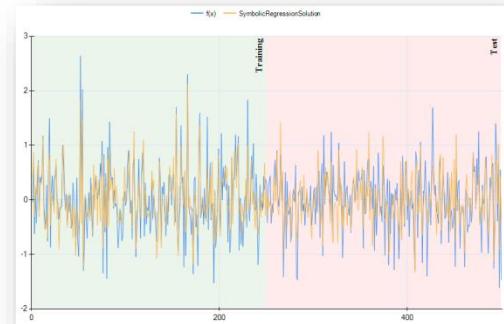
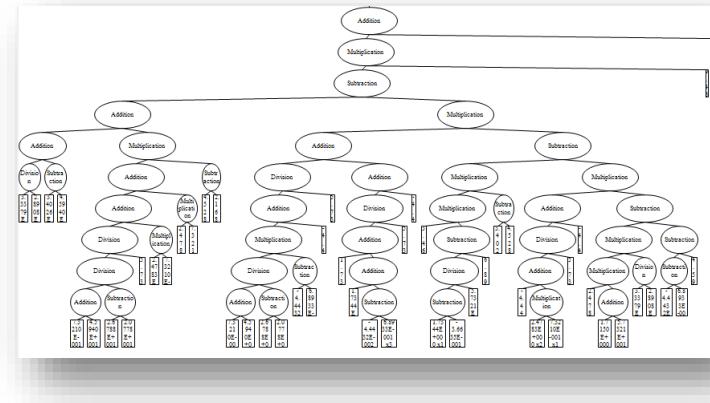
- Linear regression produced an inaccurate model.
- Next: produce a nonlinear symbolic regression model using genetic programming
- Genetic programming
  - evolve variable-length models
  - model representation: symbolic expression tree
  - structure and model parameters are evolved side-by-side
  - white-box models



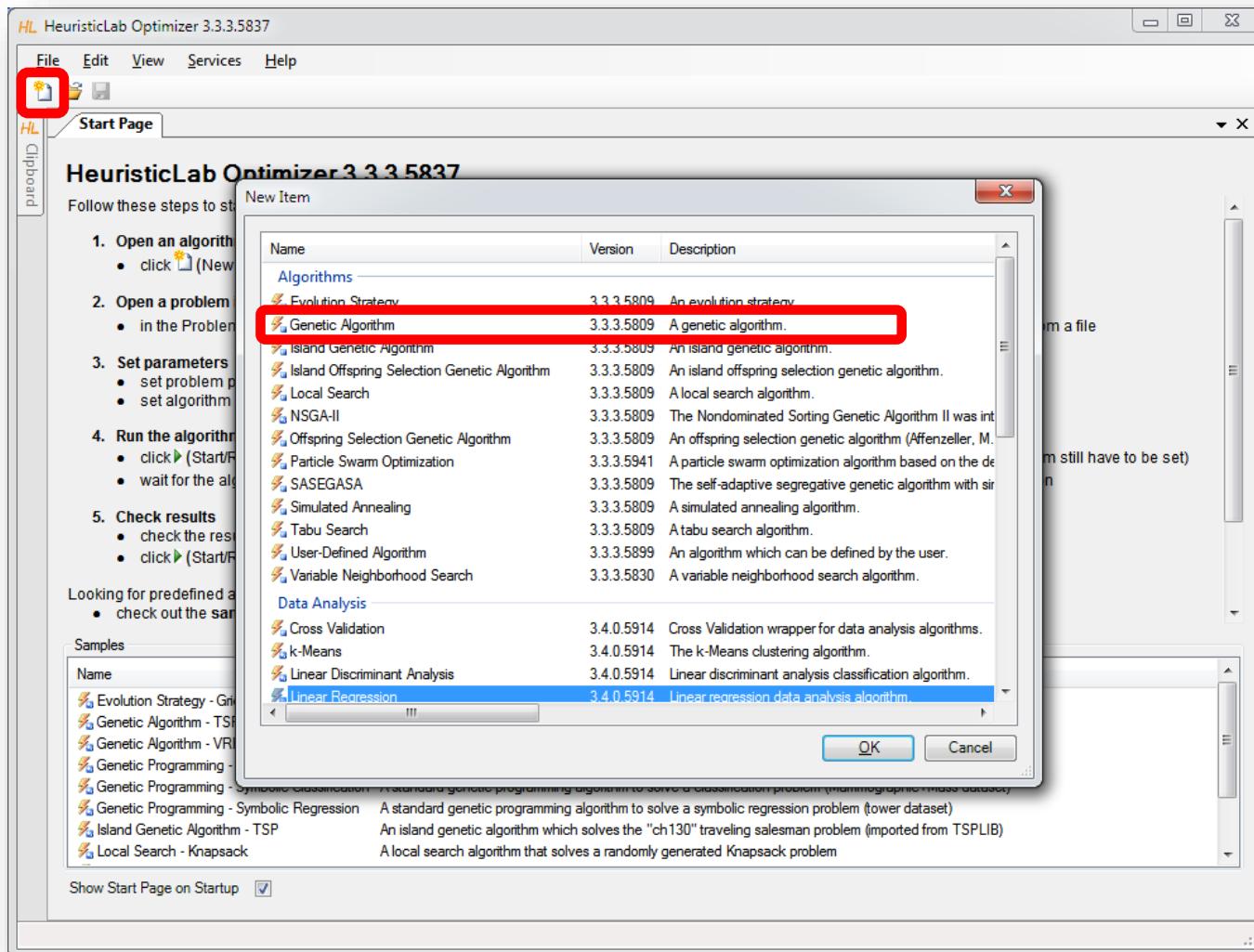
# Symbolic Regression with HeuristicLab



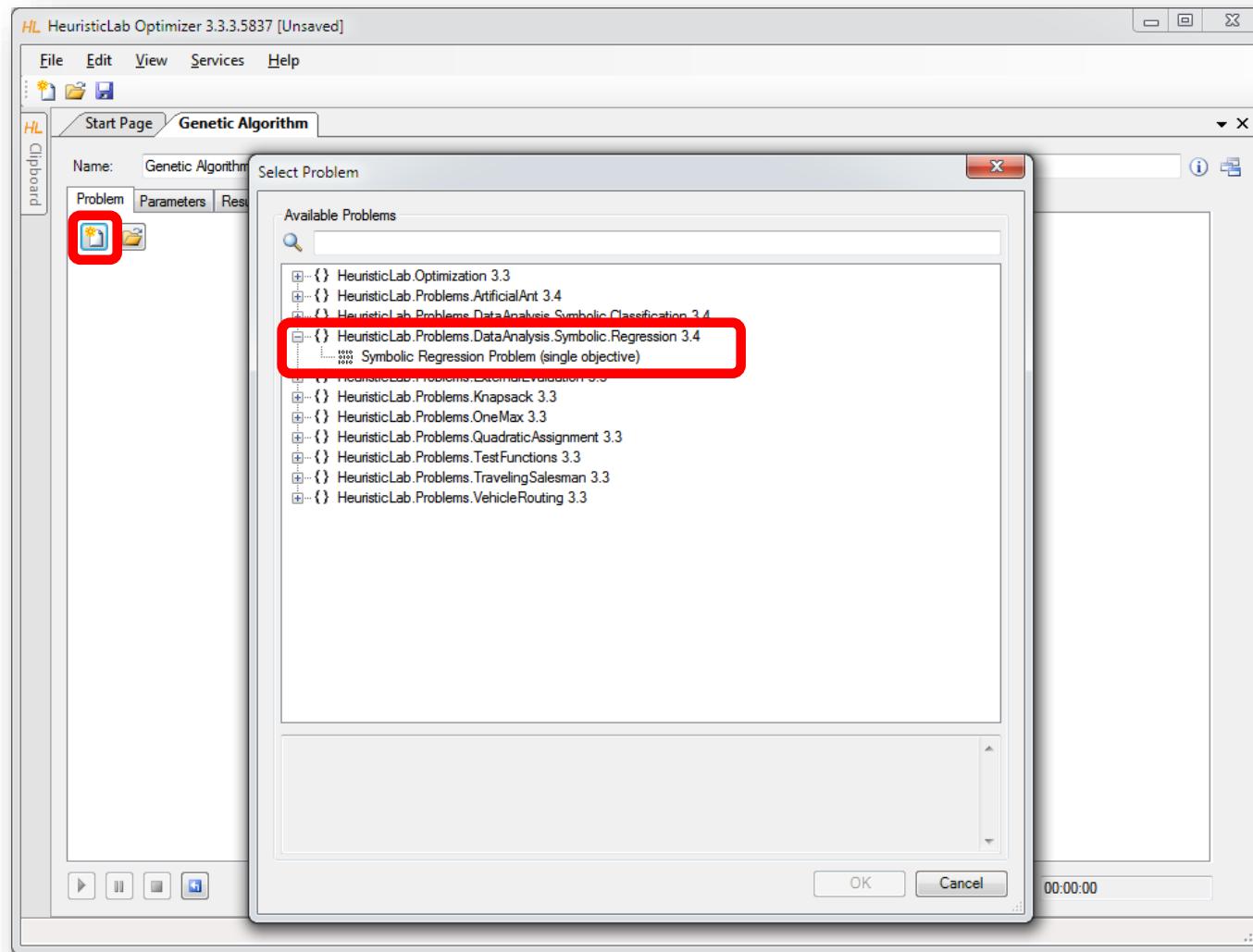
- Demonstration
  - problem configuration
  - function set and terminal set
  - model size constraints
  - evaluation
- Algorithm configuration
  - selection
  - mutation
- Analysis of results
  - model accuracy
  - model structure and parameters



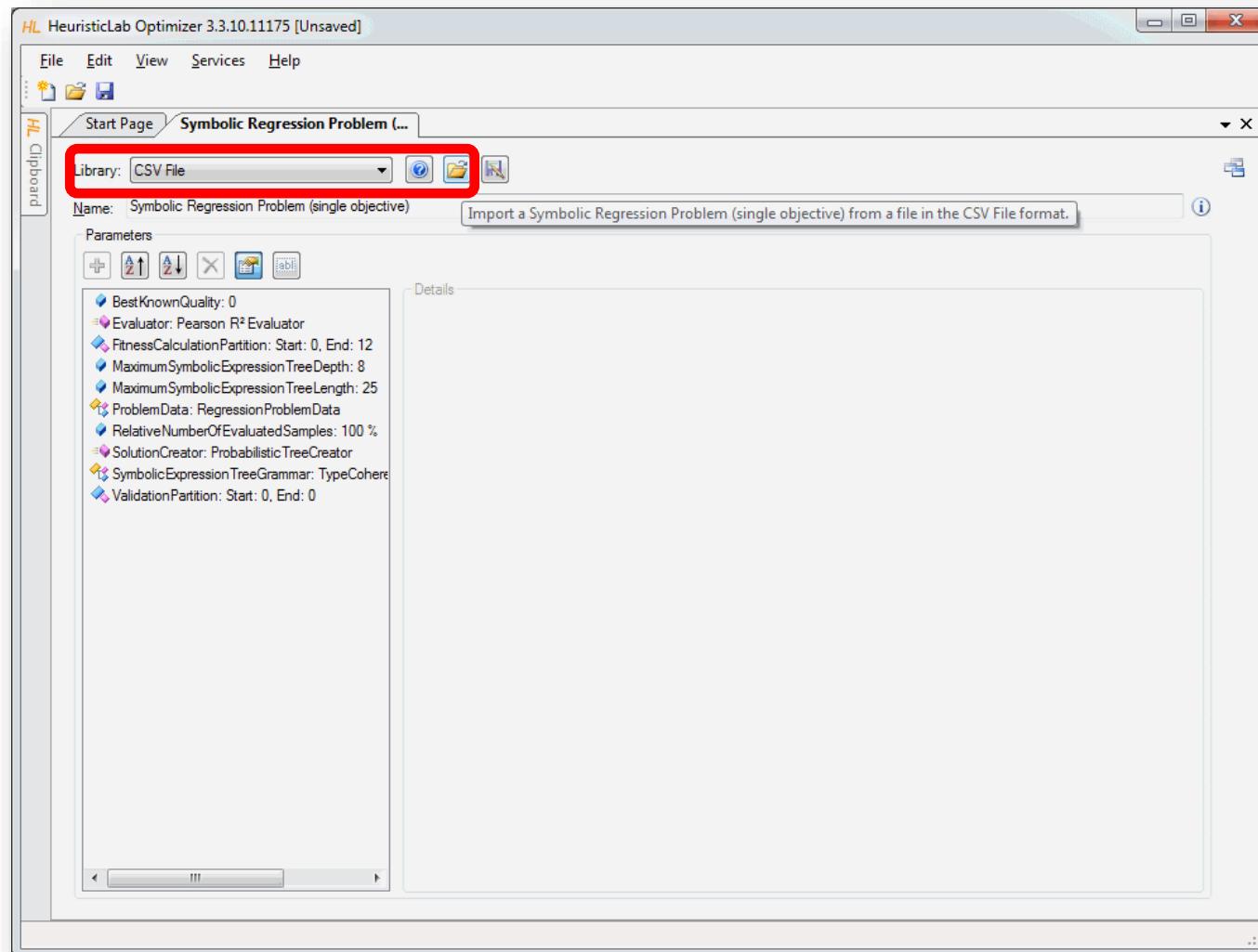
# Create New Genetic Algorithm



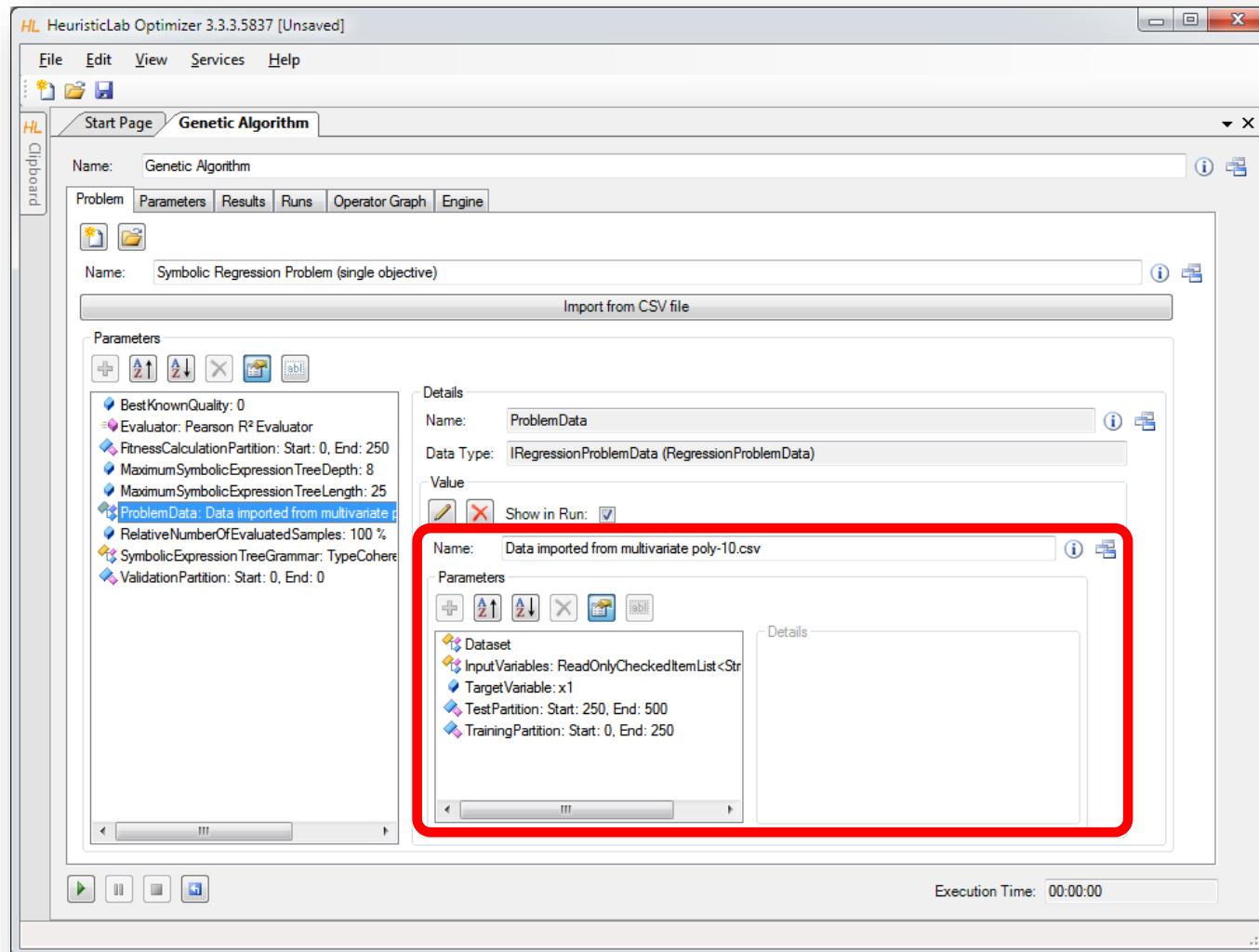
# Create New Symbolic Regression Problem



