CMPL

<Coliop|Coin> Mathematical Programming Language

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Manual

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1 About CMPL

CMPL (<Coliop|Coin> Mathematical Programming Language) is a mathematical programming language and a system for mathematical programming and optimization of linear optimization problems.

The CMPL syntax is similar in formulation to the original mathematical model but also includes syntactic elements from modern programming languages. CMPL is intended to combine the clarity of mathematical models with the flexibility of programming languages.

CMPL executes the COIN-OR OSSolverService, GLPK, Gurobi, SCIP or CPLEX directly to solve the generated model instance. Because it is also possible to transform the mathematical problem into MPS, Free-MPS or OSiL files, alternative solvers can be used.

CMPL is an open source project licensed under GPL. It is written in C++ and is available for most of the relevant operating systems (Windows, OS X and Linux).

The CMPL distribution contains Coliop which is an (simple) IDE (Integrated Development Environment) for CMPL. Coliop is an open source project licensed under GPL. It is written in Java and is as an integral part of the CMPL distribution.

Since release of version 1.8, the CMPL package contains also pyCMPL and CMPLServer. pyCMPL is the CMPL API for Python and an interactive shell. The main idea of this API is to define sets and parameters within the user application, to start and control the solving process and to read the solution(s) into the application if the problem is feasible. All variables, objective functions and constraints are defined in CMPL. These functionalities can be used with a local CMPL installation or a CMPLServer.

CMPLServer is an XML-RPC-based web service for distributed optimization. It is reasonable to solve large models remotely on the CMPLServer that is installed on a high performance system. pyCMPL provides a client API for CMPLServer. CMPL provides three XML-based file formats for the communication between a CMPLServer and its clients. (CmplInstance, CmplSolutions, CmplMessages)

pyCMPL and CMPLServer are licensed under LGPLv3.

CMPL, Coliop, pyCMPL and CMPLServer are COIN-OR projects initiated by the Technical University of Applied Sciences Wildau and the Institute for Operations Research and Business Management at the Martin Luther University Halle-Wittenberg.

For further information please visit the CMPL website (www.coliop.org).

2 CMPL elements

2.1 General structure of a CMPL model

The structure of a CMPL model follows the standard model of linear programming (LP), which is defined by a linear objective function and linear constraints. Apart from the variable decision vector x all other components are constant.

$$c^T \cdot x \rightarrow max!$$
$$s.t.$$
$$A \cdot x \leq b$$
$$x \geq 0$$

A CMPL model consists of four sections, the `parameters` section, the `variables` section, the `objectives` section and the `constraints` section, which can be inserted several times and mixed in a different order. Each sector can contain one or more lines with user-defined expressions.

```
parameters:
    # definition of the parameters
variables:
    # definition of the variables
objectives:
    # definition of the objective(s)
constraints:
    # definition of the constraints
```

A typical LP problem is the production mix problem. The aim is to find an optimal quantity for the products, depending on given capacities. The objective function is defined by the profit contributions per unit c and the variable quantity of the products x. The constraints consist of the use of the capacities and the ranges for the decision variables. The use of the capacities is given by the product of the coefficient matrix A and the vector of the decision variables x and restricted by the vector of the available capacities b.
The simple example:

$$1 \cdot x_1 + 2 \cdot x_2 + 3 \cdot x_3 \rightarrow max!$$
$$s.t.$$
$$5.6 \cdot x_1 + 7.7 \cdot x_2 + 10.5 \cdot x_3 \leq 15$$
$$9.8 \cdot x_1 + 4.2 \cdot x_2 + 11.1 \cdot x_3 \leq 20$$
$$0 \leq x_n \;\; ; n = 1(1)3$$

can be formulated in CMPL as follows:

```
parameters:
    c[] := ( 1, 2, 3 );
    b[] := ( 15, 20 );

    A[,] := (( 5.6, 7.7, 10.5 ),
             ( 9.8, 4.2, 11.1 ));

variables:
    x[1..count(c[])]: real;

objectives:
    c[]T * x[] -> max;

constraints:
    A[,] * x[] <= b[];
    x[] >= 0;
```

