IBM Software Group

Examples of Flow Control in OPL

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Agenda

- Introduction to Flow Control
  - Basic Structure of Flow Control
  - Templates for Flow Control
- Examples
  - Preprocessing and Postprocessing
  - Performing Iterative solves
  - Data access and modification
  - Column Generation
  - Problem Decomposition
- Important Tools
  - Debugging
  - Memory Management
- Conclusion

Introduction to Flow Control

What is Flow Control ?

Flow control enables control over how models are instantiated and solved in OPL using IBM ILOG Script:

- solve several models with different data in sequence or iteratively
- run multiple “solves” on the same base model, modifying data, constraints, or both, after each solve
- decompose a model into smaller more manageable models, and solve these to arrive at a solution to the original model (model decomposition)

What is IBM ILOG Script ?

- A script is a sequence of commands. These commands could be of various types such as declarations, simple instructions or compound instructions
- **IBM ILOG Script is different from OPL modeling language**
- IBM ILOG Script is an implementation of JavaScript
- Includes extension classes for OPL using which Model elements can be accessed and modified in Flow Control
- All IBM ILOG Script extension classes for OPL start with **Ilo,** (for example IloOplModel, IloCplex, IloCP)

Basic Structure of Flow Control

The main block

```
main {
        ...
}
```

- To implement Flow Control include a **main** block
- A .mod file can contain at most only **one** main block
- Main block will be **first executed** regardless of where it is placed in the .mod file

The main block using CPLEX Optimizer

```
main {

 thisOplModel.generate();

 if (cplex.solve()) {
  var obj=cplex.getObjValue();
 }

}
```

- **thisOplModel** is an IBM ILOG Script variable referring to the current model instance
- **generate()** is a method used to generate the model instance
- **cplex** is an IBM ILOG Script variable available by default, that refers to the CPLEX Optimizer instance
- **solve()** calls one of CPLEX Optimizer's MP algorithms to solve the model
- **getObjValue()** is a method to access the value of the objective function

The main block using CP Optimizer

```
main {

 thisOplModel.generate();

 if (cp.solve()) {
  var obj=cp.getObjValue();
 }

}
```

- **cp** is an IBM ILOG Script variable available by default, that refers to the CP Optimizer instance
- If the **main** block is in a model file starting with **using cp;**, the **cp** variable is available by default
- If the model file starts with **using cp;**, you'll have to declare the **cplex** variable explicitly if you want to call CPLEX in that same **main** block:

var cplex = new IloCplex();

Templates for Flow Control

Templates for Flow Control

To Construct a Main Block you can apply one of the two methods:

- Start with an OPL project and create a run configuration
- Start with an OPL model and OPL data file

Script template calling a project

```
main {
 var proj = new IloOplProject("../../../../../opl/mulprod");
 var rc = proj.makeRunConfiguration();
 rc.oplModel.generate();
 if (rc.cplex.solve()) {
  writeln("OBJ = ", rc.cplex.getObjValue());
 }
 else {
  writeln("No solution");
 }
 rc.end();
 proj.end();
}
```

Script template calling a model and data

```
main {
 var source = new
IloOplModelSource("../../../../../opl/mulprod/mulprod.mod");
 var def = new IloOplModelDefinition(source);
 var opl = new IloOplModel(def,cplex);
 var data = new
 IloOplDataSource("../../../../../opl/mulprod/mulprod.dat");
 opl.addDataSource(data);
 opl.generate();
 if (cplex.solve()) {
  writeln("OBJ = ", cplex.getObjValue());
 }
 else {
  writeln("No solution");
 }
 opl.end();
 data.end();
 def.end();
 source.end();
}
```

Create source using .mod

Create model definition using source

Create model instance

Add data to model instance

Which template to use?

- The two templates are similar in behavior, both are useful for generating and solving a model
- The Run Configuration approach has the added advantage of being able to use an OPL Settings file (for example, to invoke the tuning tool on a set of models)
- If you are using the current model instance in the flow control, you can use the **thisOplModel** to refer to the current model

Preprocessing and Postprocessing in Flow Control

Preprocessing and Postprocessing

```
execute{
  writeln("Preprocessing block");
  }
minimize
...

subject to {
  ...
}
execute{
  writeln("Postprocessing block");
}
```

- Use preprocessing execute blocks to prepare the data before solving, or to set any parameters
- Preprocessing execute blocks are called by default before each solve
- Use postprocessing execute blocks to control and manipulate the solutions, such as data display or scripting log
- In flow control to execute the postprocessing blocks use:

```
thisOplModel.postProcess();
```