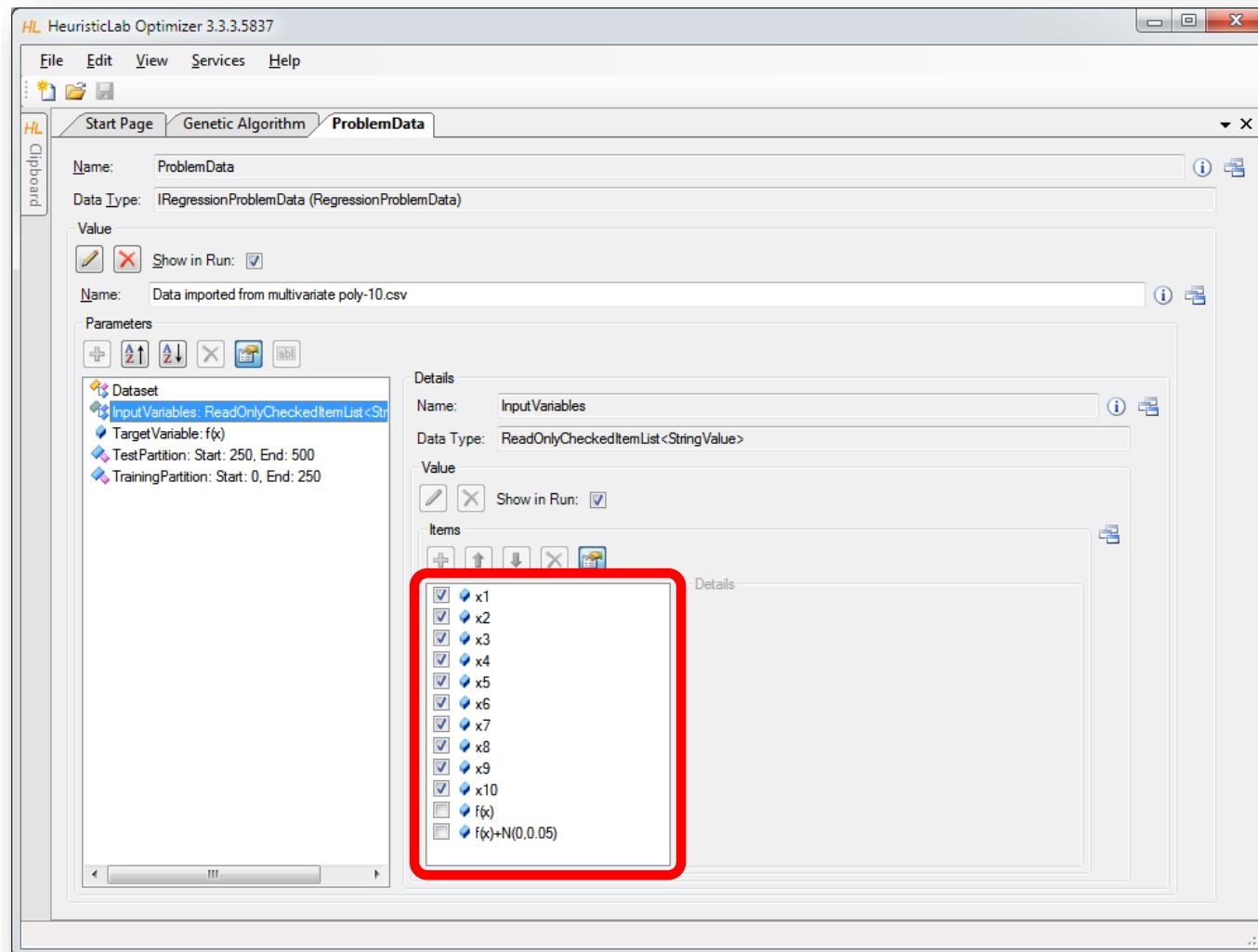
# Import Data



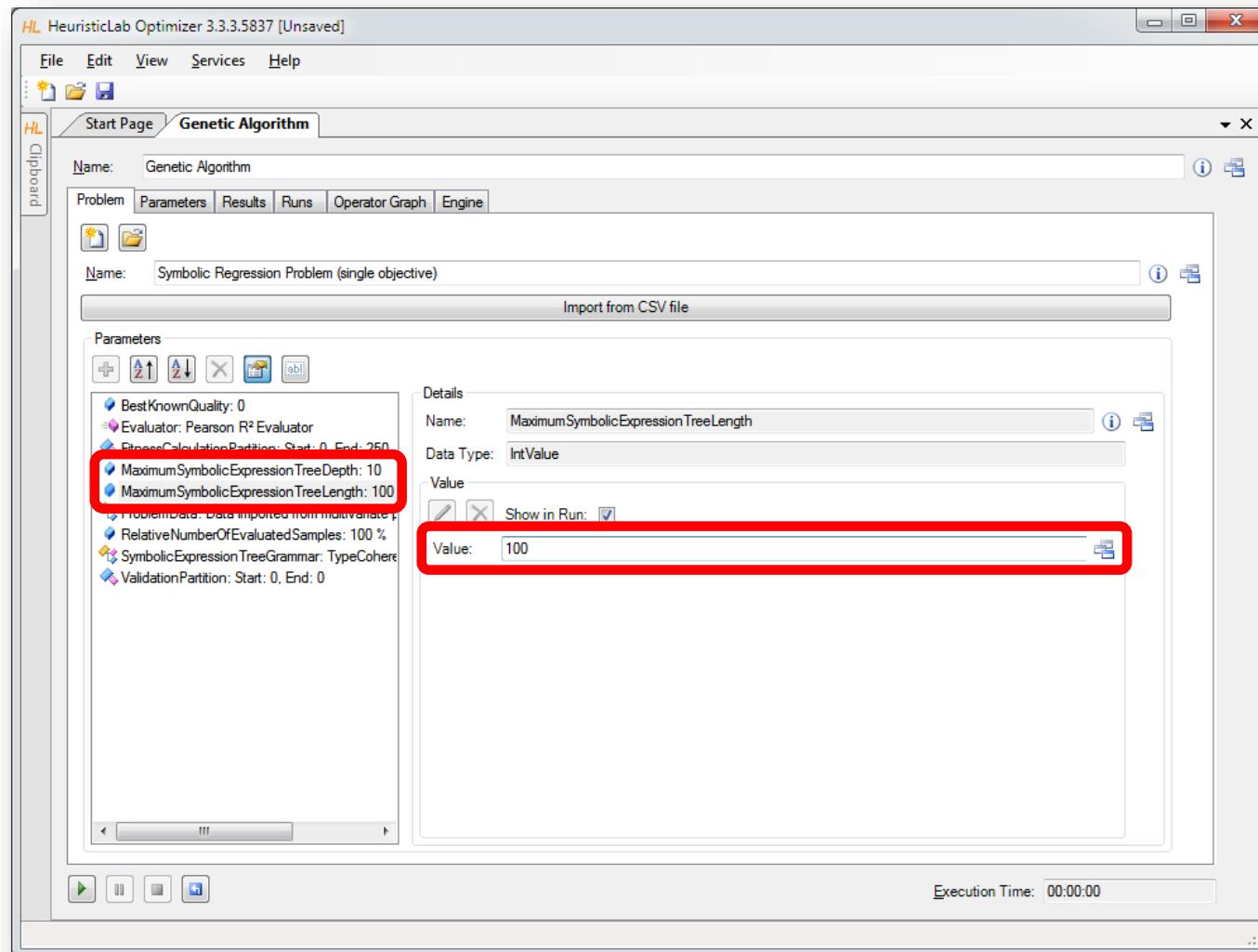
# Inspect Data and Configure Dataset



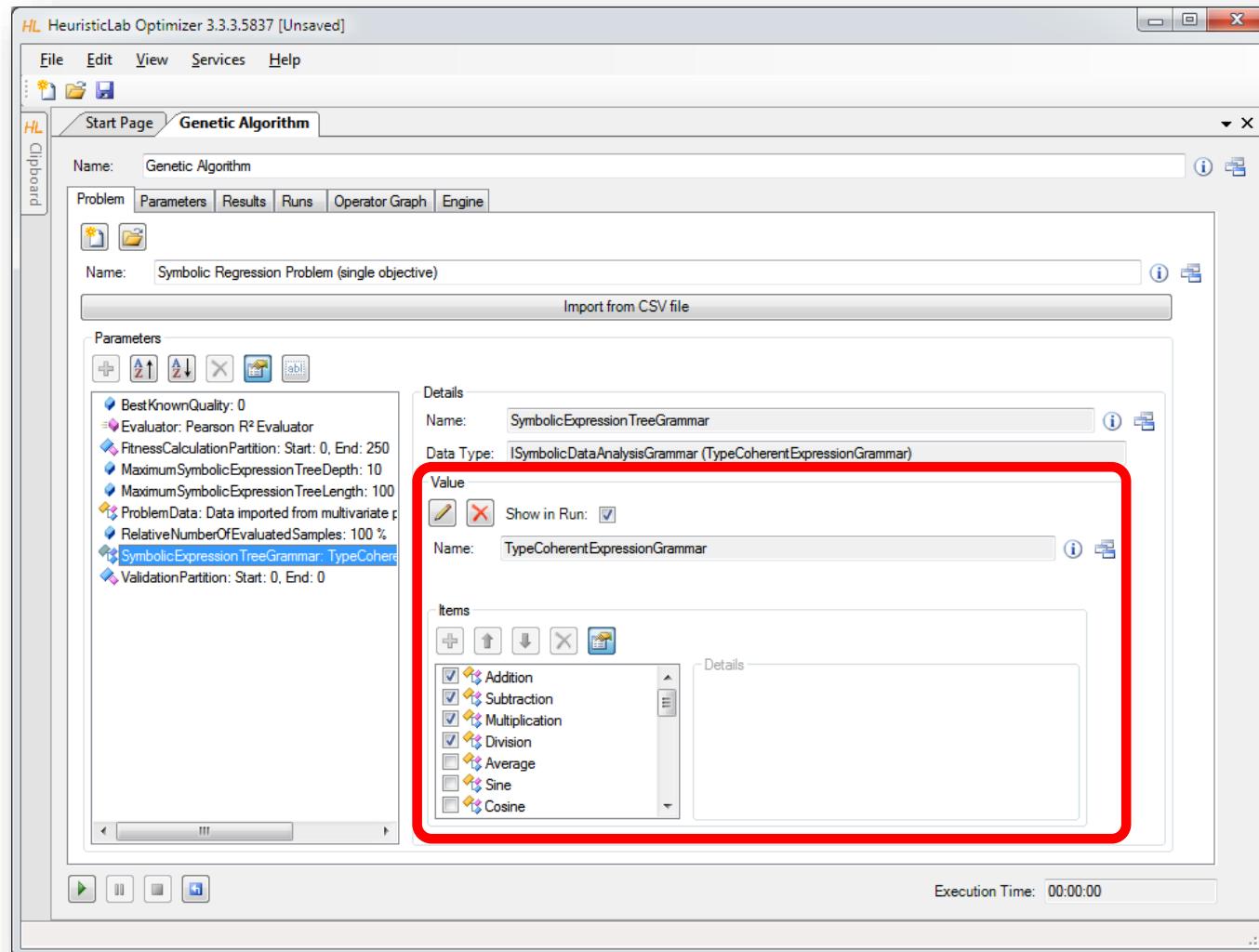
# Set Target and Input Variables



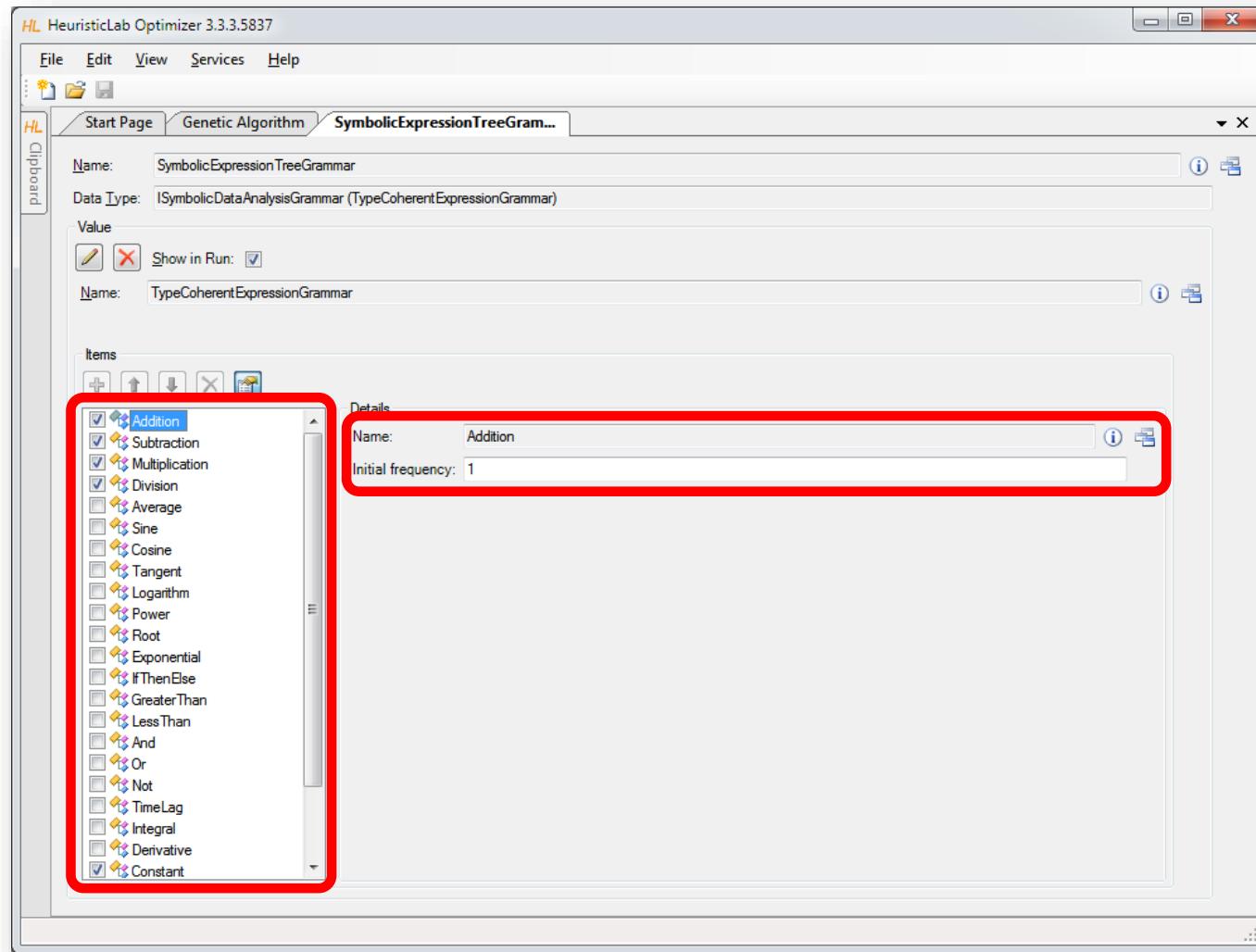
# Configure Maximal Model Depth and Length



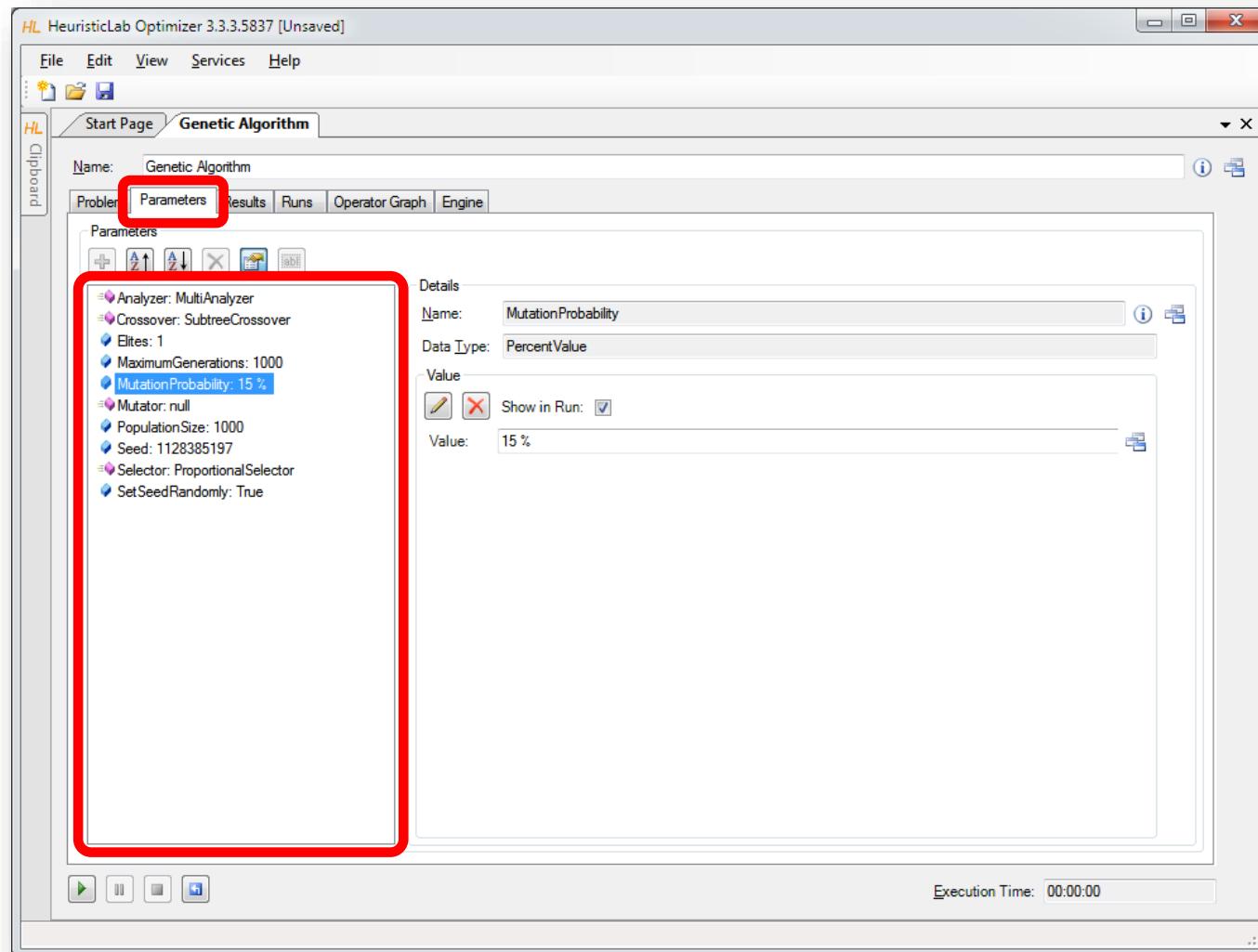
# Configure Function Set (Grammar)



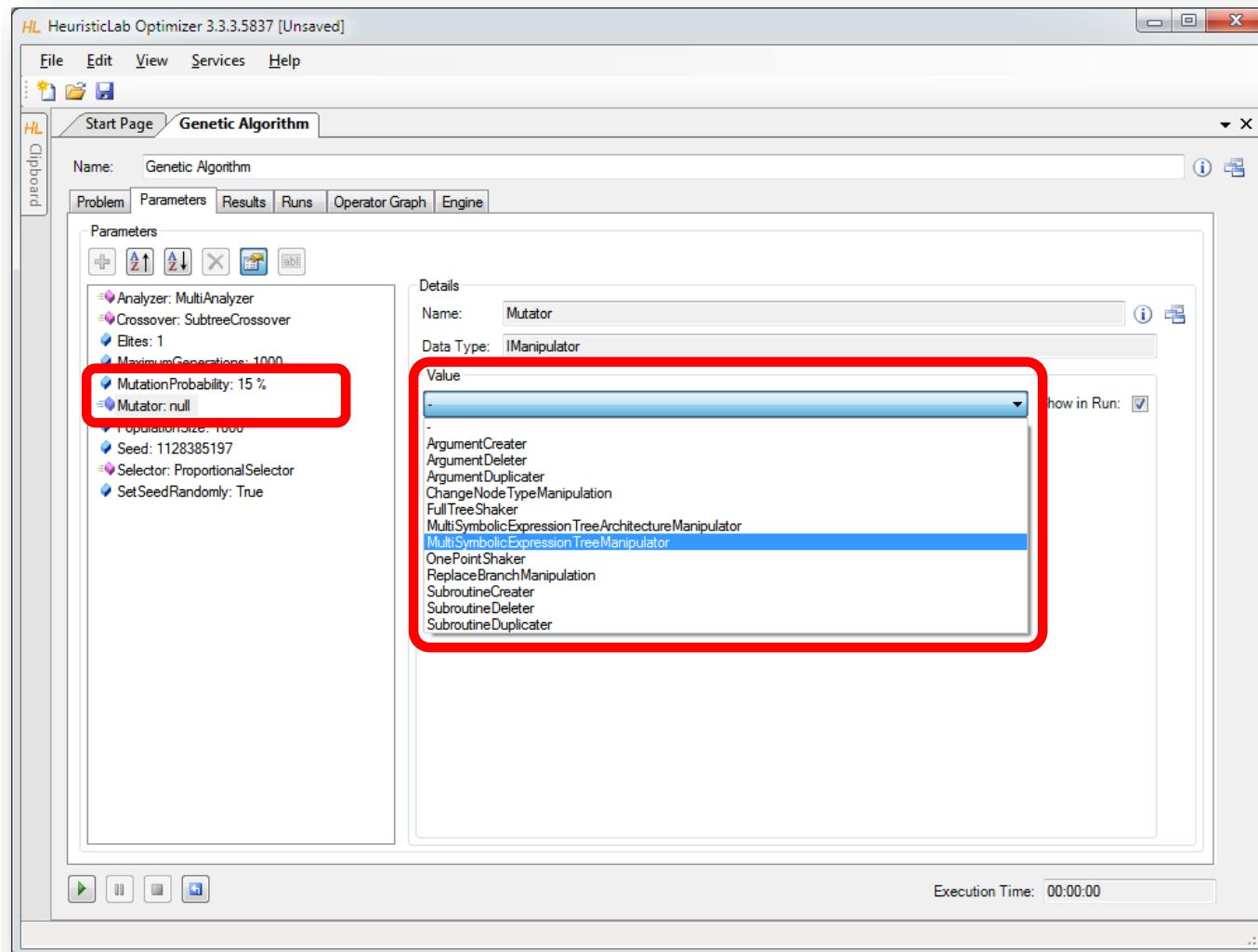
# Configure Function Set (Grammar)