2.2 Keywords and other syntactic elements

Keywords

`parameters, variables, objectives, constraints`	section markers
`real, integer, binary`	types of variable
`real, integer, binary, string, set`	types only used for type casts
`max, min`	objective senses
`set, in, len, defset`	key words for sets
`max, min, count, format, type`	functions for parameter expressions
`sqrt, exp, ln, lg, ld, srand, rand, sin, cos, tan, acos, asin, atan, sinh, cosh, tanh, abs, ceil, floor, round`	mathematical functions that can be used for parameter expressions
`include`	include of a CMPL file
`readcsv, readstdin`	data import from a CSV file or from user input
`error, echo`	error and user message
`sum`	summation
`continue, break, default, repeat`	key words for control structures

Arithmetic operators

`+ -`	signs for parameters or addition/subtraction
`^`	to the power of
`* /`	multiplication and division
`div mod`	integer division and remainder on division
`:=`	assignment operator

Condition operators

`= <= >=`	conditions for constraints, while-loops and if-then clauses
`== < > != <>`	additional conditions in while-loops and if-then clauses
`&& || !`	logical operations (and, or, not)
`<<`	element operator for checking whether an index is an element of a set

Other syntactic elements

`( )`	- arithmetical bracketing in constant expressions - lists for initialising vectors of constants - parameters for constant functions - increment in an algorithmic set
`[ ]`	- indexing of vectors - range specification in variable definitions
`{ }`	- control structures

`..`	- algorithmic set (e.g. range for indices or loop counters) - range specification in variable definitions
`,`	- element separation in an initialisation list for constant vectors and enumeration sets - separation of function parameters - separation of indices - separation of loop heads in a loop
`:`	- mark indicating beginning of sections - definition of variables - definition of parameter type - separation of loop header from loop body - separation of line names
`|`	- separation of alternative blocks in a control structure
`;`	- mark indicating end of a statement - every statement is to be closed by a semicolon
`#` `/*  */`	- comment (up to end of line) - comment (between /* and */)

2.3 Objects

2.3.1 Parameters

A `parameters` section consists of parameter definitions and assignments to parameters. A parameter can only be defined within the `parameters` section using an assignment or through using a cmplData file (see 4.2 cmplData files) and a corresponding CMPL header option.

Note that a parameter can be used as a constant in a linear optimization model as coefficients in objectives and constraints. Otherwise parameters can be used like variables in programming languages. Parameters are usable in expressions, for instance in the calculation and definition of other parameters. A user can assign a value to a parameter and can then subsequently change the value with a new assignment.

A parameter is identified by name and, if necessary, by indices. A parameter can be a scalar or an array of parameter values (e.g. vector, matrix or another multidimensional construct). A parameter is defined by an assignment with the assignment operator `:=`.

Usage:

```
name := scalarExpression;
name[index] := scalarExpression;
name[[set]] := arrayExpression;
```

name	Name of the parameter
index	Indexing expression that defines a position in an array of parameters. Described in 2.3.3 Indices and sets
scalarExpression	A scalar parameter or a single part of an array of parameters is assigned a single integer or real number, a single string, the scalar result of a mathematical function.
set	(Optional) set expression (list of indices) for the definition of the dimension of the array If more than one set is used then the sets have to be separated by commas. Described in 2.3.3 Indices and sets
arrayExpression	A non-scalar expression consists of a list of *scalarExpressions* or *arrayExpression*. The elements of the list are separated by commas and imbedded in brackets. The elements of the list can also be sets. But it is not possible to mix set and non-set expressions. If an array contains only one element, then it is necessary to include an additional comma behind the element. Otherwise the expression is interpreted as an arithmetical bracket.