Examples of Preprocessing

- Use Preprocessing execute blocks to prepare the data before calling solve

```
execute{
  for(var w in workers){
   w.salary = w.salaryPerHr * w.hoursWorked;
  }
}
```

- Use Preprocessing execute blocks to set any OPL or CPLEX or CP parameter settings before calling solve

```
execute{
 cplex.numericalemphasis  = true;
}
```

Examples of Postprocessing

- Use Postprocessing execute blocks to display the output data

```
plan Plan[p in Products][t in Periods] =
  <Inside[p,t],Outside[p,t],Inv[p,t]>;

execute{
  writeln("Current Plan = ",Plan);
}
```

- Use Postprocessing execute blocks to display the current solution values

```
execute {
 writeln("Solution Objective value = ", cplex.getObjValue());
}
```

Iterative Solves using Flow Control

What is an Iterative Solve?

- Iterative Solve refers to the approach of incrementally building the mathematical model over several iterations
  - Start with a base mathematical model
  - After each iteration modify the model (either data or definition) to improve the final solution
  - If there is no further improvement, stop the iteration
  - Apart from the Final Optimal Solution, this approach also gives the Optimal Solution after each iteration
  - A powerful yet simple technique for “what-if” analysis
- We will use this technique today on a Multi-Period Production Planning Problem
  - A variation of basic production-planning problem
  - Consider the demand for the products over several periods and allow the company to produce more than the demand in a given period
  - There is an inventory cost associated with storing the additional production

Example for Iterative solves using mulprod

Multi-period production planning problem mulprod.mod

```
minimize
 sum( p in Products , t in Periods )
   (InsideCost[p]*Inside[p][t] +
    OutsideCost[p]*Outside[p][t] +
    InvCost[p]*Inv[p][t]);

subject to {
 forall( r in Resources , t in Periods )
   ctCapacity:
     sum( p in Products )
       Consumption[r][p] * Inside[p][t] <= Capacity[r];

 forall( p in Products , t in Periods )
   ctDemand:
     Inv[p][t-1] + Inside[p][t] + Outside[p][t] ==
     Demand[p][t] + Inv[p][t];

 forall( p in Products )
   ctInventory:
     Inv[p][0] == Inventory[p];
}

tuple plan {
 float inside;
 float outside;
 float inv;
}

plan Plan[p in Products][t in Periods] =
 <Inside[p,t],Outside[p,t],Inv[p,t]>;
```

A data instance from mulprod.dat

```
Products =  { kluski capellini fettucine };
Resources = { flour eggs };
NbPeriods = 3;

Consumption = [
                [ 0.5, 0.4, 0.3 ],
                [ 0.2, 0.4, 0.6 ]
              ];
Capacity = [ 20, 40 ];
Demand = [
           [ 10 100 50 ]
           [ 20 200 100]
           [ 50 100 100]
         ];
Inventory = [ 0 0 0];
InvCost = [ 0.1 0.2 0.1];
InsideCost = [ 0.4, 0.6, 0.1 ];
OutsideCost  = [ 0.8, 0.9, 0.4 ];
```

Example for Iterative solves using mulprod

```
main {
    thisOplModel.generate();
    var produce = thisOplModel;
    var capFlour = produce.Capacity["flour"];
    var best;
    var curr = Infinity;
    var ofile = new IloOplOutputFile("mulprod_main.txt");
    while ( 1 ) {
        best = curr;
        writeln("Solve with capFlour = ",capFlour);
        if ( cplex.solve() ) {
            curr = cplex.getObjValue();
            writeln();
            writeln("OBJECTIVE: ",curr);
            ofile.writeln("Objective with capFlour = ", capFlour, " is ", curr);
        } else {
            writeln("No solution!");
            break;
        }
        if ( best==curr ) break;
        capFlour++;
        for(var t in thisOplModel.Periods)
            thisOplModel.ctCapacity["flour"][t].UB = capFlour;
    }
    if (best != Infinity) {
        writeln("plan = ",produce.Plan);
    }
    ofile.close();
}
```

Using the current model instance

Obtain the starting Flour Capacity

Solving iteratively using **while** loop

Stopping criteria

Modifying the upper bound (flour capacity)

Data Access in Flow Control

Data Access in Flow Control

- Before modifying the data in the Flow Control, you must get the data elements from the OPL model instance using:

```
thisOplModel.dataElements;
```