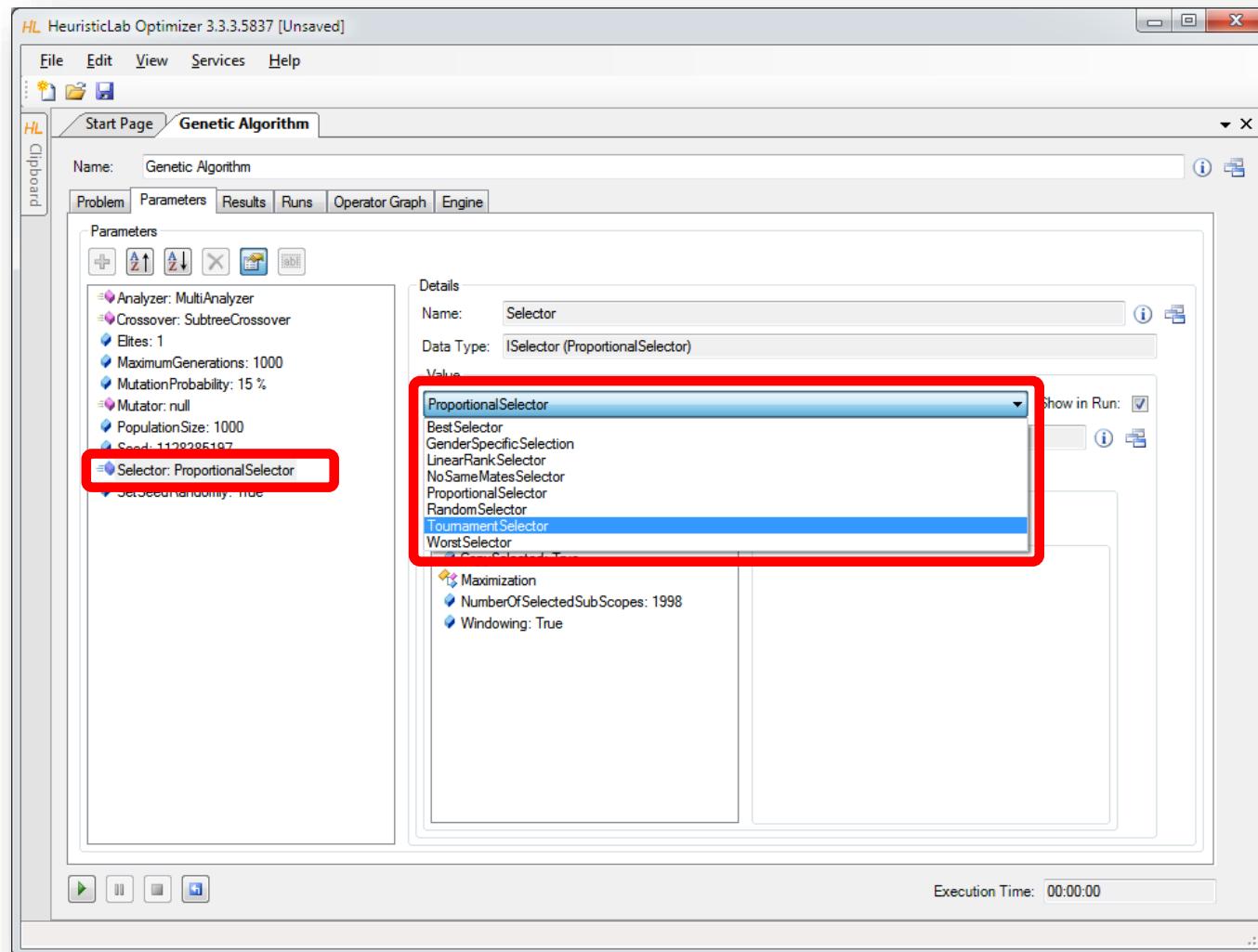
# Configure Algorithm Parameters



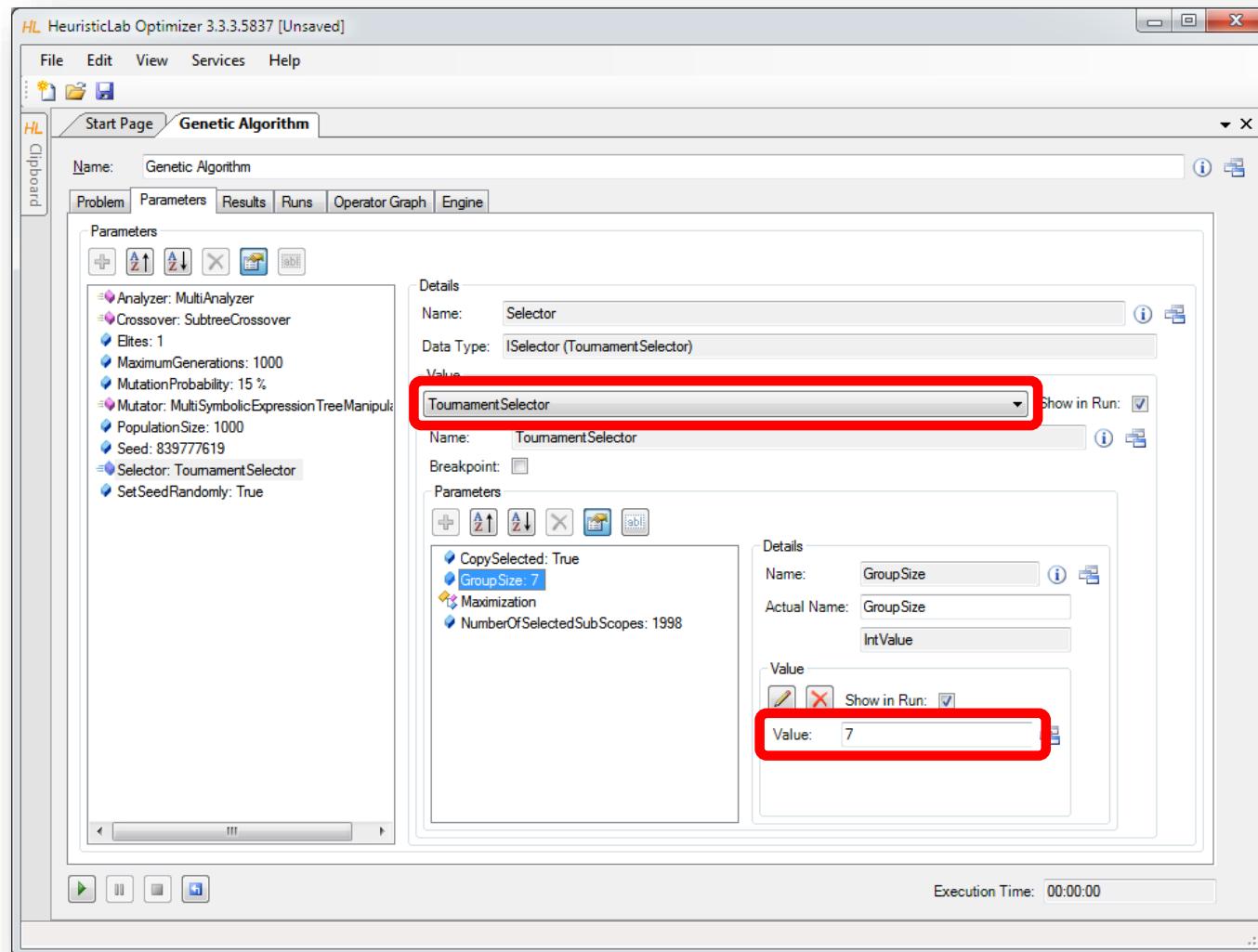
# Configure Mutation Operator



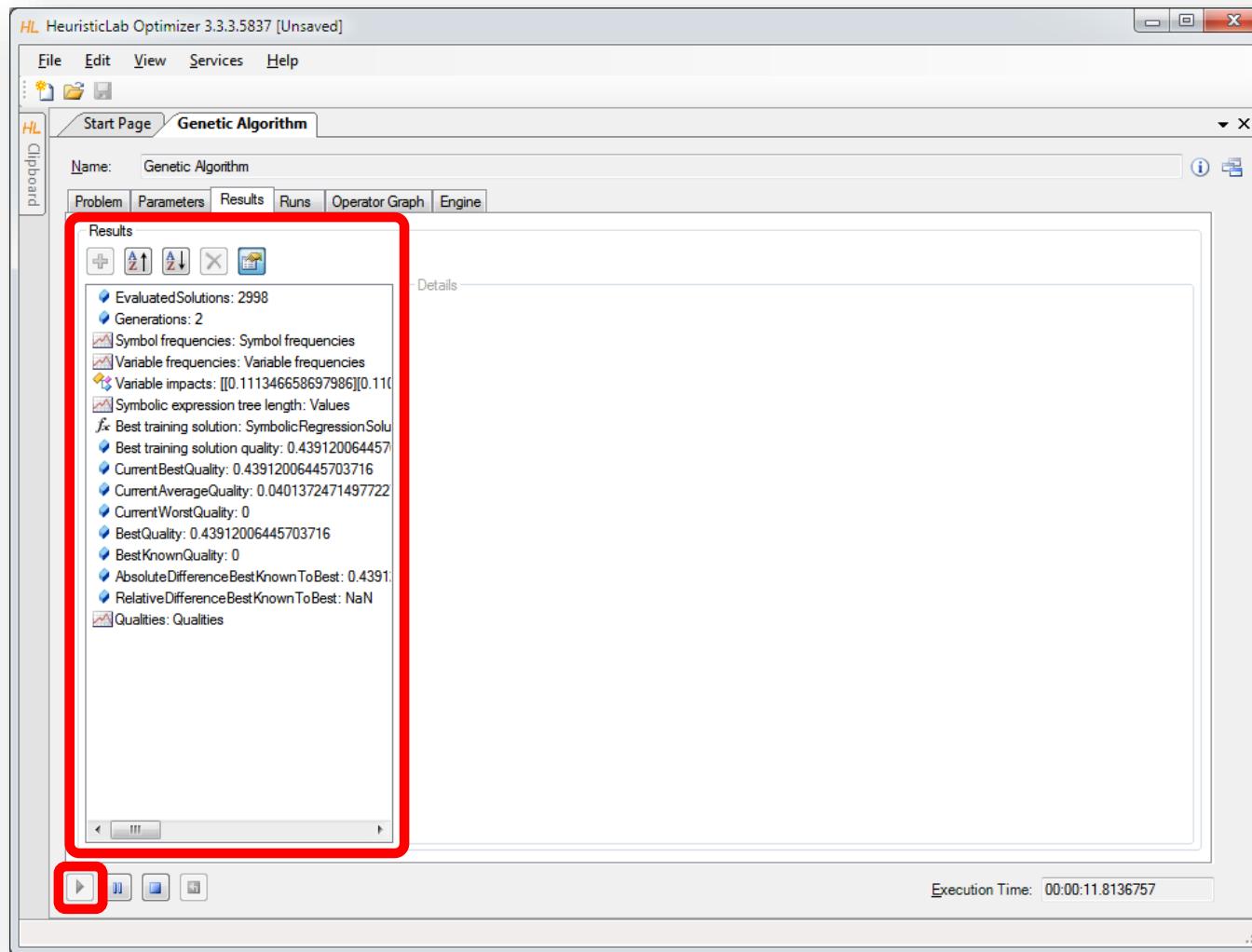
# Configure Selection Operator



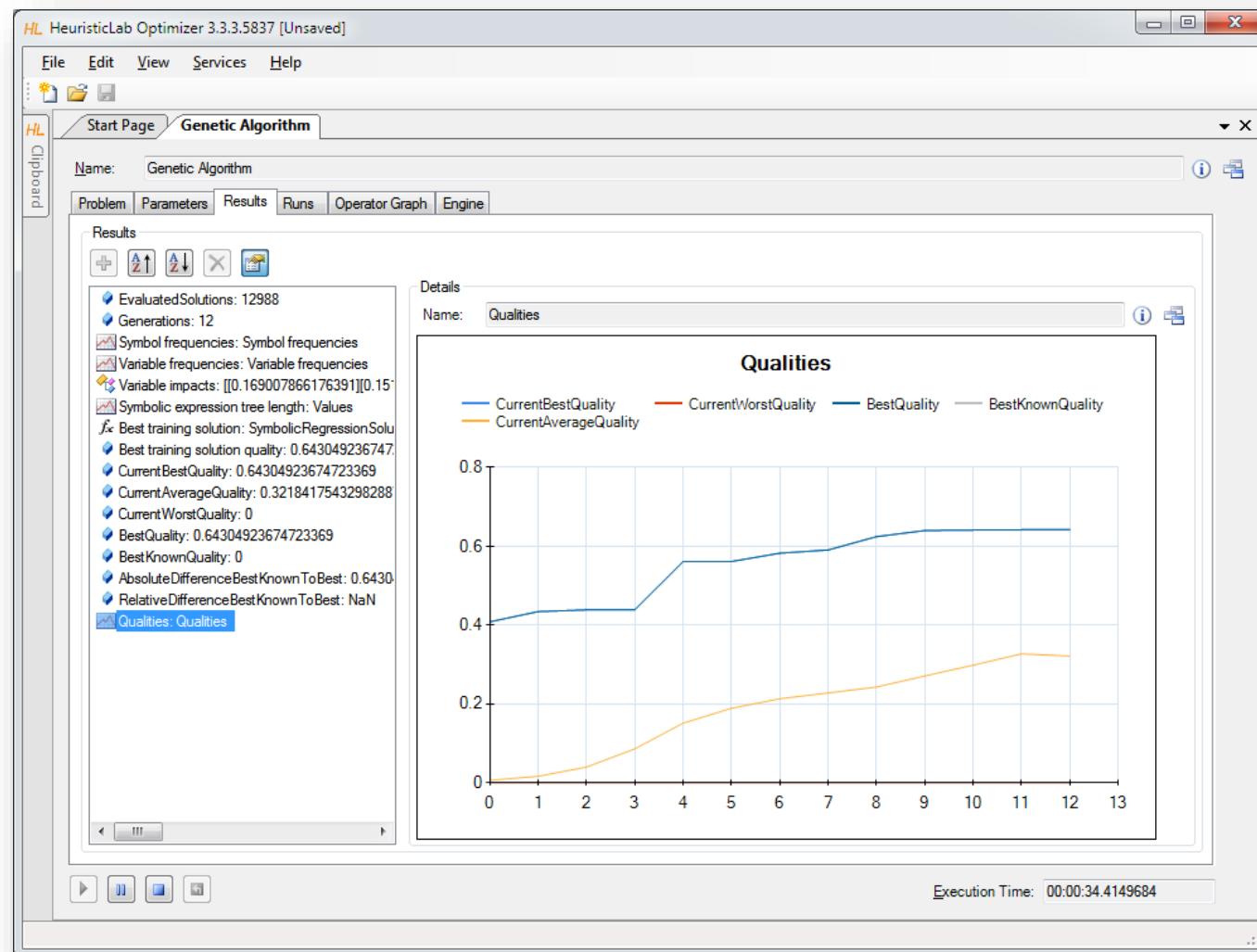
# Configure Tournament Group Size



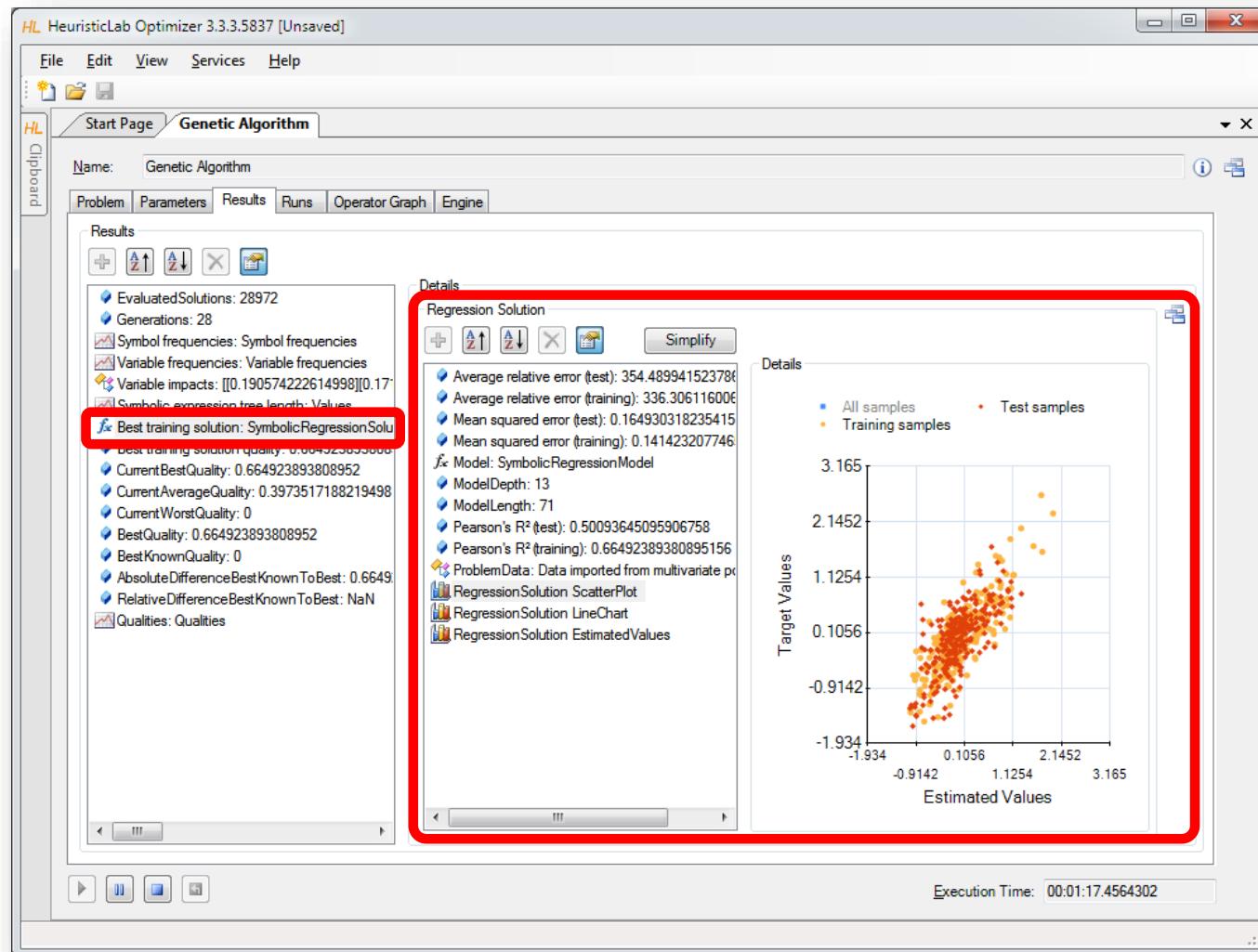
# Start Algorithm and Inspect Results



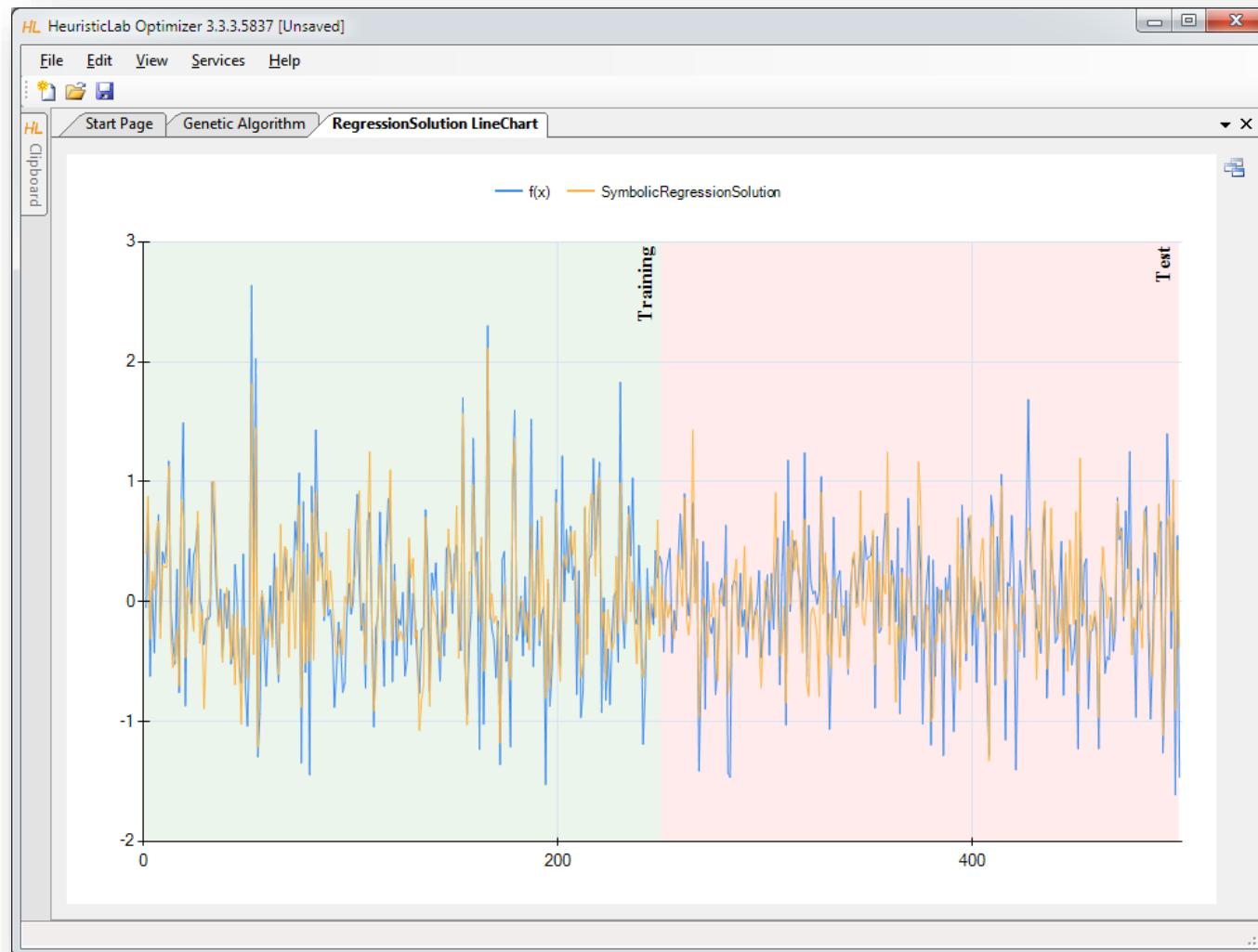
# Inspect Quality Chart



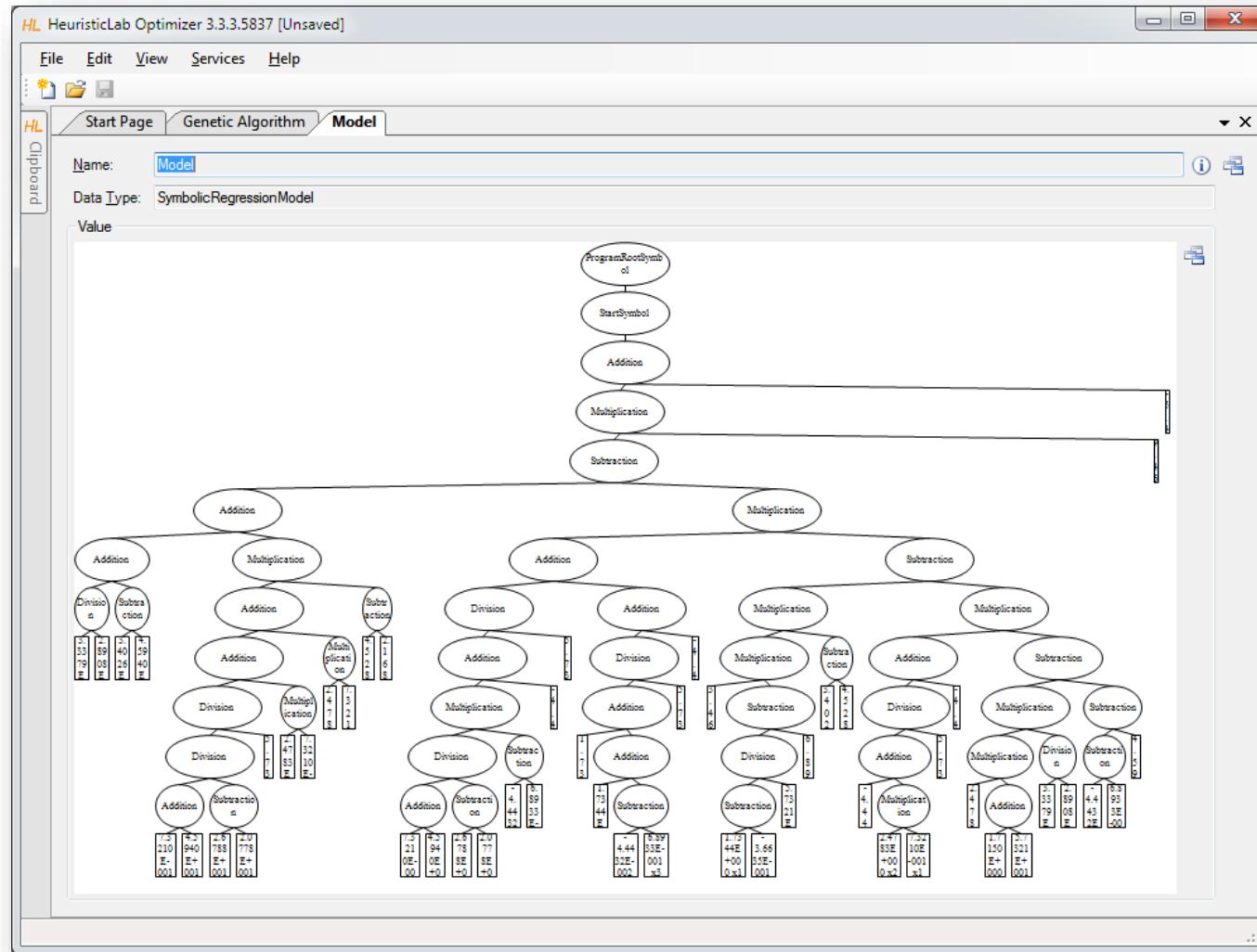
# Inspect Best Model on Training Partition



# Inspect Linechart of Best Model on Training Partition



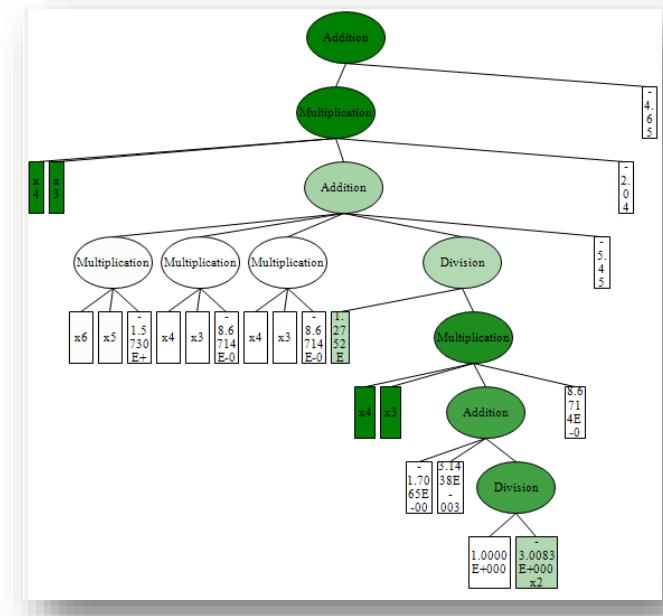
# Inspect Structure of Best Model on Training Partition



# Model Simplification and Export

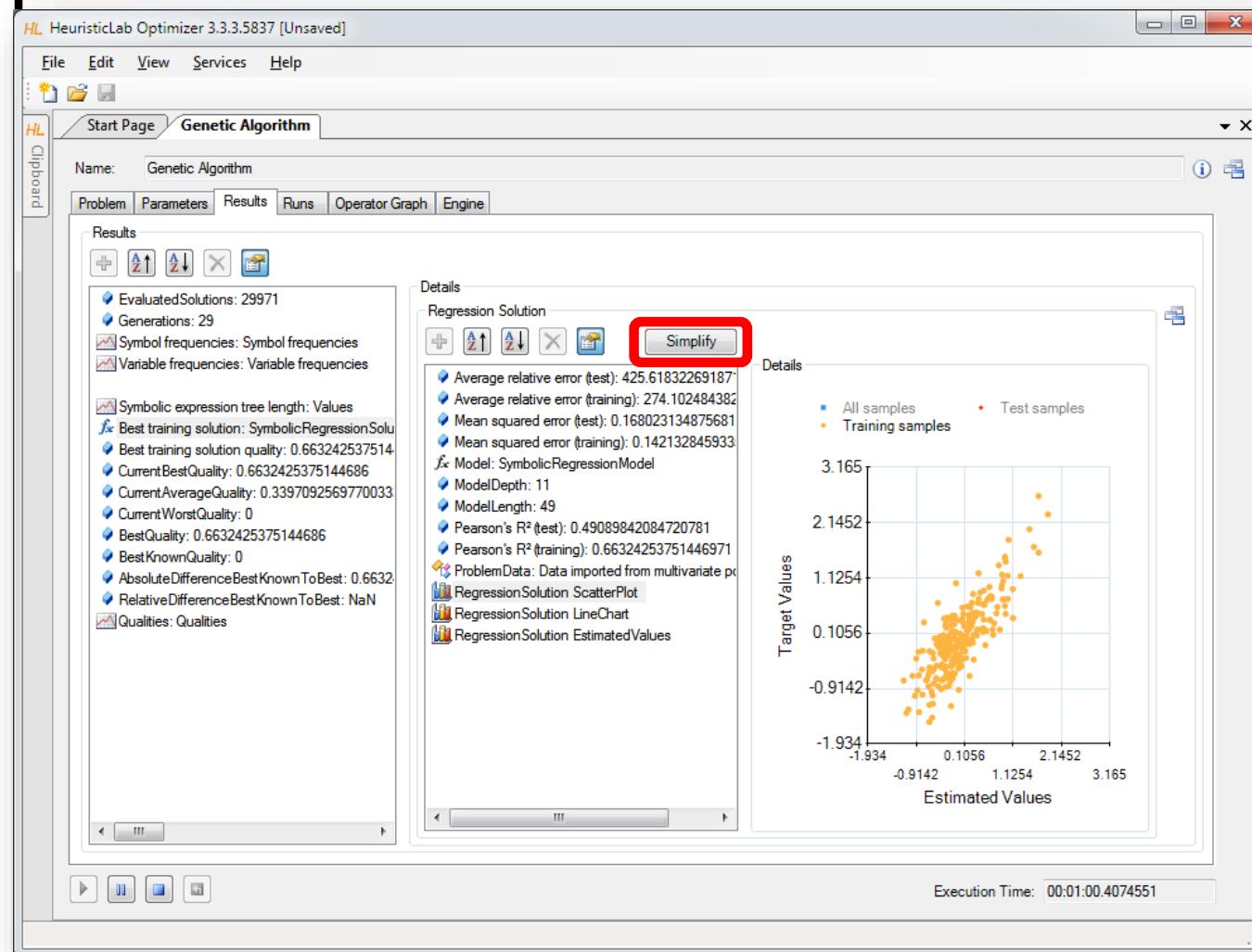


- Demonstration