Examples:

`k := 10;`	parameter `k` with value 10
`k[1..5] := ( 0.5, 1, 2, 3.3, 5.5);` `k[] := ( 0.5, 1, 2, 3.3, 5.5);`	vector of parameters with 5 elements
`A[]:= (16, 45.4);`	definition of a vector with two integer values `a[1]`=16 and `a[2]`=45.
`a[, ] := (( 5.6, 7.7, 10.5 ),` `( 9.8, 4.2, 11.1 ));`	dense matrix with 2 rows and 3 columns
`b[] := ( 22 ,);`	definition of the vector `b` with only one element.
`b[] := ( 22 );`	causes an error: `array dimensions don't match`, since `(22)` is not interpreted as an array but as an assignment of a scalar expression.
`products := set( "bike1", "bike2");` `machineHours[products ]:= (5.4, 10);`	defines a vector for machine hours based on the set `products`
`myString := "this is a string";`	string parameter
`q := 3;`	parameter `q` with value 3
`g[1..q] := ( 1, 2, 3);`	usage of `q` for the definition of the parameter `g`

`x := 1(1)2;`
`y := 1(1)2;`
`z := 1(1)2;`
 	
`cube[x,y,z]:= ( ( (1,2),(3,4) ) ,`
`( (5,6),(7,8 ) ) );`
	definition of a parameter cube that is based on the sets `x`, `y` and `z`.

`a := set( [1,1],[1,2],[2,2],[3,2] );` `b[a] := ( 10, 20, 30 , 40);`	definition of a sparse matrix `b` that is based on the 2-tuple set `a`.

If a name is used for a parameter the name cannot be used for a variable.
A special kind of parameter is local parameters, which can only be defined within the head of a control structure. A local parameter is only valid in the body of the control structure and can be used like any other parameter. Only scalar parameters are permitted as local parameters. Local parameters are mainly used as loop counters that are to be iterated over a set.

2.3.2 Variables

The `variables` section is intended to declare the variables of a decision model, which are necessary for the definition of objectives and constraints in the decision model. A model variable is identified by name and, if necessary, by an index. A type must be specified. A model variable can be a scalar or a part of a vector, a matrix or another array of variables. A variable cannot be assigned a value.

Usage:

```
variables:
  name : type [[lowerBound]..[upperBound]];
  name[index] : type [[lowerBound]..[upperBound]];
  name[set] : type [[lowerBound]..[upperBound]];
```

name	name of model variable
type	type of model variable. Possible types are `real`, `integer`, `binary`.
[*lowerBound..upperBound*]	optional parameter for limits of model variable *lowerBound* and *upperBound* must be a real or integer expression. For the type `binary` it is not possible to specify bounds.
index	Indexing expression that defines a position in an array of variables. Described in 2.3.3 Indices and sets

set (Optional) set expression (list of indices) for the definition of the dimension of the array

If more than one set is used then the sets have to be separated by commas.

Described in 2.3.3 Indices and sets

Examples:

`x: real;`	`x` is a real model variable with no ranges
`x: real[0..100];`	`x` is a real model variable, $0 \le x \le 100$
`x[1..5]: integer[10..20];`	vector with 5 elements, $10 \le x_n \le 20; n = 1(1)5$
`x[1..5,1..5,1..5]: real[0..];`	a three-dimensional array of real model variables with 125 elements identified by indices, $x_{i,j,k} \ge 0; i,j,k = 1(1)5$

`parameters:`
`  prod := set( "bike1", "bike2");`
`variables:`
`  x[prod]: real[0.. ];`
	defines a vector of non-negative real model variables based on the set `prod`

`y: binary;`	`x` is a binary model variable $y \in \{0,1\}$

`parameters:`
`  a:=set([1,1],[1,2],[2,2],[3,2]);`
`variables:`
`  x[a]: real[0..];`
	defines a sparse matrix of non-negative real model variables based on the set `a` of 2-tupels.

Different indices may cause model variables to have different types. (e.g. the following is permissible: variables: x[1]: real; x[2]: integer;)

If a name is used for a model variable definition, different usages of this name with indices can only refer to model variables and not to parameters.

2.3.3 Indices and sets

Sets are used for the definitions of arrays of parameters or model variables and for iterations in loops. Indices are necessary to identify an element of an array like a vector or matrix of parameters or variables.

An index is always an *n*-tuple (pair of *n* entries), where *n* is the count of dimensions of an array. Entries are single integers or strings. If *n*>1 then the entries have to be separated by commas.

Usage:

```
[ entry-1 [, entry-2, … , entry-n]  ]   # n-Tuple
```

A set is a collection of indices. Sets can be defined by an enumeration of elements or by algorithms within the `parameters` section. A set can be stored in a scalar parameter or in an element of an array of parameters. A set can also be defined by using a cmplData file and a corresponding CMPL header option.