- Every time a model data element is modified the OPL model needs to be re-generated
- If generating your OPL model is time consuming, consider directly modifying the generated optimization model
  - You can modify the CPLEX Optimizer matrix directly, without modifying the OPL model
  - For example to modify the flour capacity:

```
thisOplModel.ctCapacity["flour"].UB = flourCapacity;
```

- Only external data can be modified (for example data declared in a .mod file and initialized in a .dat file)
- Scalar data (for example int NumPeriods = 10) cannot be modified in Flow Control

Example for modifying model data using mulprod

```
var def = produce.modelDefinition;
var data = produce.dataElements;
if ( produce!=thisOplModel ) {
 produce.end();
}
produce = new IloOplModel(def,cplex);
capFlour++;
data.Capacity["flour"] = capFlour;
produce.addDataSource(data);
produce.generate();
```

- `var def = produce.modelDefinition;` — Create new model definition
- `var data = produce.dataElements;` — Reference new data elements
- `produce.end();` — End the previous OPL model instance
- `produce = new IloOplModel(def,cplex);` — Create new OPL model instance
- `data.Capacity["flour"] = capFlour;` — Change data (new flour capacity)
- `produce.addDataSource(data);` — Add new data to OPL model instance
- `produce.generate();` — Generate the new OPL model instance

Few tips to remember when performing iterative/multi model solves

- Choose wisely which template will work best for your model design. Both templates can essentially perform the same tasks, but each template has its own advantages
  - If you have multiple data instances to run, with different settings choosing the Template with OPL project with different run configurations would be a better option
  - If you have only one OPL model instance being solved iteratively then a data model template would work better
- When modifying the data elements (or model definition) of a OPL Model instance, remember to add the modified data (or the modified model definition) to the model source and generate the new OPL Model Instance
- If your OPL model generation is time consuming, consider modifying the generated optimization model directly (note: this will not modify the OPL model)
- Remember to end the objects not in use by using the **end()** method
- If using the CPLEX Studio IDE set **mainEndEnabled** to **true**

Column Generation using Flow Control

What is Column Generation?

- Classic example is the Cutting Stock problem:
  - There exist boards of a fixed width (for instance 110 inches)
  - There are also a number of shelves of different lengths (for instance, 20 inches, 45 inches, etc.)
  - It is possible to cut multiple shelves from a single board
  - There is a specified demand the number of shelves
  - Objective: minimize the number of boards used to satisfy demand
- The naïve approach is nearly impossible to write:
  - One variable per possible pattern will only work if there are very few possible patterns
  - In practice, there are too many possible patterns to make this workable
  - Impossible to scale, with even a modest number of possibilities

What is Column Generation?

- Column Generation builds these pattern variables iteratively
- The main approach starts with a rudimentary form of the original problem
- The first half solves the main model, then uses information from this main problem to initialize a sub problem
- The second half solves the sub model, then uses information from this sub problem to create new variables for main problem
- **Requires flow control to manage two different models**

Basic Approach to Column Generation

- Step 1: Solve Master Model, get some basic solution
- Step 2: Use dual information to initialize sub model
- Step 3: Solve Sub Model, get information on new pattern variable that will best improve the objective.
- If the sub model suggests that there is no more improvement, stop
- Step 4: Otherwise, use sub model solution to create new variable, go back to step 1

Basic Approach to Column Generation

- Solve Master Model

```
75    writeln("Solve master.");
76    if ( masterCplex.solve() ) {
77      curr = masterCplex.getObjValue();
78      writeln();
79      writeln("OBJECTIVE: ",curr);
80    }
81    else {
82      writeln("No solution!");
83      masterOpl.end();
84      break;
85    }
```

- Forward information from master model to sub model

```
87    subData.RollWidth = masterOpl.RollWidth;
88    subData.Size = masterOpl.Size;
89    subData.Duals = masterOpl.Duals;
90    for(var i in masterOpl.Items) {
91      subData.Duals[i] = masterOpl.ctFill[i].dual;
92    }
93
94    var subOpl = new IloOplModel(subDef, subCplex);
95    subOpl.addDataSource(subData);
96    subOpl.generate();
97
```

Basic Approach to Column Generation

- Solve Sub Model

```
 98    writeln("Solve sub.");
 99    if ( subCplex.solve() ) {
100      writeln();
101      writeln("OBJECTIVE: ",subCplex.getObjValue());
102      writeln(subOpl.Use.solutionValue);
103    }
```