  - automatic simplification
  - visualization of node impacts
  - manual simplification
    - online update of results
  - model export
    - Excel
    - MATLAB
    - LaTeX

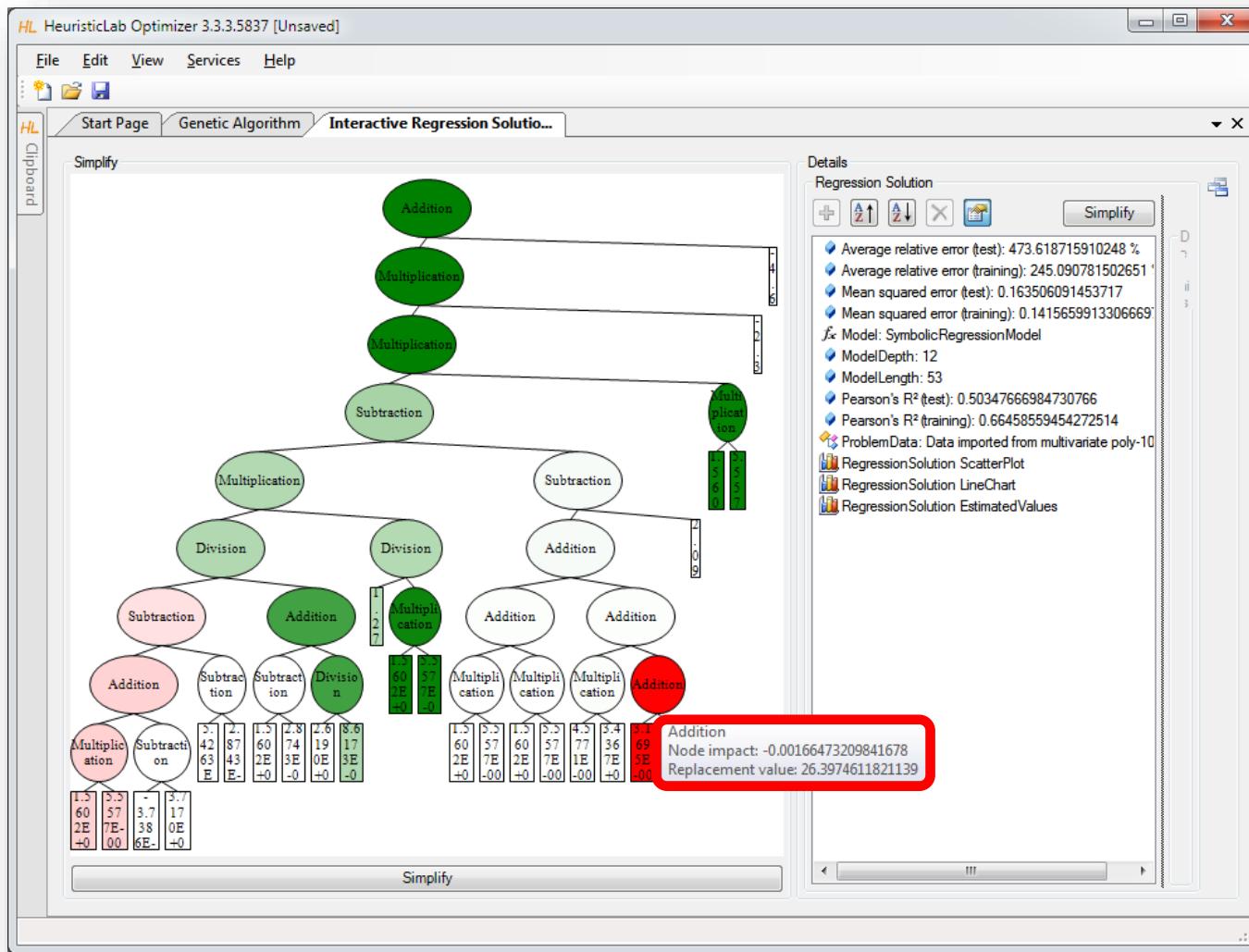


$$\begin{aligned} \text{Result} &= x4(t) \cdot x3(t) \cdot c_{20} \\ &\cdot \left( x6(t) \cdot x5(t) \cdot c_4 + x4(t) \cdot x3(t) \cdot c_7 + x4(t) \cdot x3(t) \cdot c_{10} + \frac{c_{11}x1(t)}{x4(t) \cdot x3(t) \cdot \left( c_{14}x4(t) + c_{15}x5(t) + \frac{1}{c_{17}x2(t)} \right) \cdot c_{18}} + c_{19} \right) + c_{21} \end{aligned} \quad (13)$$
$$(14)$$

# Detailed Model Analysis and Simplification



# Symbolic Simplification and Node Impacts



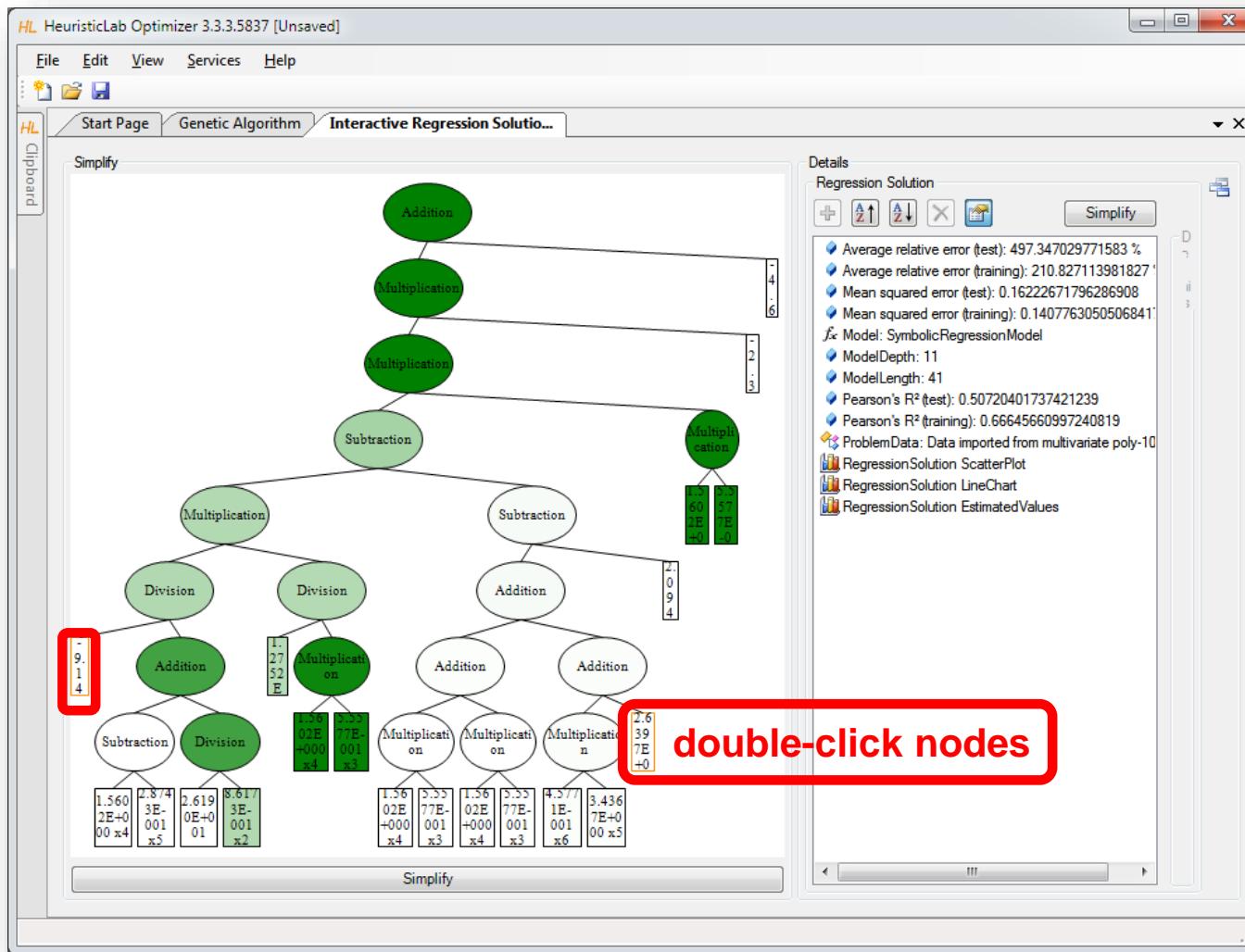
# Manual Simplification

HL HeuristicLab Optimizer 3.3.3.5837 [Unsaved]