Usage of set definitions:

```
startNumber(in/decrementor)endNumber          #algorithmic 1-tuple set
[startNumber]..[endNumber]                    #algorithmic 1-tuple set

.integer.                                     #algorithmic 1-tuple set
.string.                                      #algorithmic 1-tuple set

set(entry-1 [, entry-2, … , entry-n])         #enumeration 1-tuple set
set(n-tuple-1 [, n-tuple-2, … ,n-tuple-n])    #enumeration (n>1)-tuple set
```

startNumber`(`*in/decrementor*`)`*endNumber*	1-tuple set of integers based on an algorithm The set starts at the *startNumber*, is changed by an *incrementer* or *decrementer* at every iteration and ends at the *endNumber*.
startNumber`..`*endNumber*	1-tuple set of integers based on an algorithm The set starts at the *startNumber*, is changed by the number one at every iteration and ends at the *endNumber*. `startNumber` and `endNumber` are optional elements.
startNumber`..`	infinite 1-tuple set with all integers greater than or equal to *startNumber*
`..`*endNumber*	infinite 1-tuple set with all integers less than or equal to *endNumber*
`..`	infinite 1-tuple set with all integers and strings
`.integer.`	infinite 1-tuple set with all integers
`.string.`	infinite 1-tuple set with all strings
`set(``entry-1 [, entry-2, … , entry-n]`***`)`***	definition of a 1-tuple enumeration set An enumeration 1-tuple set consists of one or more integer expressions or string expressions separated by commas and embedded in brackets, and is described by the key word `set`.
`set(``n-tuple-1[,n-tuple-2,… ]`***`)`***	definition of an *n*-tuple enumeration set with *n*>1 An enumeration (*n*>1)-tuple set consists of one or more tuples separated by commas and embedded in brackets, and is described by the key word `set`.

Examples:

`s:=..;`	`s` is assigned an infinite 1-tuple set of all integers and strings
`s:=..6;`	`s` is assigned $s \in (\ldots, 4, 5, 6)$
`s:=6..;`	`s` is assigned $s \in (6, 7, 8, \ldots)$
`s:=0..6;` `s:=0(1)6;`	`s` is assigned $s \in (0, 1, \ldots, 6)$
`s:=10(-2)4;`	`s` is assigned $s \in (10, 8, 6, 4)$
`prod := set( "bike1", "bike2");`	enumeration 1-tuple set of strings

`a:= set( 1, "a", 3, "b", 5, "c" );`
 	
`x[a]:=(10,20,30,40,50,60);`
 	
`echo x[1];`
`echo x["a"];`
`{i in a: echo x[i];}`
	enumeration 1-tuple set of strings and integers
	
	vector `x` identified by the set `a` is assigned an integer vector
	
	The following user messages are displayed:
	`10`
	`20`
	`10 20 30 40 50 60`

`a:=[1,2];`	`a` is assigned a 2-tuple of integers
`b:=["p1","p2"];`	`b` is assigned a 2-tuple of strings
`routes := set( [1,1],[1,2],[1,4], [2,2],[2,3],[2,4],[3,1],[3,3] );`	`routes` is assigned a 2-tuple set of integers
`c[routes] := ( 3, 2, 6, 5, 2, 3, 2, 4 );`	The parameter array is defined over routes and is assigned `3, 2, 6, 5, 2, 3, 2, 4.`

`{ [i,j] in routes:`
`  echo "["+i+","+j+"]: " + c[i,j];`
`}`
	The following user messages are displayed:
	`[1,1]: 3`
	`[1,2]: 2`
	`[1,4]: 6`
	`[2,2]: 5`
	`[2,3]: 2`
	`[2,4]: 3`
	`[3,1]: 2`
	`[3,3]: 4`

2.3.4 Line names

Line names are useful in huge models to provide a better overview of the model. In CMPL a line name can be defined by characters, numbers and the underscore character _ followed by a colon. Names that are used for parameters or model variables cannot be used for a line name. Within a control structure a line name can include the current value of local parameters. This is especially useful for local parameters which are used as a loop counter.