- If the sub model suggests that there is no more improvement, stop. Otherwise, use sub model solution to create new variable

```
111    if (subCplex.getObjValue() > -RC_EPS) {
112      subOpl.end();
113      masterOpl.end();
114      break;
115    }
116
117
118    // Prepare the next iteration:
119    masterData.Patterns.add(masterData.Patterns.size,1,subOpl.Use.solutionValue);
```

Key Points of Column Generation

- This particular approach relies on the concepts of “dual” in linear programming
- This can be extended to other ways to identify new patterns
  - The key is that the sub problem identifies new variables that will definitely improve the objective, then stops
- Similar approaches work in other industries, like crew scheduling, or vehicle routing
  - Start with a rudimentary formulation, then improve this iteratively
- **Flow control allows you to forward information from one model to another**

Problem Decomposition using Flow Control

What is Problem Decomposition?

- Classic example is a Cost Minimization problem with penalties
  - There is a standard model with demand constraints, and supply constraints, and cost coefficients
  - Some constraints can be violated. This is expressed by adding a “slack” variable on the constraints
  - Each slack variable has a very large cost coefficient
  - As the goal is to minimize cost, this will also minimize the slack variables

- The direct approach is very common, but has a couple of drawbacks
  - If the penalty cost coefficients are too large, can introduce numerical instability and related performance issues
  - If the penalty cost coefficients are too small, constraints may be violated when they should not
  - It may be difficult to prove optimality of particular model

What is Problem Decomposition?

- Problem Decomposition splits (or decomposes) the model into two or more parts
- The first broad model solves to minimize the slacks and/or other very large costs
- Once the large costs are determined, they are fixed in the main model
- The main model can then optimize on the small, fine-grained details, without letting the big variables interfere
- **Requires flow control to manage the different models**

Basic Approach to Problem Decomposition

- Basic Monolithic Model

```
21 float Cost[Products][Cities][Cities] = ...;
22
23 dvar float+ Trans[Products][Cities][Cities];
24 dvar float+ Slack[Products][Cities][Cities];
25
26
27 minimize
28   sum( p in Products , o , d in Cities )
29     Cost[p][o][d]  * Trans[p][o][d]  +
30   sum( p in Products , o , d in Cities )
31     100000000  * Slack[p][o][d];
32
33 subject to {
34   forall( p in Products , o in Cities )
35     ctSupply:
36       sum( d in Cities )
37         Trans[p][o][d] == Supply[p][o];
38   forall( p in Products , d in Cities )
39     ctDemand:
40       sum( o in Cities )
41         Trans[p][o][d] == Demand[p][d];
42    forall( o , d in Cities )
43      ctCapacity:
44        sum( p in Products )
45          (Trans[p][o][d] - Slack[p][o][d]) <= Capacity;
46 }
```

Slack Cost Coefficient

Slack Variables

Basic Approach to Problem Decomposition

- Revised Model for large costs (note objective only has large costs)

```
27 minimize
28   sum( p in Products , o , d in Cities )
29     100000000 * Slack[p][o][d];
30
31 subject to {
```

Only Slack Costs

- Revised Model for small costs (note that slacks are fixed)

```
25 float Slack[Products][Cities][Cities] = ...;
26
27 minimize
28   sum( p in Products , o , d in Cities )
29     Cost[p][o][d] * Trans[p][o][d] ;
30
31 subject to {
32   forall( p in Products , o in Cities )
33     ctSupply:
34       sum( d in Cities )
35         Trans[p][o][d] == Supply[p][o];
36   forall( p in Products , d in Cities )
37     ctDemand:
38       sum( o in Cities )
39         Trans[p][o][d] == Demand[p][d];
40    forall( o , d in Cities )
```

Fixed Slack Values

Only Normal Costs

Basic Approach to Problem Decomposition

- Flow Control to link both models

```
// First Model
var bigModelSource = new IloOplModelSource("first.mod");
var bigModelDef = new IloOplModelDefinition(bigModelSource);
var opl = new IloOplModel(bigModelDef,cplex);
var data = new IloOplDataSource("data.dat");
opl.addDataSource(data);
opl.generate();
if (cplex.solve()) {
   writeln("FIRST OBJ = ", cplex.getObjValue());
   writeln("FIRST Slack = ", opl.Slack.solutionValue);

   // Second Model
   var smallModelSource = new IloOplModelSource("second.mod");
   var smallModelDef = new IloOplModelDefinition(smallModelSource);
   var newOpl = new IloOplModel(smallModelDef,cplex);
   var data = new IloOplDataSource("data.dat");
   newOpl.addDataSource(data);

   var newData = new IloOplDataElements();
   newData.Slack = opl.Slack.solutionValue;
   newOpl.addDataSource(newData);

   newOpl.generate();
   if (cplex.solve()) {
     writeln("SECOND OBJ = ", cplex.getObjValue());
   }
```