File Edit View Services Help

Start Page Genetic Algorithm Interactive Regression Solution

Simplify



Details

Regression Solution

- Average relative error (test): 497.347029771583 %
- Average relative error (training): 210.827113981827 %
- Mean squared error (test): 0.16222671796286908
- Mean squared error (training): 0.1407763050506841

Model: SymbolicRegressionModel

- ModelDepth: 11
- ModelLength: 41
- Pearson's R<sup>2</sup> (test): 0.50720401737421239
- Pearson's R<sup>2</sup> (training): 0.66645660997240819

ProblemData: Data imported from multivariate poly-10

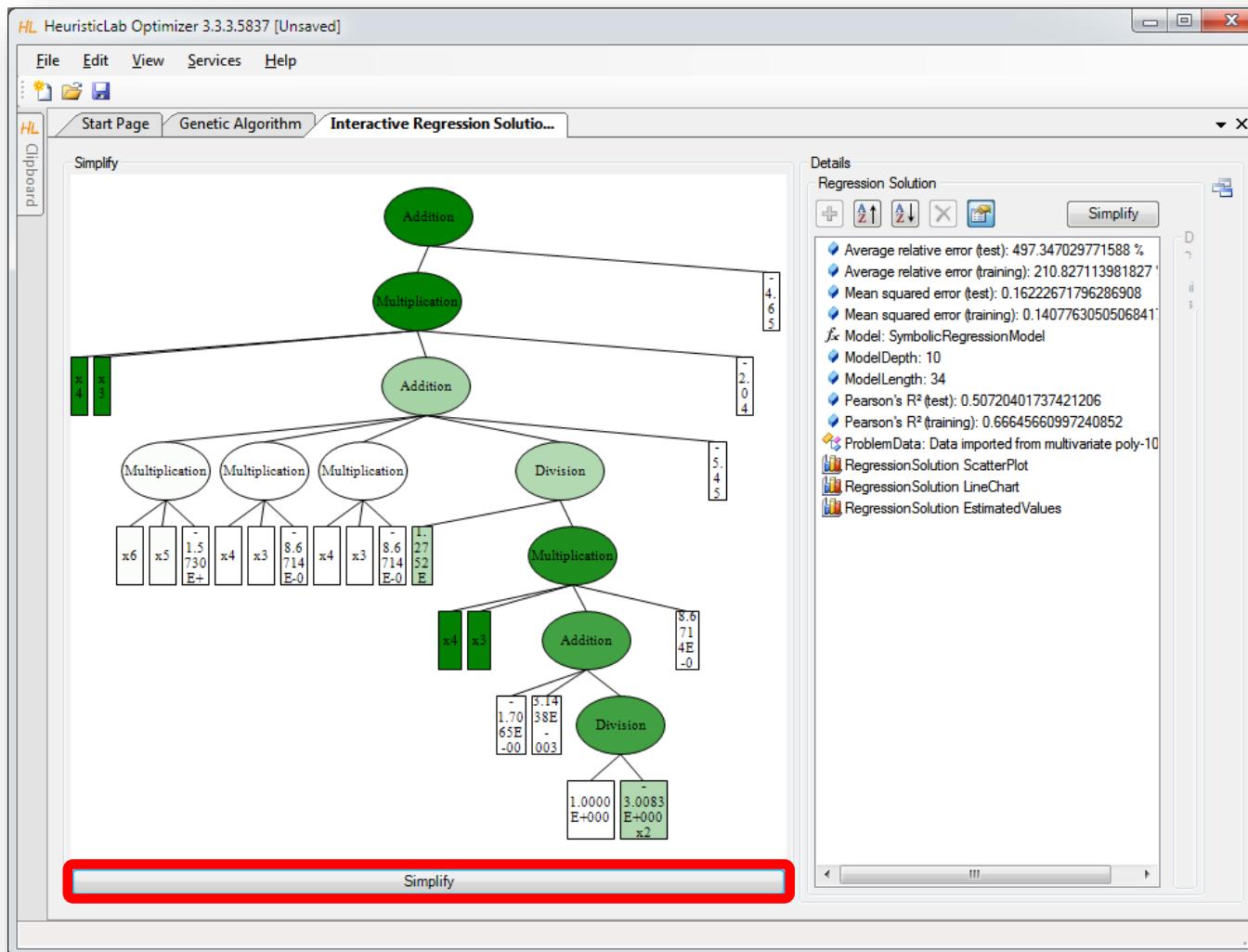
Regression Solution ScatterPlot  
Regression Solution LineChart  
Regression Solution EstimatedValues

Clipboard

Simplify

double-click nodes

# Automatic Symbolic Simplification



Simplify

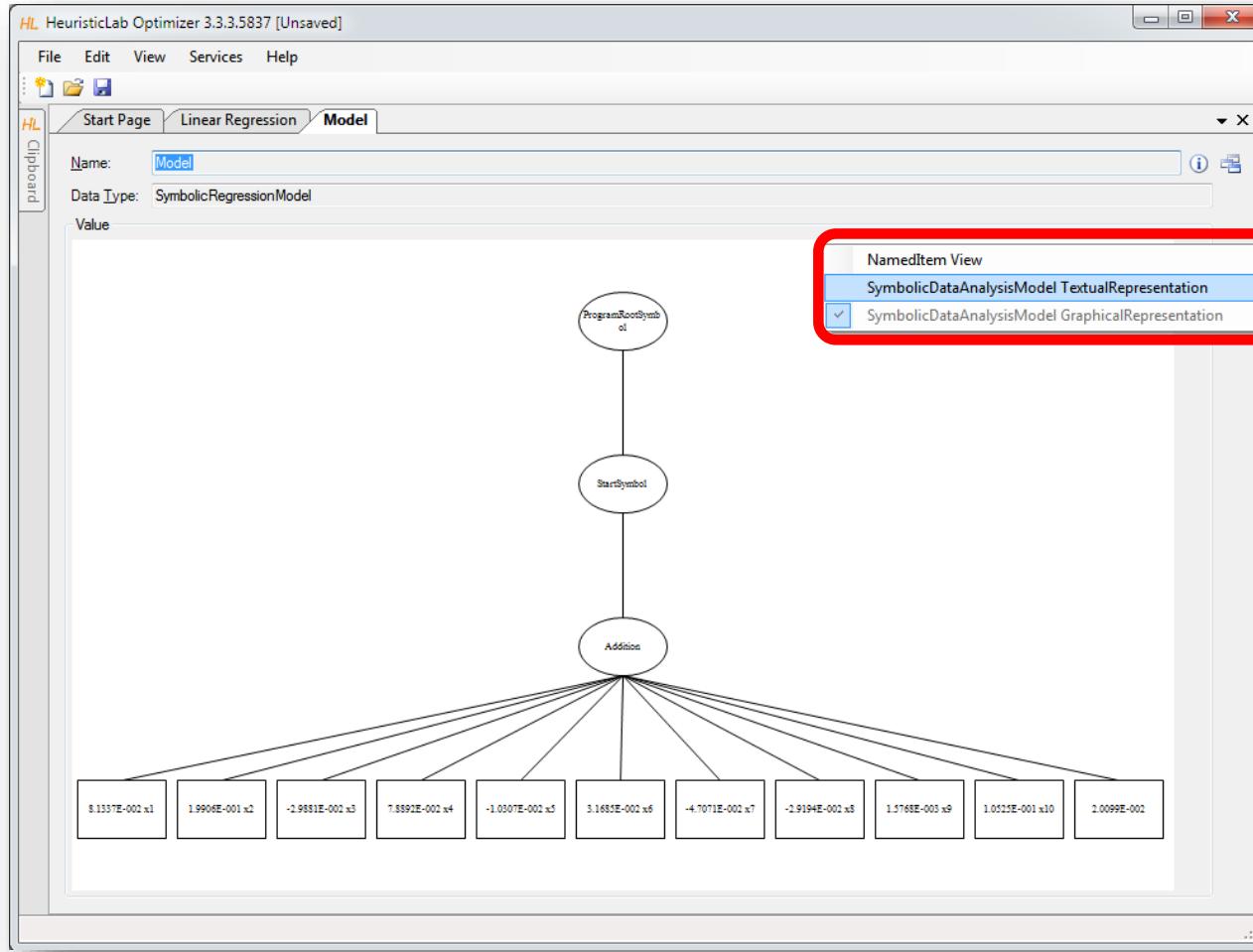
**Details**  
Regression Solution

- Average relative error (test): 497.347029771588 %
- Average relative error (training): 210.827113981827 %
- Mean squared error (test): 0.16222671796286908
- Mean squared error (training): 0.1407763050506841
- Model: SymbolicRegressionModel
- ModelDepth: 10
- ModelLength: 34
- Pearson's R<sup>2</sup> (test): 0.50720401737421206
- Pearson's R<sup>2</sup> (training): 0.66645660997240852

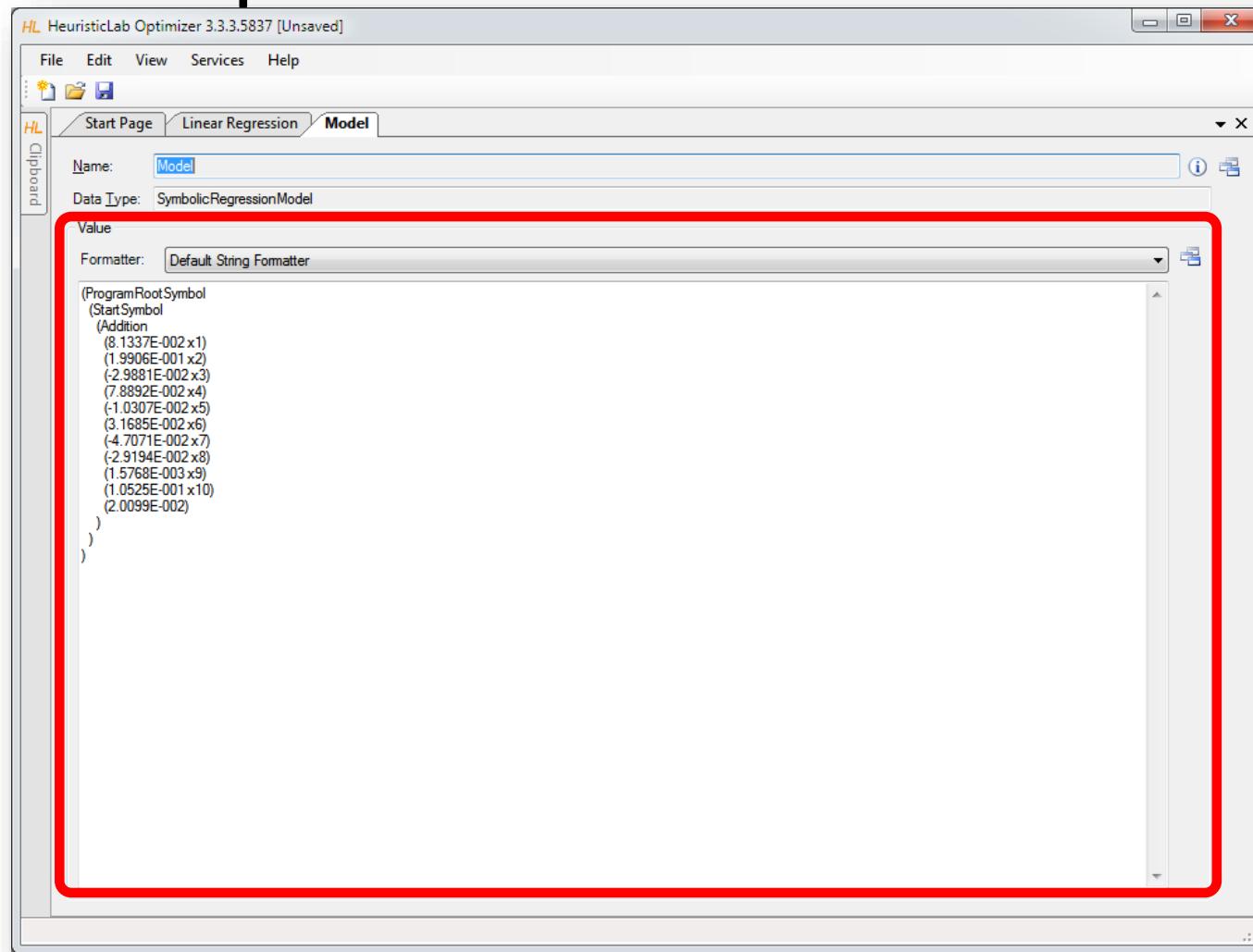
ProblemData: Data imported from multivariate poly-10  
Regression Solution ScatterPlot  
Regression Solution LineChart  
Regression Solution EstimatedValues

# Textual Representations Are Also Available

- Use *ViewHost* to switch to textual representation view.



# Default Textual Representation for Model Export



# Textual Representation for Export to LaTeX



HL HeuristicLab Optimizer 3.3.3.5837 [Unsaved]

File Edit View Services Help

Start Page Linear Regression Model

Name: Model

Data Type: SymbolicRegressionModel

Value

Formatter: **LaTeX String Formatter**

```
% needs \usepackage{amsmath}
\begin{aligned}
Result &= \left( c_{(0)} x_1(t) + c_{(1)} x_2(t) + c_{(2)} x_3(t) + c_{(3)} x_4(t) + c_{(4)} x_5(t) + c_{(5)} x_6(t) + c_{(6)} x_7(t) + c_{(7)} x_8(t) + c_{(8)} x_9(t) + c_{(9)} x_{10}(t) + c_{(10)} \right) \\
c_{(0)} &= 0.0813371220642195 \\
c_{(1)} &= 0.199055016563887 \\
c_{(2)} &= -0.0298811744629839 \\
c_{(3)} &= 0.078891883541302 \\
c_{(4)} &= -0.0103065273366223 \\
c_{(5)} &= 0.0316849536396099 \\
c_{(6)} &= -0.0470707585925129 \\
c_{(7)} &= -0.0291939124032144 \\
c_{(8)} &= 0.00157679665070775 \\
c_{(9)} &= 0.105250443686677 \\
c_{(10)} &= 0.0200987846293256
\end{aligned}
```

Result =  $(c_0 x_1(t) + c_1 x_2(t) + c_2 x_3(t) + c_3 x_4(t) + c_4 x_5(t) + c_5 x_6(t) + c_6 x_7(t) + c_7 x_8(t) + c_8 x_9(t) + c_9 x_{10}(t) + c_{10})$

(1)

$c_0 = 0.0813371220642195$

(2)

$c_1 = 0.199055016563887$

(3)

$c_2 = -0.0298811744629839$

(4)

$c_3 = 0.078891883541302$

(5)

$c_4 = -0.0103065273366223$

(6)

$c_5 = 0.0316849536396099$

(7)

$c_6 = -0.0470707585925129$

(8)

$c_7 = -0.0291939124032144$

(9)

$c_8 = 0.00157679665070775$

(10)

$c_9 = 0.105250443686677$

(11)

$c_{10} = 0.0200987846293256$

(12)

# LaTeX Export



HL HeuristicLab Optimizer 3.3.3.5837 [Unsaved]

File Edit View Services Help

Start Page Genetic Algorithm Interactive Regression Solution S... Model

Name: Model

Data Type: SymbolicRegressionModel

Value

Formatter: LaTeX String Formatter

```
% needs \usepackage{amsmath}
\begin{aligned}
Result &= \left( c_{(0)} x_4(t) \cdot c_1 x_3(t) \cdot c_2 x_6(t) \cdot c_3 x_5(t) \cdot c_4 x_4(t) + c_5 x_4(t) \cdot c_6 x_3(t) \cdot c_7 x_4(t) + c_8 x_4(t) \cdot c_9 x_3(t) \cdot c_{10} + \frac{c_{(11)} x_4(t)}{c_{(12)} x_4(t)} \cdot c_{13} x_3(t) \cdot c_{14} x_4(t) + c_{15} x_5(t) + \frac{c_{(16)}}{c_{(17)} x_2(t)} \right) \cdot c_{18} \\
&\quad + c_{(19)} \cdot c_{20} + c_{(21)} \right) \\
c_{(4)} &= -1.57302367616477 \\
c_{(7)} &= -0.867137925013337 \\
c_{(10)} &= -0.867137925013337 \\
c_{(11)} &= 1.27519978915975 \\
c_{(14)} &= -0.017064976517855 \\
c_{(15)} &= 0.00314376988160885 \\
c_{(17)} &= -3.00832012161288 \\
c_{(18)} &= 0.867137925013337 \\
c_{(19)} &= -5.45190909899249 \\
c_{(20)} &= -0.204498330755849 \\
c_{(21)} &= -0.0465339907207764
\end{aligned}
```

Result =  $x_4(t) \cdot x_3(t) \cdot c_{20}$  (13)

$$\cdot \left( x_6(t) \cdot x_5(t) \cdot c_4 + x_4(t) \cdot x_3(t) \cdot c_7 + x_4(t) \cdot x_3(t) \cdot c_{10} + \frac{c_{11} x_1(t)}{x_4(t) \cdot x_3(t) \cdot \left( c_{14} x_4(t) + c_{15} x_5(t) + \frac{1}{c_{17} x_2(t)} \right) \cdot c_{18}} + c_{21} \right)$$
 (14)

$c_4 = -1.57302367616477$  (15)

$c_7 = -0.867137925013337$  (16)

$c_{10} = -0.867137925013337$  (17)

$c_{11} = 1.27519978915975$  (18)

$c_{14} = -0.017064976517855$  (19)

$c_{15} = 0.00314376988160885$  (20)

$c_{17} = -3.00832012161288$  (21)

$c_{18} = 0.867137925013337$  (22)

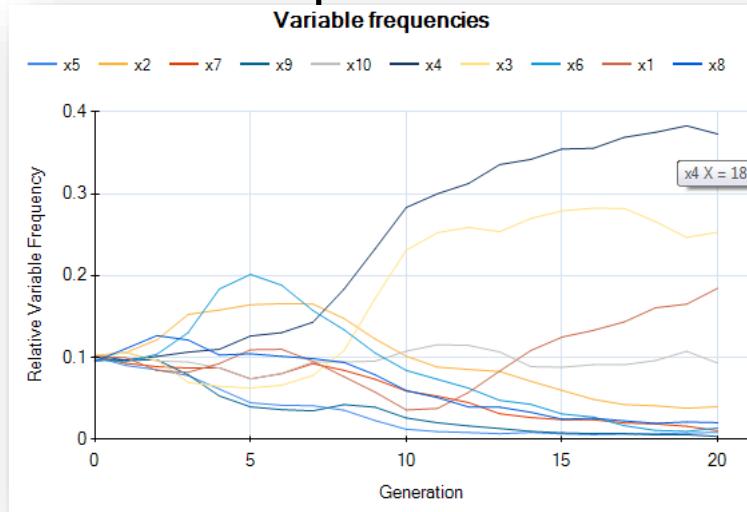
$c_{19} = -5.45190909899249$  (23)