Usage:

```
lineName:

lineName$k$:

lineName$1$:
lineName$2$:

loopName { controlStructure }
```

lineName:	Defines a line name for a single row of the model. If more than one row is to be generated by CMPL, then the line names are extended by numbers in natural order.
`$k$`	`$k$` is replaced by the value of the local parameter k.
`$1$`	`$1$` is replaced by the number of the current line of the matrix.
`$2$`	In an implicit loop `$2$` is replaced by the specific value of the free index.
loopName{*controlStructure*}	Defines a line name subject to the following control structure. The values of loop counters in the control structure are appended automatically.

Examples:

`parameters:`
`  A[1..2,1..3] :=((1,2,3),(4,5,6));`
`  b[1..2] := (100,100);`
`  c[1..3] := (20,10,10);`
 	
`variables:`
`  x[1..3]: real[0..];`
 	
`objectives:`
`  profit: c[]T *x[] ->max;`
	generates a line `profit`

`constraints:` `  restriction: A[,] * x[] <=b[];`	generates 2 lines `restriction_1` `restriction_2`

`{ i:=1(1)2:`
`  restriction_$i$: A[,]*x[]<=b[];`
`}`
	generates 2 lines `restriction_1`
	`restriction_2`

`restriction { i:=1(1)3:`
`  A[,]*x[]<=b[];`
`  }`
	generates 2 lines `restriction_1`
	`restriction_2`

```
parameters:
      products:=set("P1", "P2", "P3");
      machines:=set("M1","M2");
      A[machines,products] :=((1,2,3),
                              (4,5,6));
      b[machines] := (100,100);
      c[products] := (20,10,10);
variables:
      x[products]: real[0..];
objectives:
      profit: c[]T *x[] ->max;
constraints:
      capa_$2$: A[,] * x[] <=b[];
```

generates 3 lines

```
profit
capa_M1
capa_M2
```

2.4 CMPL header

A CMPL header is intended to define CMPL options, solver options and display options for the specific CMPL model. An additional intention of the CMPL header is to specify external data files which are to be connected to the CMPL model. The elements of the CMPL header are not part of the CMPL model and are processed before the CMPL model is interpreted.

Usage CMPL header for CMPL options, solver options and display options:

```
%arg optionName [optionValue]                          #CMPL options

%opt solverName solverOption [solverOptionValue]       #Solver options

%display var|con name[*] [name1[*]] ...                #Display options
%display nonZeros                                      #Display option
%display solutionPool                                  #Display option
```

optionName [*optionValue*]
: All CMPL command line arguments excluding a new definition of the input file. Please see subchapter 9.1.

solverName
: In this version are only solver options for `cbc`, `glpk` and `gurobi` supported.

solverOption [*solverOptionValue*]
: Please see to the solver specific parameters subchapter 13 Appendix.

var|con *name*[*****] [*name1*[*****]]
: Sets variable name(s) or constraint name(s) that are to be displayed in one of the solution reports. Different names are to be separated by spaces.

  If `name` is combined with the asterix `*` then all variables or constraints with names that start with `name` are selected.

nonZeros

Only variables and constraints with nonzero activities are shown in the solution report.

solutionPool

Gurobi and Cplex are able to generate and store multiple solutions to a mixed integer programming (MIP) problem. With the display option **solutionPool** feasible integer solutions found during a MIP optimization can be shown in the solution report. It is recommended to control the behaviour of the solution pool by setting the particular Gurobi or Cplex solver options.

Examples:

`%arg -solver glpk`	GLPK is used as the solver.
`%arg -solutionAscii`	CMPL writes the optimization results in an ASCII file.

`%arg -solver cbc`
`%arg -solverUrl ↲`
` http://194.95.44.187:8080/ ↲`
` OSServer/services/OSSolverService`
	CBC is to be executed on a OSServer located at 194.95.44.187.

`%opt cbc threads 2`	If CBC is chosen as solver then 2 threads are executed.
`%opt glpk nopresol`	If GLPK is used then the presolver is switched off.
`%display var x`	Only the variable `x` is to be displayed in the solution report.
`%display con x* y*`	All constraints with names that start with `x` or `y` are shown in the solution report.