Solve First Model

Build Second Model

Use previous data for second model

Key Points of Problem Decomposition

- This particular approach splits a large model into smaller models
- There is substantial overlap between each model
  - This may mean extra overhead if the model design changes
- The benefit is that this allows for a more natural modeling:
  - Usually the largest costs dominate the objective, so solving them and fixing them can give a better sense than solving for everything
  - Avoiding a mix of large and small values, coefficients tends to improve numerical stability, performance, and correctness
- **Flow control allows solve these related models, and forward information between them. This is the basis of decomposition**

Debugging in Flow Control

Debugging in Flow Control: writeln

- The simplest approach is to add **writeln()** statements throughout the flow control blocks, displaying different variables and expressions
- Even though it seems simple, it is often the quickest to set up, and the simplest to evolve

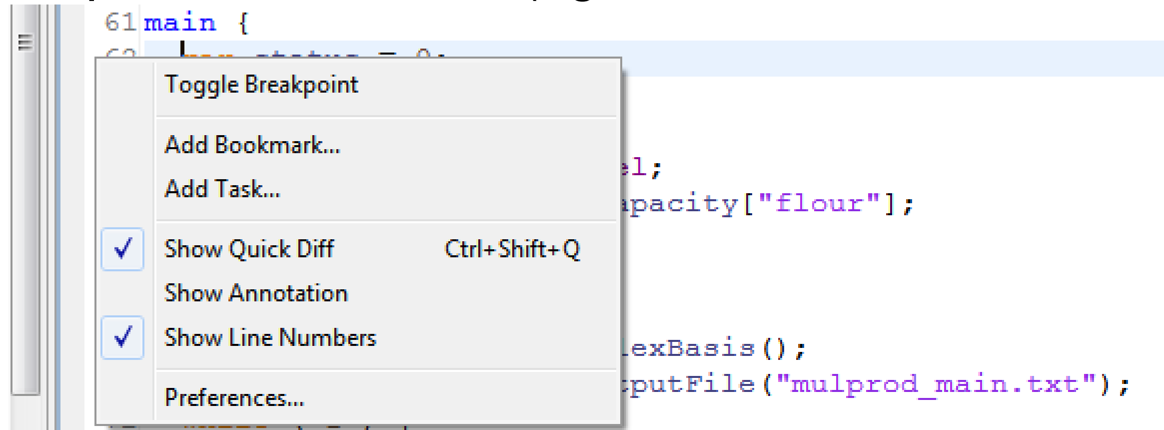
- Be careful! Too many printing statements can clutter the output, and make things less usable
- Consider using an output file (**ofile**) and redirect this extra output to an auxiliary file

Debugging in Flow Control: solve underlying model

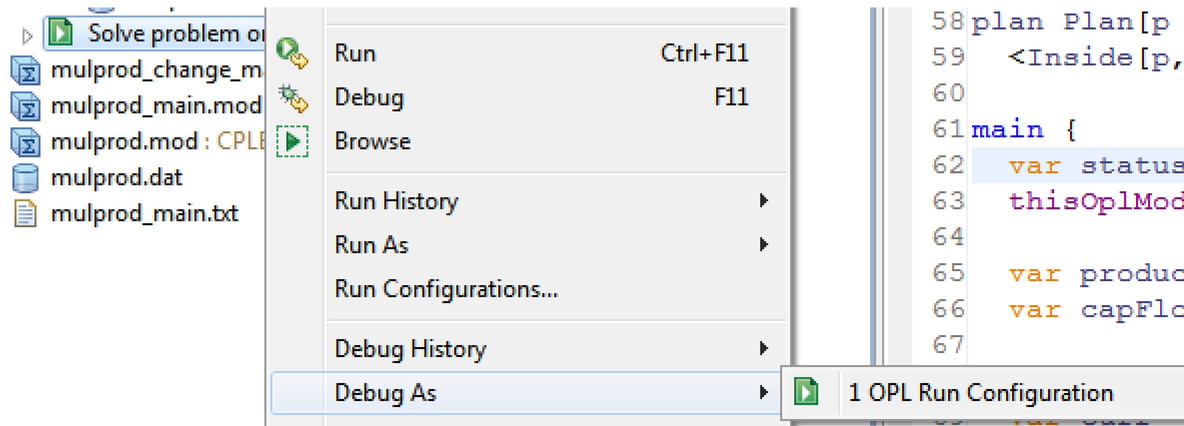
- It can be very tricky to debug master models and sub models, especially if they are built iteratively
- Sometimes, it is useful to create a new OPL project, using the original model
- The OPL data file must be created separately (or manually)
  - This can be made easier by printing out various data with **writeln()**
- This approach is very useful to determine if there are errors in the flow control statements, or with the model itself