$c_{20} = -0.204498330755849$  (24)

$c_{21} = -0.0465339907207764$  (25)

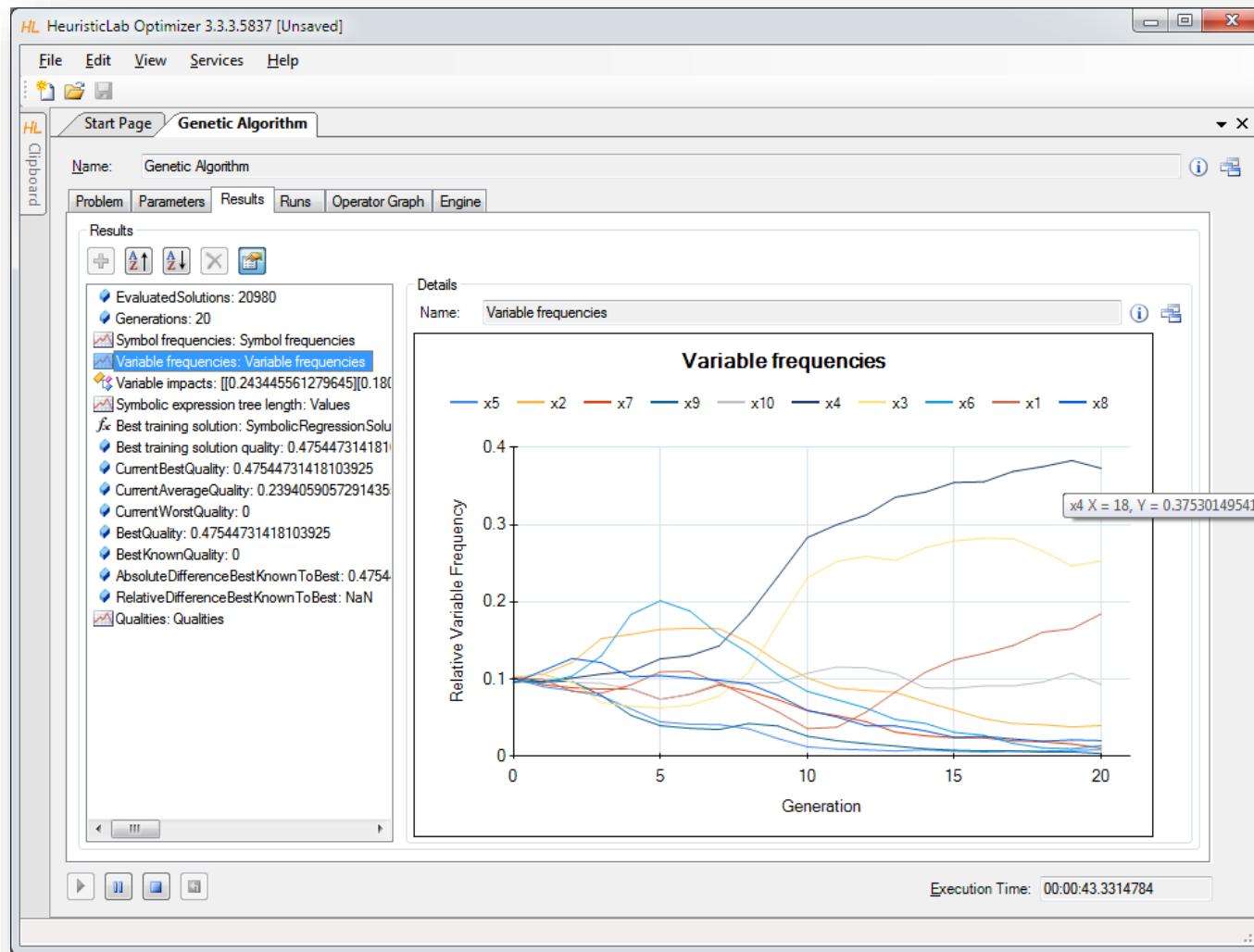
# Variable Relevance Analysis

- Which variables are important for correct predictions?
- Demonstration
  - Variable frequency analyzer
  - symbol frequency analyzer
  - variable impacts



	Relative variable relevance
x4	0.302803869106054
x3	0.241170172985569
x1	0.179112369714678
x10	0.0589664719249172
x2	0.0544635184742382
x6	0.0446774403657897
x8	0.0436011597048278
x7	0.0331173502974243
x5	0.0226252246461621
x9	0.01946242278034

# Inspect Variable Frequency Chart



# Inspect Variable Impacts



HL HeuristicLab Optimizer 3.3.3.5837 [Unsaved]

File Edit View Services Help

Start Page Genetic Algorithm

Name: Genetic Algorithm

Clipboard

Problem Parameters Results Runs Operator Graph Engine

Results

Evaluated Solutions: 43957  
Generations: 43  
Symbol frequencies: Symbol frequencies  
Variable frequencies: Variable frequencies  
Variable impacts: [[0.302803869106054][0.24]]  
Symbolic expression tree length: Values  
Best training solution: SymbolicRegressionSolu  
Best training solution quality: 0.500629316831  
CurrentBestQuality: 0.50062931683180834  
CurrentAverageQuality: 0.2875027821157774  
CurrentWorstQuality: 0  
BestQuality: 0.50062931683180834  
BestKnownQuality: 0  
Absolute Difference Best Known To Best: 0.5006  
Relative Difference Best Known To Best: NaN  
Qualities: Qualities

Details

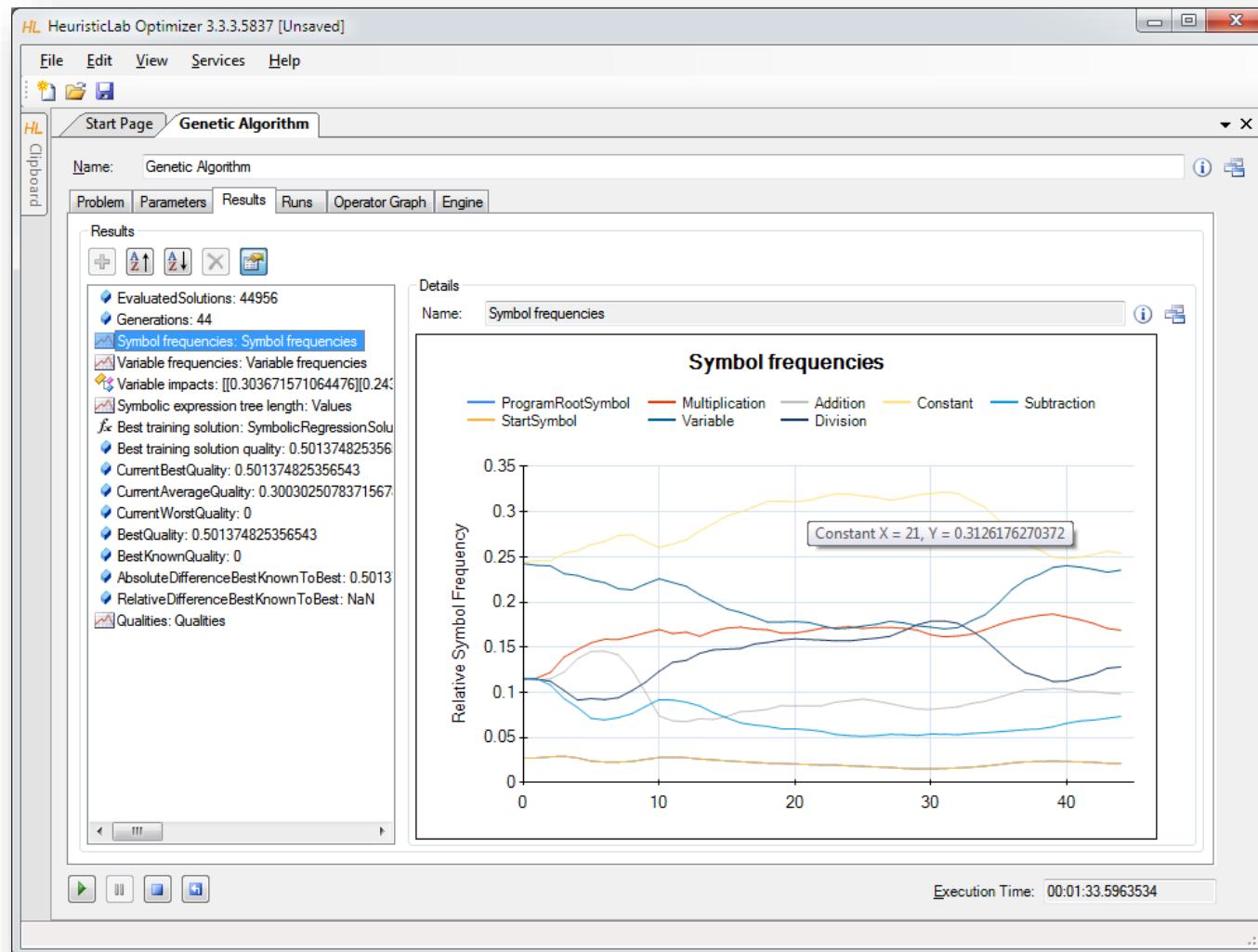
Rows: 10  
Columns: 1

	Relative variable relevance
x4	0.302803869106054
x3	0.241170172985569
x1	0.179112369714678
x10	0.0589664719249172
x2	0.0544635184742382
x6	0.0446774403657897
x8	0.0436011597048278
x7	0.0331173502974243
x5	0.0226252246461621
x9	0.01946242278034

Execution Time: 00:01:30.9862041

Relative variable relevance
0.302803869106054
0.241170172985569
0.179112369714678
0.0589664719249172
0.0544635184742382
0.0446774403657897
0.0436011597048278
0.0331173502974243
0.0226252246461621
0.01946242278034

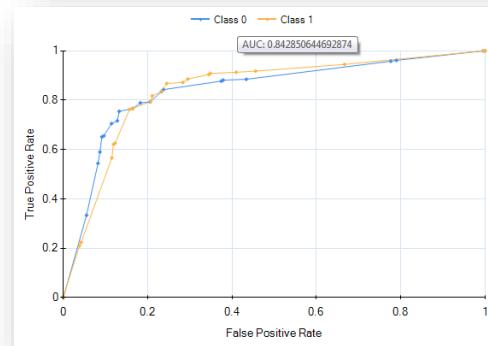
# Inspect Symbol Frequencies



# Classification with HeuristicLab



- Symbolic classification
  - evolve discriminating function using GP
  - find thresholds to assign classes
- Demonstration
  - real world medical application
  - model accuracy
  - visualization of model output
    - discriminating function output
    - ROC-curve
    - confusion matrix



	Actual Class 0	Actual Class 1
Predicted Class 0	197	29
Predicted Class 1	64	190

# Case Study: Classification



- Real world medical dataset (*Mammographic Mass*) from UCI Machine Learning Repository
  - data from non-invasive mammography screening
  - variables:
    - patient age
    - visual features of inspected mass lesions: shape, margin, density
  - target variable: severity (malignant, benign)
  - available as a benchmark problem instance in HeuristicLab

# Open Sample



**HeuristicLab Optimizer 3.3.10.11175**

Follow these steps to start working with HeuristicLab Optimizer:

1. Open an algorithm
  - click (New Item) in the toolbar and select an algorithm or click (Open File) in the toolbar and load an algorithm from a file
2. Open a problem in the algorithm
  - in the Problem tab of the algorithm click (New Problem) and select a problem or click (Open Problem) and load a problem from a file
3. Set parameters
  - set problem parameters in the Problem tab of the algorithm
  - set algorithm parameters in the Parameters tab of the algorithm
4. Run the algorithm
  - click (Start/Resume Algorithm) to execute the algorithm (if the button is grayed out some parameters of the algorithm or the problem still have to be set)
  - wait for the algorithm to terminate or click (Pause Algorithm) to interrupt its execution or click (Stop Algorithm) to stop its execution
5. Check results
  - check the results on the Results tab of the algorithm
  - click (Start/Resume Algorithm) to continue the algorithm or click (Reset Algorithm) to prepare a new run

Looking for predefined algorithms which can be executed immediately?

- check out the **sample algorithms** below

Any feedback, questions, problems or requests for new features?

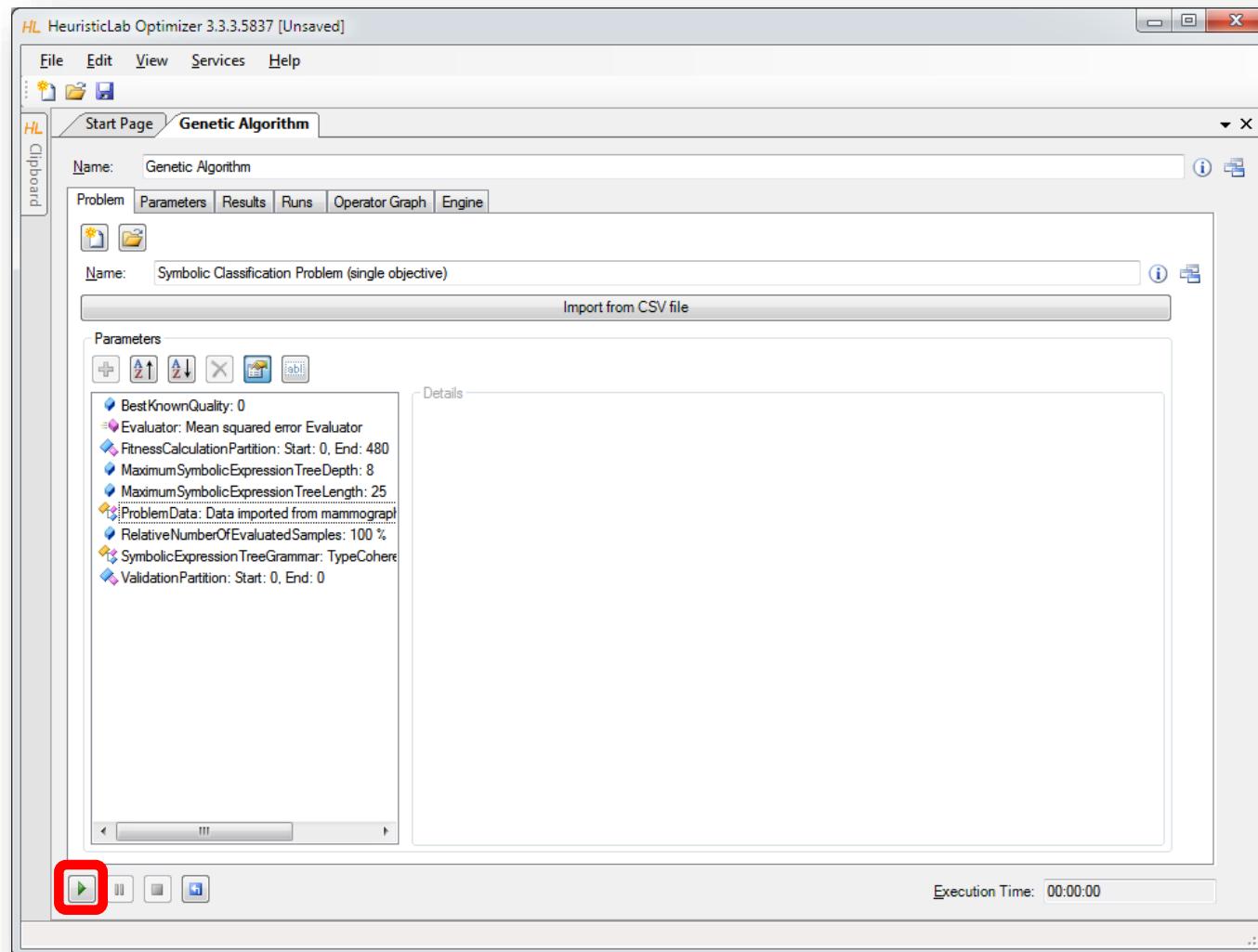
- visit the HeuristicLab trac at <http://dev.heuristiclab.com>
- watch the HeuristicLab video tutorials at <http://www.youtube.com/heuristiclab>
- join the HeuristicLab mailing list <mailto:heuristiclab@googlegroups.com>
- visit the HeuristicLab facebook site at <http://www.facebook.com/heuristiclab>
- write an e-mail to <mailto:support@heuristiclab.com> to contact the HeuristicLab

Show Start Page on Startup

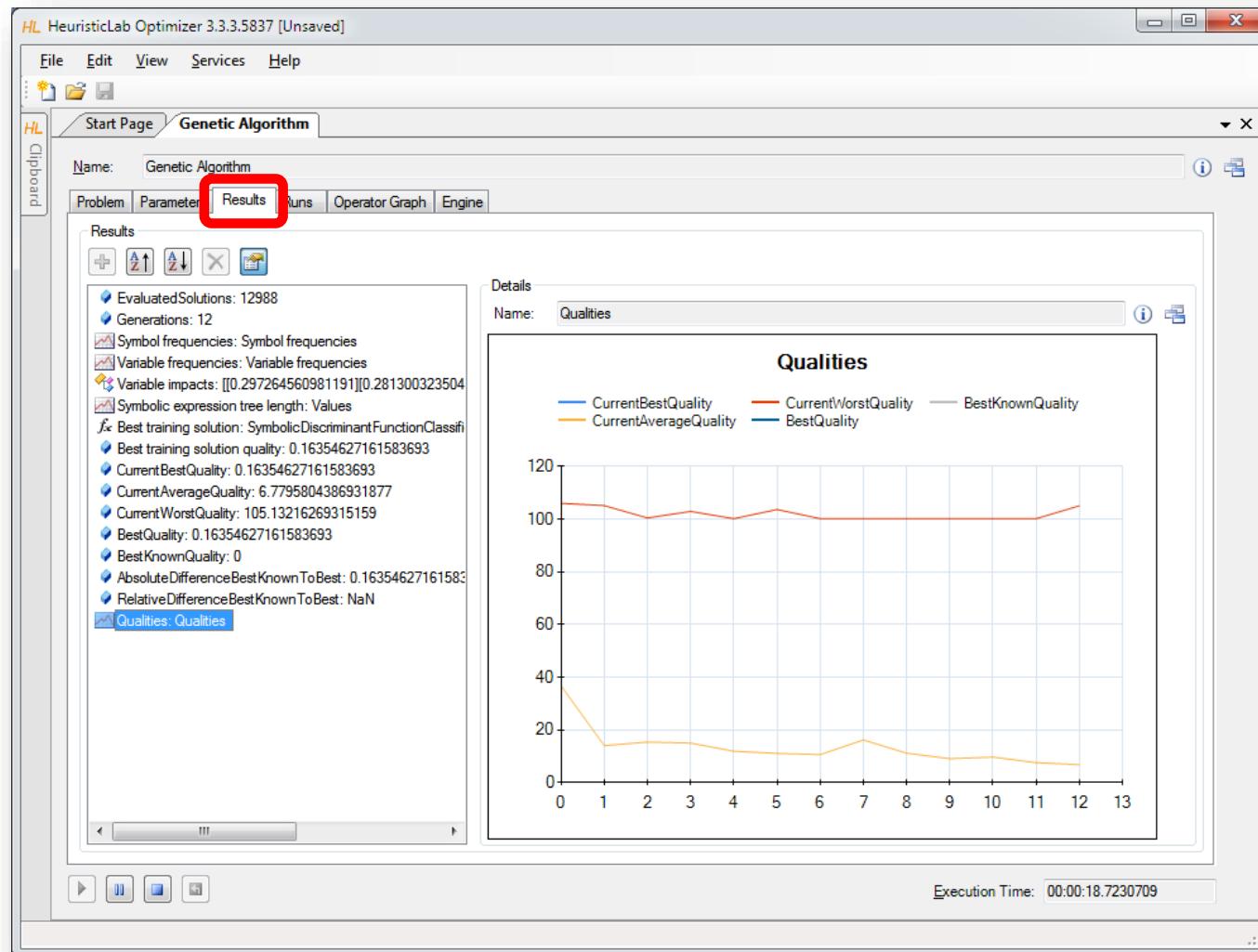
**Samples**

Name	Description
<b>Standard Problems</b>	
Evolution Strategy - Griewank	An evolution strat
Genetic Algorithm - TSP	A genetic algorith
Genetic Algorithm - VRP	A genetic algorith
Genetic Programming - Artificial Ant	A standard geneti
Genetic Programming - Multiplexer 11 problem	A genetic program
Grammatical Evolution - Artificial Ant (SantaFe)	Grammatical evoluti
Island Genetic Algorithm - TSP	An island genetic
Local Search - Knapsack	A local search alg
Particle Swarm Optimization - Schwefel	A particle swarm o
RAPGA - Job Shop Scheduling	A relevant alleles
Scatter Search - VRP	A scatter search a
Simulated Annealing - Rastrigin	A simulated anneal
Tabu Search - TSP	A tabu search alg
Tabu Search - VRP	A tabu search alg
Variable Neighborhood Search - TSP	A variable neighb
<b>Data Analysis</b>	
Gaussian Process Regression	A Gaussian proces
Genetic Programming - Symbolic Classification	A standard geneti
Genetic Programming - Symbolic Regression	A standard geneti
Genetic Programming - Time Series Prediction (Mackey-Glass-17)	A genetic program
Grammatical Evolution - Symbolic Regression (Poly-10)	Grammatical evoluti
<b>Scripts</b>	
Genetic Algorithm Script - QAP	A scripted genetic
GUI Automation Script	A script that runs
Offspring Selection Genetic Algorithm Script - Rastrigin	A scripted offsprin