If an external cmplData file is to be read into the CMPL model then a user can specify the file name and the needed parameters and sets within the CMPL header. All definitions of the parameters and sets can be mixed with another. The syntax of a cmplData is described in subchapter 4.2 cmplData files.

Usage CMPL header for defining external data:

```
%data [filename] : [set1 set[[rank]]] [, set2 set[[rank]] , … ]
%data [filename] : [param1] [, param2 , … ]
%data [filename] : [paramarray1[set]] [, paramarray2[set] , … ]
```

filename

file name of the cmplData file

If the file name contains white spaces the name can be enclosed in double quotes.

If *filename* is not specified a generic name `modelname.cdat` will be used.

[set1 **set***[***[***rank***]***]][,set2* **set***[***[***rank***]***], …]*	specifies a set with the name *set1* and the rank *rank* The `rank` defines the number *n* of the entries in the *n*-tuples that are contained in the set. For 1-tuple sets is the definition of the `rank` optional. For more than one set the sets are to be separated by commas.
[param1] [, param2 , …]	specifies a scalar parameter If more than one parameters are to be specified then the parameters are to be separated by commas.
*[paramarray1***[***set***]***][,paramarray2***[***set***]***,…]*	specifies a parameter array and the set over which the array is defined For more than one parameter array the entries are to be separated by commas.

The easiest form to specify external data is `%data`. In this case a generic filename `modelname.cdat` will be used and all sets and parameters that are defined in `modelname.cdat` will be read.

Examples:

`%data myProblem.cdat : n set,  a[n]`	reads the 1-tuple set `n` and the vector `a` which is defined over the set `n` from the file `myProblem.cdat`
`%data myProblem.cdat`	reads all parameters and sets that are defined in the file `myProblem.cdat`
`%data : n set[1],  a[n]`	reads (assuming a CMPL model name `myproblem2.cmpl`) the 1-tuple set `n` and the vector `a` which is defined over `n` from `myProblem2.cdat`.
`%data`	Assuming a CMPL model name `myproblem2.cmpl` all sets and parameters are to be read from `myProblem2.cdat`.
`%data : routes set[2], costs[routes]`	Assuming a CMPL model name `myproblem.cmpl` the 2-tuple set `routes` and the matrix `costs` defined over `routes` are to be read from `myProblem.cdat`.

3 Parameter Expressions

3.1 Overview

Parameter expressions are rules for computing a value during the run-time of a CMPL program. Therefore a parameter expression generally cannot include a model variable. Exceptions to this include special functions whose value depends solely on the definition of a certain model variable. Parameter expressions are a part of an assignment to a parameter or are usable within the echo function. Assignments to a parameter are only permitted within the `parameters` section or within a control structure. An expression can be a single number or string, a function, a set or a tupel. Therefore only real, integer, binary, string, set or tupel expressions are possible in CMPL. A parameter expression can contain the normal arithmetic operations.

3.2 Array functions

With the following functions a user may identify specific characteristics of an array or a single parameter or model variable.

Usage:

```
max(expressions)#returns the numerically largest of a list of values
min(expressions)#returns the numerically smallest of a list of values

count(parameter|variable|parameterArray|variableArray)
                      #returns the count of elements or 0 if the parameter
                      #or the variable does not exist
```

expressions can be a list of numerical expressions separated by commas or can be a multi-dimensional array of parameters

Examples:

`a[]:= (1,2,5);`
`echo max( a[] );`
`echo min( a[] );`
	
	returns user message `5`
	returns user message `1`

`echo count( a[] );`	returns user message `3`

`echo count( a[1] );`
`echo count( a[5] );`
`echo count( a[] );`
	returns user message `1`
	returns user message `0`
	returns user message `3`

`b[,]:=((1,2,3,4), (2,3,4,5));`
`echo count(b[1,]);`
`echo count(b[,1]);`
`echo count(b[,]);`
`echo count(b[1,35]);`
	user messages:
	`4` - 4 elements in the first row
	`2` - 2 elements in the first column
	`8` - 4 x 2 elements in the entire matrix
	`0` - parameter does not exist

`a := set( [1,1],[1,2],[2,2],[3,2] );`
`b[a] := ( 10, 20, 30 , 40);`
`echo "count : " + count(b[a]);`
`echo "min   : " + min(b[a]);`
`echo "max   : " + max(b[a]);`
	user messages:
	
	`count : 4`
	`min   : 10`
	`max   : 40`

3.3 Set operations and functions

Set operations and functions can be used to manipulate sets, to create sets or to analyse the characteristics of a set.