Debugging in Flow Control: use the IDE

- Create a breakpoint in the model (right-click on the line numbers)

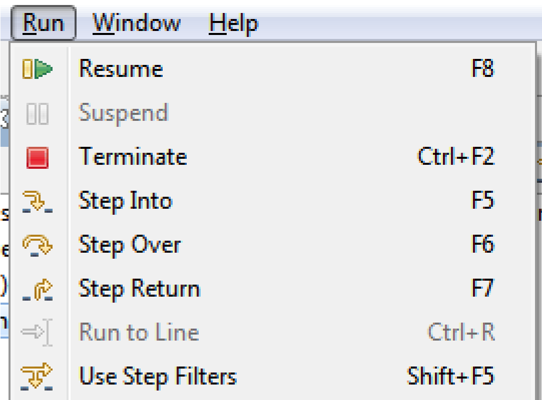


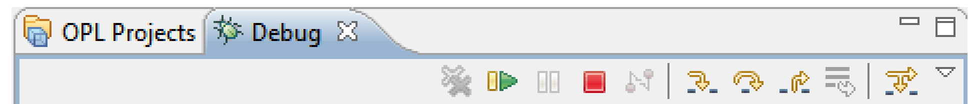
- Start the debugger



Debugging in Flow Control: use the IDE

- Use the Debug options to step through the flow control model line-by-line





- Use the expression window to keep track of variables

Problem browser | (x)= Variables | Breakpoints

Name	Value
status	0
produce	[a IloOplMain.IloOplModel]
capFlour	24
best	452.5
curr	450.25
ofile	[a IloOplOutputFile]
basis	[a IloOplMain.IloOplCplexBasis]
def	[a IloOplMain.IloOplModelDefinition]
data	[a IloOplMain.IloOplDataElements]
[with]	[object Object]

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112
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Memory Management in Flow Control

Ending Objects in Flow Control

- Iterative solves can lead to out of memory errors if the objects are not handled correctly

- IBM ILOG Script provides the **end()** methods to end the objects in Flow Control

- The **end()** method is disabled by default in CPLEX Studio IDE, to enable it use:

thisOplModel.settings.mainEndEnabled = true;

- Use caution when calling **end()** method, if you try access the object after it has been deleted could lead to a crash

Ending Objects in Flow Control

Template calling a model and data

```
main {
var source = new
IloOplModelSource("../../../../../opl/mulprod/mulprod.mod
");
var def = new IloOplModelDefinition(source);
var opl = new IloOplModel(def,cplex);
var data = new
IloOplDataSource("../../../../../opl/mulprod/mulprod.dat"
);
opl.addDataSource(data);
opl.generate();

opl.settings.mainEndEnabled = true;

if (cplex.solve()) {
writeln("OBJ = ", cplex.getObjValue());
}
else {
writeln("No solution");
}
opl.end();
data.end();
def.end();
source.end();
}
```

Template calling a project

```
main {
var proj = new
IloOplProject("../../../../../opl/mulprod");
var rc = proj.makeRunConfiguration();
rc.oplModel.generate();

rc.oplModel.settings.mainEndEnabled = true;

if (rc.cplex.solve()) {
writeln("OBJ = ", rc.cplex.getObjValue());
}
else {
writeln("No solution");
}
rc.end();
proj.end();
}
```

Conclusion

Summary

- Flow control is a powerful concept, allowing you to control how different models are solved
- Preprocessing and postprocessing can be used to initialize, prepare, and output data in different ways
- Solving multiple related models in sequences is possible with a simple loop and flow control statements
- The flow control approach also works to decompose larger complicated models into smaller models
- **Flow control allows you to approach more problems than a pure OPL model approach**

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