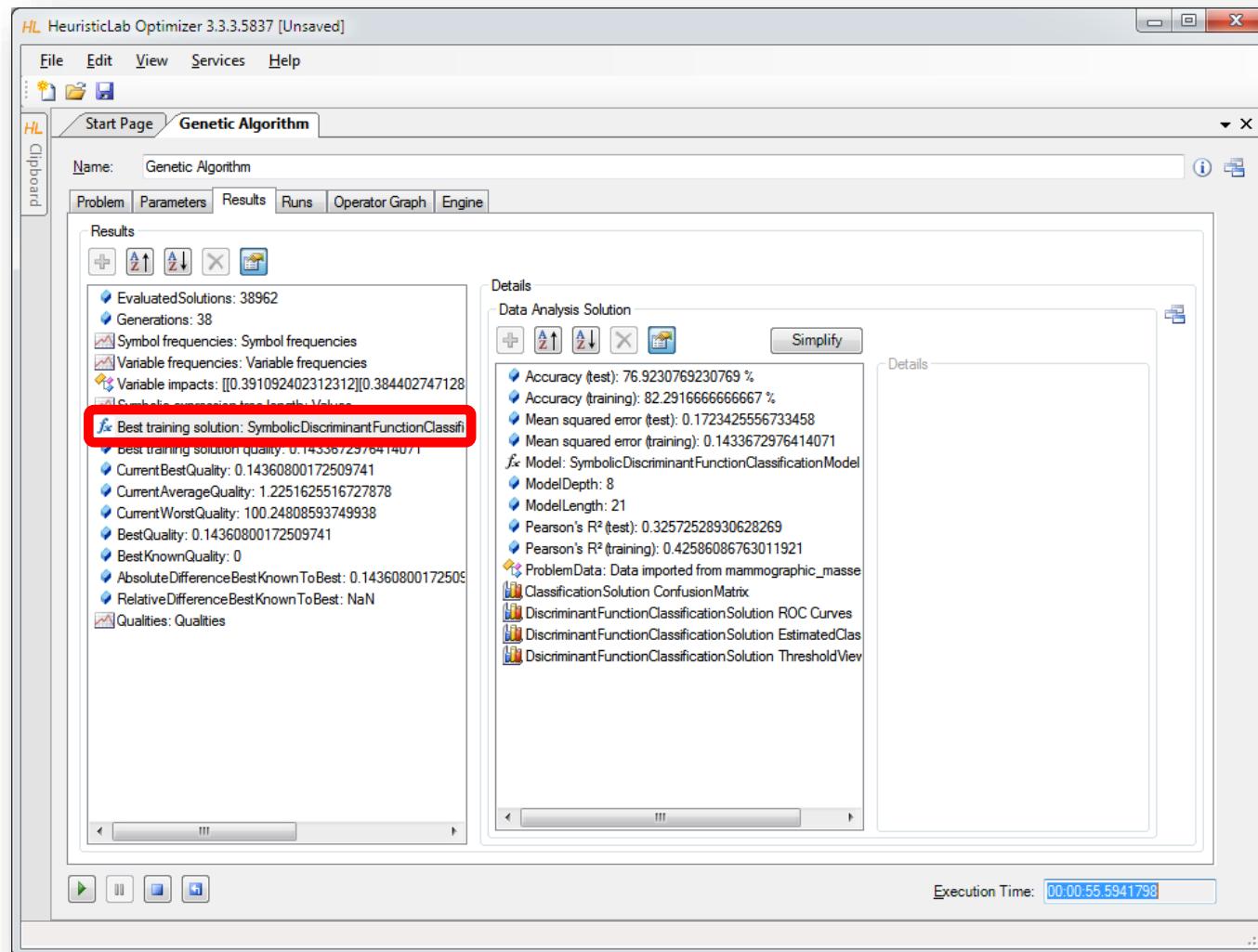
# Configure and Run Algorithm



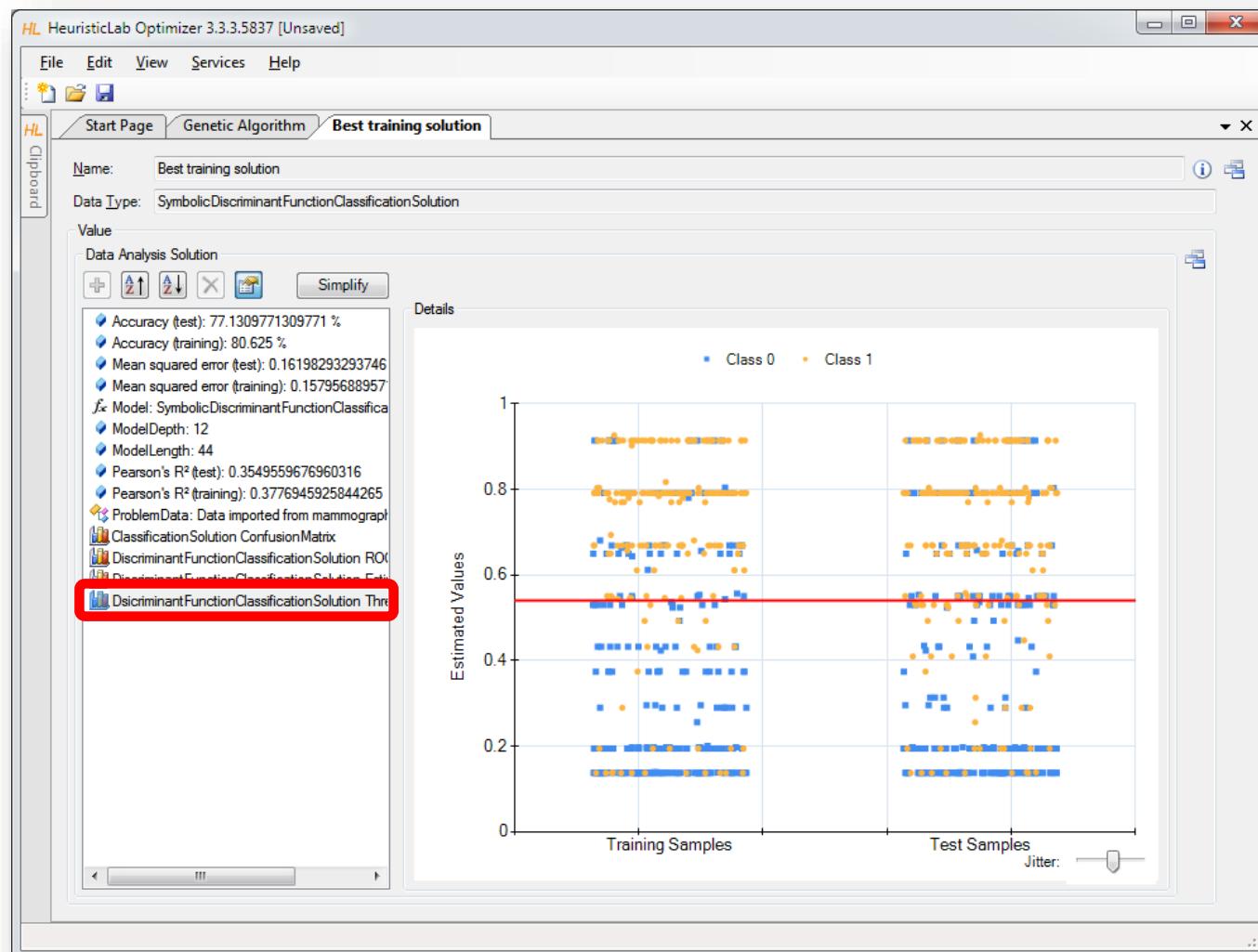
# Inspect Quality Linechart



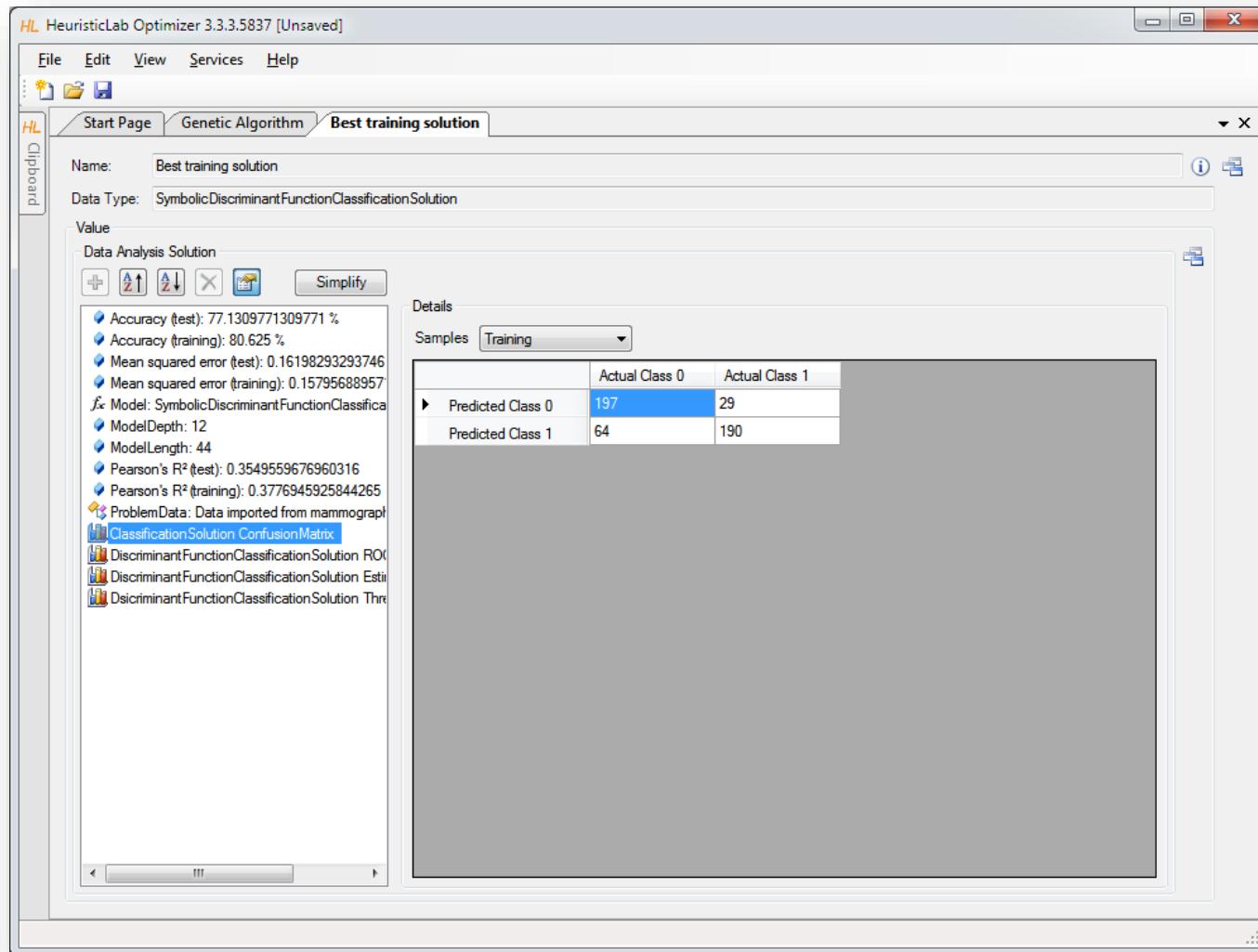
# Inspect Best Training Solution



# Inspect Model Output and Thresholds



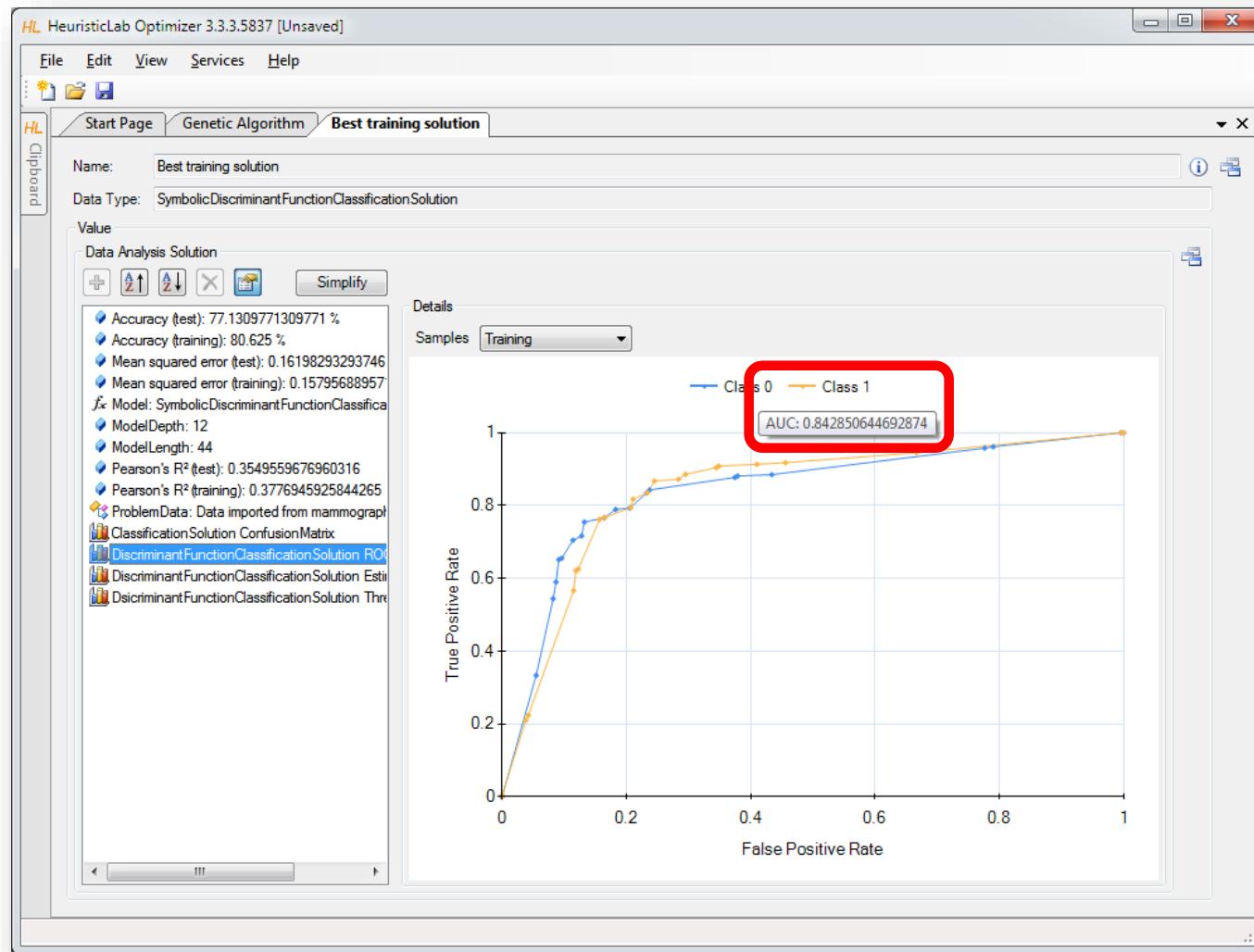
# Inspect Confusion Matrix



The screenshot shows the HeuristicLab Optimizer interface with the title bar "HL HeuristicLab Optimizer 3.3.3.5837 [Unsaved]". The menu bar includes File, Edit, View, Services, and Help. The tabs at the top are Start Page, Genetic Algorithm, and Best training solution, with Best training solution selected. The left sidebar has a "Clipboard" section and a "Details" section. The "Details" section has a "Samples" dropdown set to "Training". A table titled "Classification Solution ConfusionMatrix" displays the following data:

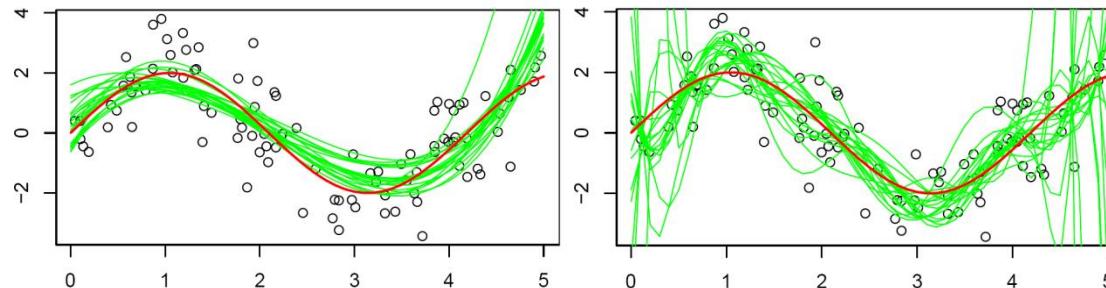
	Actual Class 0	Actual Class 1
Predicted Class 0	197	29
Predicted Class 1	64	190