Usage:

```
set{ controlHeader : bodyExpressions  };
                      #condition set (only for 1-tupel sets)

set1 + set2;          #union set (only for 1-tupel sets)


set1 * set2;          #intersection set

len(set)              #count of the elements of the set - returns an integer

defset(array)         #returns the set of the first free index of the array
                      #only useful for dense arrays

index << set          #returns 1 - if the index is an element of the set
                      #returns 0 - otherwise

set *> [tuppelPattern]      #Set pattern matching
                            /*Returns an n-tuple set consisting of unique
                            elements of the set set which match tuplePattern
                            in the order of their first appearance. */
```

set{*controlHeader*:*bodyExpressions***}**	Constructs a set consisting of the *bodyexpressions* that satisfy the conditions in the *controlHeader.*
set1 **+** *set2*	union of *set1* and *set2*
set1 ***** *set2*	intersection of *set1* and *set2*
array	array of parameters or model variables with at least one free index.

set ***>** **[***tuppelPattern***]**

Returns an *n*-tuple set consisting of unique elements of the set *set* which match *tuplePattern* in order of their first appearance.

A *tuplePattern* have to be formulated in the form of a tuple and has to have the same rank as the original *set*.

The following entries are allowed and to be separated by commas.

`*` all elements at the position of the indexing entry

`/` ignore all elements at the position of the indexing entry

`string` or `integer`
A `string` or `integer` fixes the indexing entry at its specific position. The fixed indexing entry will not be returned by the set pattern matching expression. It is also possible to use a parameter which is assigned a `string` or `integer`.

*****`string` or *****`integer`
Fixes also the indexing entry at the specific position, but returns the fixed indexing entry too.

Can also be understood as an intersection of two sets followed by a rank reduction controlled by `*` or `/`.

Examples:

`s1 := set( "a","b","c","d");`
`s2 := set( "a","e","c","f");`
 	
`s3 := s1 + s2;`
`s4 := s1 * s2;`
	
	`s3` is assigned `("a","b","c","d","e","f" )`
	`s4` is assigned `( "a", "c" )`

`s5 := set{i in 1..10, i mod 2 = 0: i};`	`s5` is assigned `(2,4,6,8,10)`
`s6 := set{i in s1, !(i << s2): i};`	`s6` is assigned `( "b", "d" )`

`a := set( [1,1],[1,2],[2,2],[3,2] );`
`b := set( [1,1],[4,4],[2,2],[3,7] );`
 	
`c :=  a * b;`
	
	`c` is assigned the set `( [1, 1], [2, 2] )`

`a:= set( 1, "a", 3, "b", 5, "c" );`
 	
`echo "length of the set: "+ len(a);`
	returns the user message
	
	`length of the set: 6`

`A[,] := (  ( 1,2,3,4,5),`
`  (1,2,3,4,5,6,7));`
 	
`row := defset(A[,]);`
`col := defset(A[1,]);`
	
	`row` is assigned the set `1..2`
	`col` is assigned the set `1..5`

`a:= set( 1, "a", 3, "b", 5, "c" );`
 	
`echo "a" << a;`
`echo 5 << a;`
`echo "bb" << a;`
	
	returns the user message `1`
	returns the user message `1`
	returns the user message `0`

`a := set( [1,1],[1,2],[2,2],[3,2] );`
 	
`echo len(a);`
`echo [1,1] << a;`
`echo [1,7] << a;`
	
	returns the user message `4`
	returns the user message `1`
	returns the user message `0`