# Inspect ROC Curve

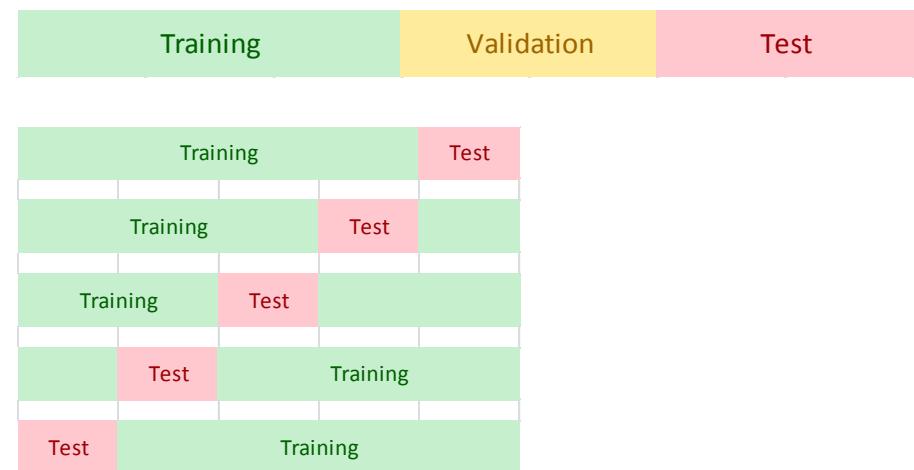


# Validation of Results

- Overfitting = memorizing data

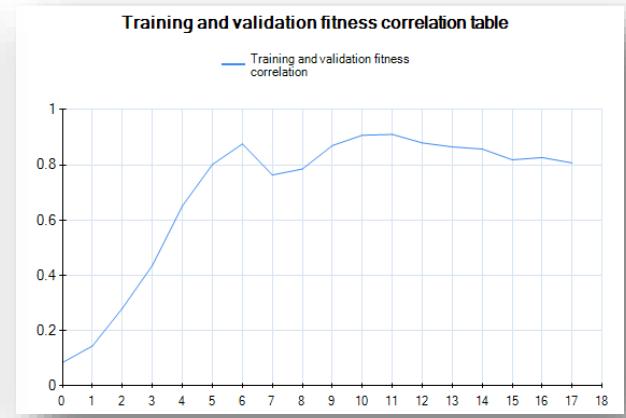
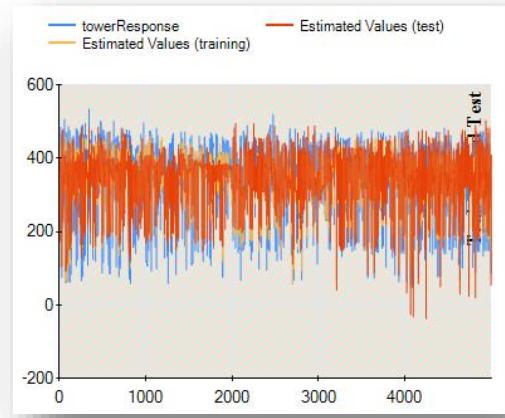
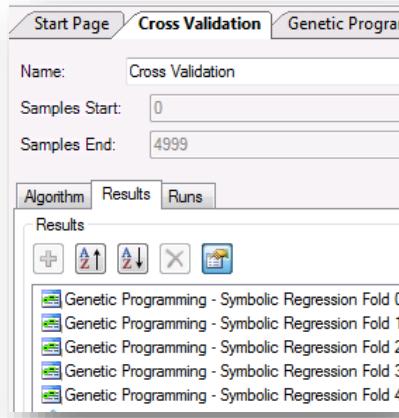


- Strategies to reduce overfitting
  - validation partition
  - cross-validation

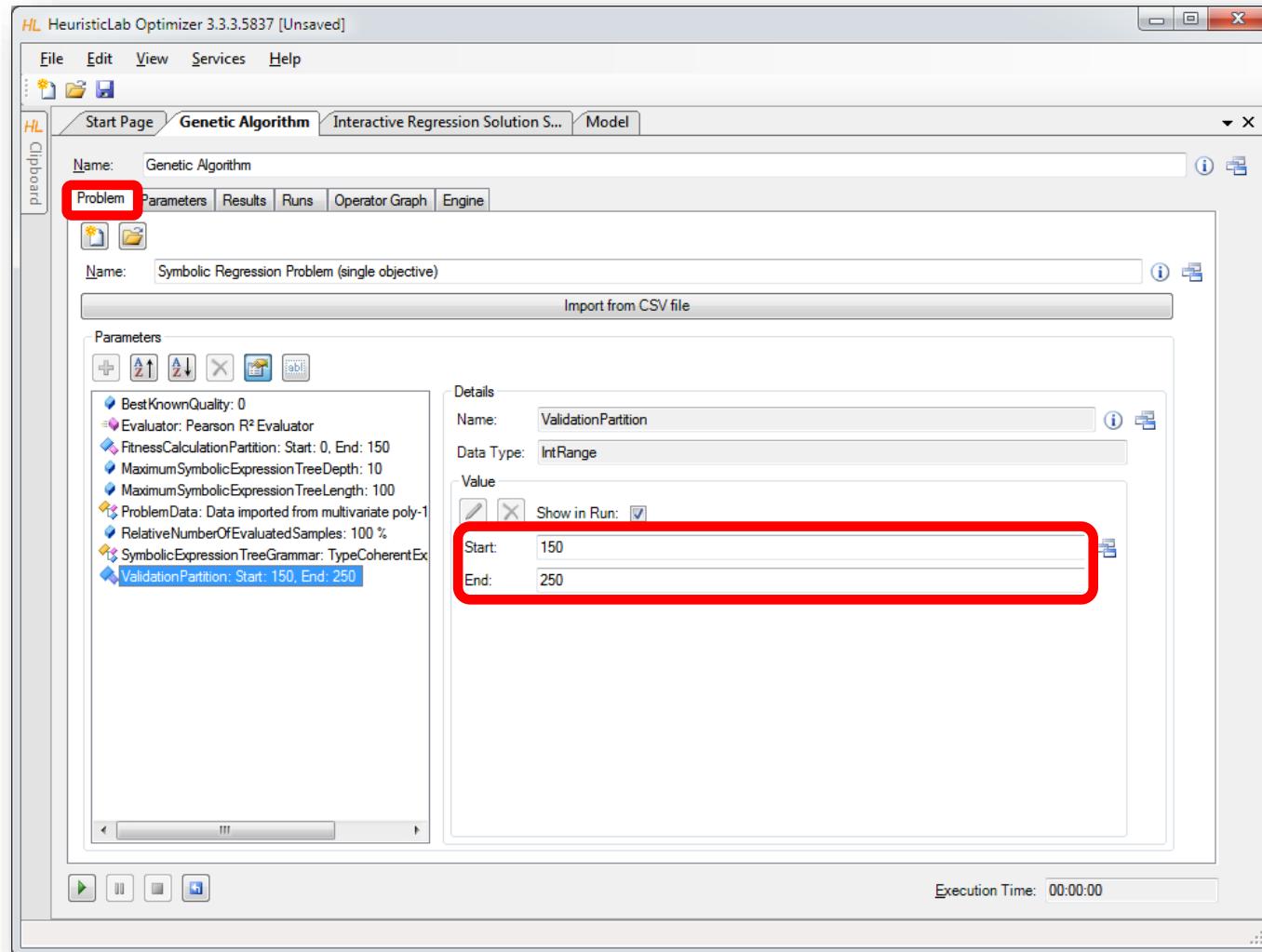


# Validation of Results

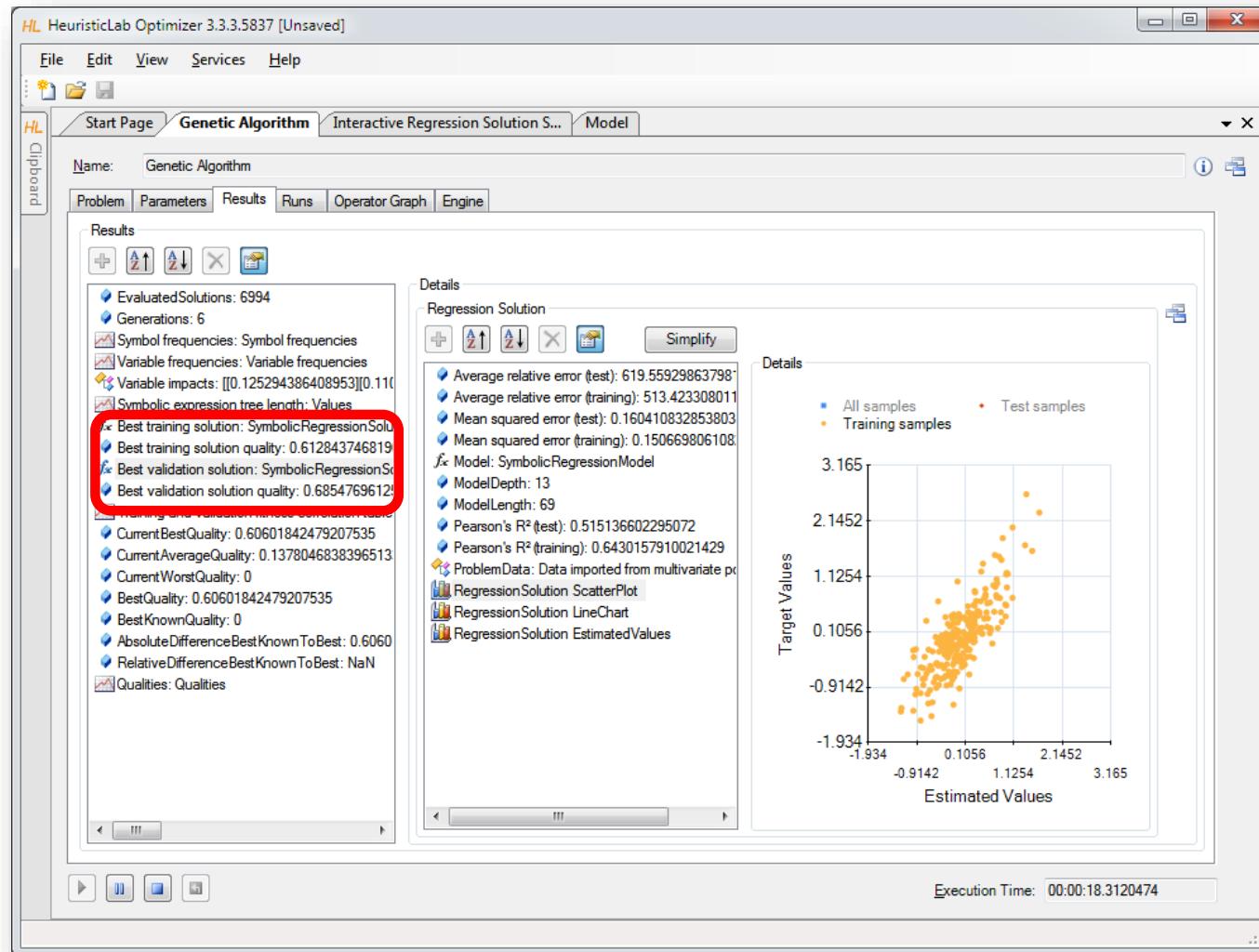
- Demonstration
  - Configuration of a validation set
  - Inspection of best solution on validation set
  - Analysis of training- and validation fitness correlation
  - Cross-validation
    - Configuration
    - Analysis of results



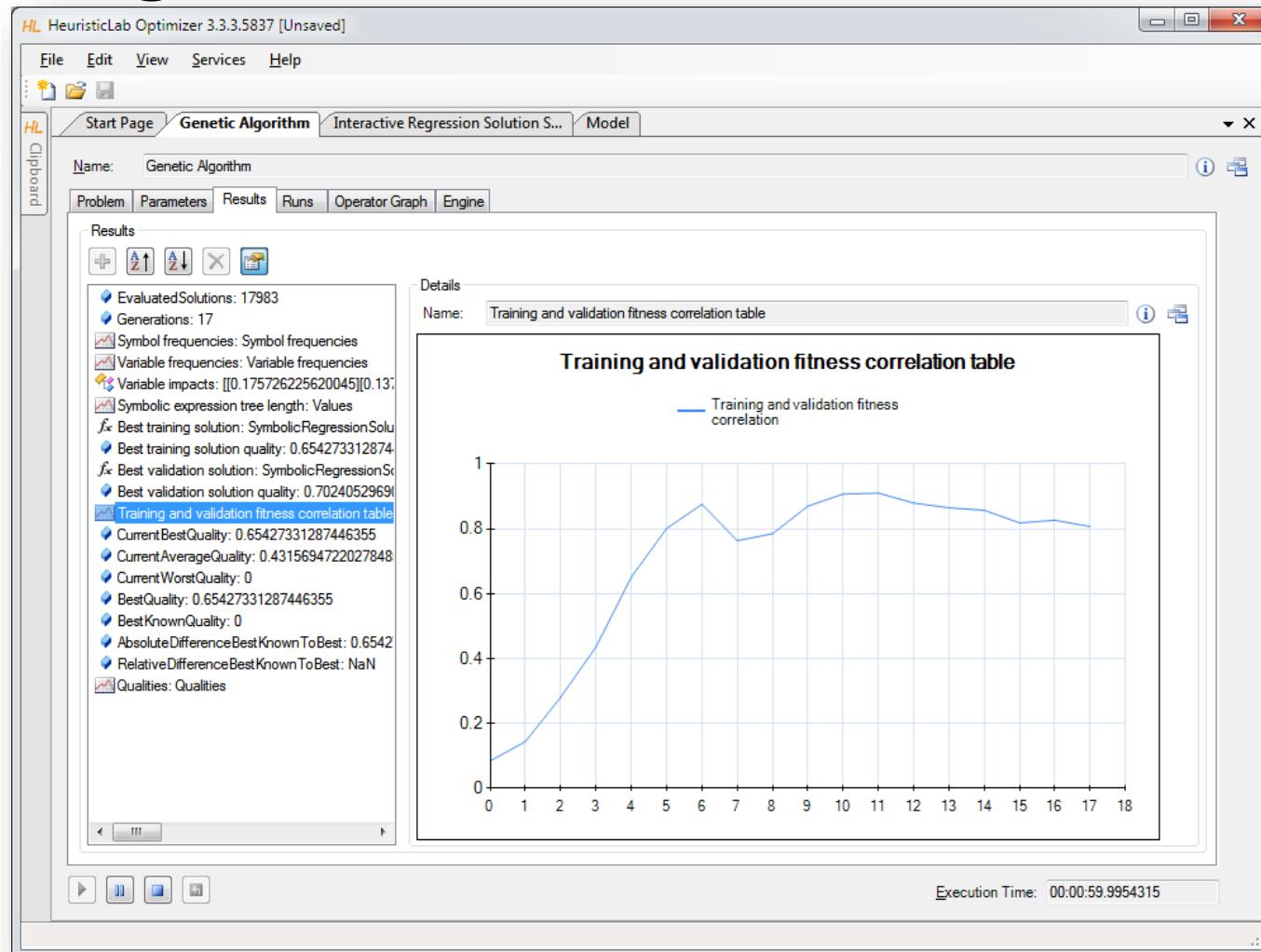
# Configuration of Validation Partition



# Inspect Best Model on Validation Partition



# Inspect Linechart of Correlation of Training and Validation Fitness



# Agenda

- Objectives of the Tutorial
- Introduction
- Where to get HeuristicLab?
- Plugin Infrastructure
- Graphical User Interface
- Available Algorithms & Problems
- **Demonstration Part I: Working with HeuristicLab**
- **Demonstration Part II: Data-based Modeling**
- Some Additional Features
- Planned Features
- Team
- Suggested Readings
- Bibliography
- Questions & Answers

# Some Additional Features

- HeuristicLab Hive
  - parallel and distributed execution of algorithms and experiments on many computers in a network
- Optimization Knowledge Base (OKB)
  - database to store algorithms, problems, parameters and results
  - open to the public
  - open for other frameworks
  - analyze and store characteristics of problem instances and problem classes
- External solution evaluation and simulation-based optimization
  - interface to couple HeuristicLab with other applications (MATLAB, Simulink, SciLab, AnyLogic, ...)
  - supports different protocols (command line parameters, TCP, ...)
- Parameter grid tests and meta-optimization
  - automatically create experiments to test large ranges of parameters
  - apply heuristic optimization algorithms to find optimal parameter settings for heuristic optimization algorithms



# Planned Features

- Algorithms & Problems
  - steady-state genetic algorithm
  - unified tabu search for vehicle routing
  - estimation of distribution algorithms
  - evolution of arbitrary code (Robocode, controller, etc.)
  - ...
- Cloud Computing
  - port HeuristicLab Hive to Windows Azure
- Statistics
  - implement statistical tests and automated statistical analysis
- Have a look at the HeuristicLab roadmap
  - <http://dev.heuristiclab.com/trac.cgi/roadmap>
- Any other ideas, requests or recommendations?
  - join our HeuristicLab Google group [heuristiclab@googlegroups.com](mailto:heuristiclab@googlegroups.com)
  - write an e-mail to [support@heuristiclab.com](mailto:support@heuristiclab.com)

# HeuristicLab Team



Heuristic and Evolutionary Algorithms Laboratory (HEAL)  
School of Informatics, Communications and Media  
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Softwarepark 11  
A-4232 Hagenberg  
AUSTRIA

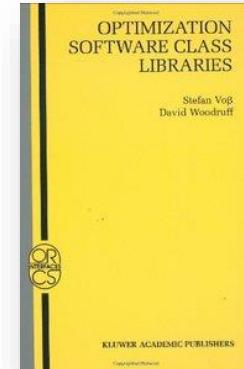
WWW: <http://heal.heuristiclab.com>



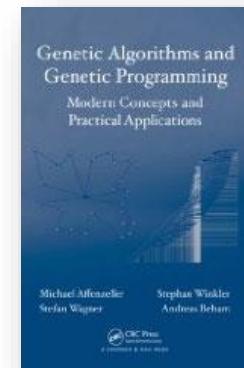
# Suggested Readings



- S. Voß, D. Woodruff (Edts.)  
**Optimization Software Class Libraries**  
Kluwer Academic Publishers, 2002



- M. Affenzeller, S. Winkler, S. Wagner, A. Beham  
**Genetic Algorithms and Genetic Programming  
Modern Concepts and Practical Applications**  
CRC Press, 2009



# Bibliography

- S. Wagner, M. Affenzeller  
**HeuristicLab: A generic and extensible optimization environment**  
Adaptive and Natural Computing Algorithms, pp. 538-541  
Springer, 2005
- S. Wagner, S. Winkler, R. Braune, G. Kronberger, A. Beham, M. Affenzeller  
**Benefits of plugin-based heuristic optimization software systems**  
Computer Aided Systems Theory - EUROCAST 2007, Lecture Notes in Computer Science, vol. 4739, pp. 747-754  
Springer, 2007
- S. Wagner, G. Kronberger, A. Beham, S. Winkler, M. Affenzeller  
**Modeling of heuristic optimization algorithms**  
Proceedings of the 20th European Modeling and Simulation Symposium, pp. 106-111  
DIPTEM University of Genova, 2008
- S. Wagner, G. Kronberger, A. Beham, S. Winkler, M. Affenzeller  
**Model driven rapid prototyping of heuristic optimization algorithms**  
Computer Aided Systems Theory - EUROCAST 2009, Lecture Notes in Computer Science, vol. 5717, pp. 729-736  
Springer, 2009
- S. Wagner  
**Heuristic optimization software systems - Modeling of heuristic optimization algorithms in the HeuristicLab software environment**  
Ph.D. thesis, Johannes Kepler University Linz, Austria, 2009.
- S. Wagner, A. Beham, G. Kronberger, M. Kommenda, E. Pitzer, M. Kofler, S. Vonolfen, S. Winkler, V. Dorfer, M. Affenzeller  
**HeuristicLab 3.3: A unified approach to metaheuristic optimization**  
Actas del séptimo congreso español sobre Metaheurísticas, Algoritmos Evolutivos y Bioinspirados (MAEB'2010), 2010
- S. Wagner, G. Kronberger, A. Beham, M. Kommenda, A. Scheibenpflug, E. Pitzer, S. Vonolfen, M. Kofler, S. Winkler, V. Dorfer, M. Affenzeller  
**Architecture and Design of the HeuristicLab Optimization Environment**  
Advanced Methods and Applications in Computational Intelligence, vol. 6, pp. 197-261, Springer, 2014
- Detailed list of all publications of the HEAL research group: <http://research.fh-ooe.at/de/orgunit/356#showpublications>

# Questions & Answers



<http://dev.heuristiclab.com>

[heuristiclab@googlegroups.com](mailto:heuristiclab@googlegroups.com)

<http://www.youtube.com/heuristiclab>

<http://www.facebook.com/heuristiclab>