`a := set( [1,1],[1,2],[2,2],[3,2] );`
`b := [1..2, 1..2];`
 	
`echo a * b;`
	
	returns the user message
	`set([1, 1], [1, 2], [2, 2])`

`a := set( [1,1],[1,2],[2,2],[3,2] );`
`b := [.. , 2];`
 	
`echo a * b;`
	
	returns the user message
	`set([1, 2], [2, 2], [3, 2])`

`b:=set([1,1],[1,2],[1,4],[2,2],[2,3],`
`[2,4],[3,1],[3,3]);`
`echo b *> [*,/];`
`echo b *> [/,*];`
`echo b *> [*1,*];`
`echo b *> [1,*];`
	
	displays the user messages:
	`[1..3]`
	`[set( 1, 2, 4, 3 )]`
	`set([1, 1], [1, 2], [1, 4])`
	`[set( 1, 2, 4 )]`

`c:=set([1,1,1],[1,2,2],[2,2,5],[3,2,2]);`
`echo  c *> [1,*,*];`
`p:=2;`
`echo  c *> [*,p,*];`
`echo  c *> [*,*p,*];`
`echo  c *> [1,/,*];`
	displays the user messages:
	`set([1, 1], [2, 2])`
	
	`set([1, 2], [2, 5], [3, 2])`
	`set([1, 2, 2], [2, 2, 5], [3, 2, 2])`
	`[1..2]`

3.4 Mathematical functions

In CMPL there are the following mathematical functions which can be used in expressions. Excluding `div` and `mod` all these functions return a real value.

Usage:

```
p div q        #integer division
p mod q        #remainder on division
sqrt( x )      #sqrt function
exp( x )       #exp function
ln( x )        #natural logarithm
lg( x )        #common logarithm
ld( x )        #logarithm to the basis 2
srand( x )     #Initialisation of a pseudo-random number generator using the
               argument x. Returns the value of the argument x.
rand( x )      #returns an integer random number in the range 0<= rand <= x
sin( x )       #sine measured in radians
cos( x )       #cosine measured in radians
tan( x )       #tangent measured in radians
acos( x )      #arc cosine measured in radians
asin( x )      #arc sine measured in radians
atan( x )      #arc tangent measured in radians
sinh( x )      #hyperbolic sine
cosh( x )      #hyperbolic cosine
tanh( x )      #hyperbolic tangent
abs( x )       #absolute value
ceil( x )      #smallest integer value greater than or equal to a given value
floor( x )     #largest integer value less than or equal to a given value
round( x )     #simple round
```

p, q	integer expression
x	real or integer expression

Examples:

```
c[1] := sqrt( 36 );
c[2] := exp(10);
c[3] := ln(10);
c[4] := lg(10000);
c[5] := ld(8);
c[6] := rand(10);
c[7] := sin(2.5);
c[8] := cos(7.7);
c[9] := tan(10.1);
c[10] := acos(0.1);
c[11] := asin(0.4);
c[12] := atan(1.1);
```

```
value is:
6.000000
22026.465795
2.302585
4.000000
3.000000
7.000000    (random number)
0.598472
0.153374
0.800789
1.470629
0.411517
0.832981
```

`c[13] := sinh(10);`	`11013.232875`
`c[14] := cosh(3);`	`10.067662`
`c[15] := tanh(15);`	`1.000000`
`c[16] := abs(-12.55);`	`12.550000`
`c[17] := ceil(12.55);`	`13.000000`
`c[18] := floor(-12.55);`	`-13.000000`
`c[19] := round(12.4);`	`12.000000`
`c[20] := 35 div 4;`	`8`
`c[21] := 35 mod 4;`	`3`

3.5 Type casts

It is useful in some situations to change the type of an expression into another type. A set expression can only be converted to a string. A string can only be converted to a numerical type if it contains a valid numerical string. Every expression can be converted to a string.

Usage:

```
type(expression)      #type cast
```

type	Possible types are: `real, integer, binary, string`.
expression	expression

Examples:

	returns the user messages:

`a := 6.666;`
`echo integer(a);`
`echo binary(a);`
`a:=0;`
`echo binary(a);`
`a := 6.6666;`
`echo string(a);`
	
	`7`
	`1`
	
	`0`
	
	`6.666600`

`b := 100;`
`echo real(b);`
`echo binary(b);`
`b := 0;`
`echo binary(b);`
`b:= 100;`
`echo string(b);`
	
	`100.000000`
	`1`
	
	`0`
	
	`100`

`c :=1;`
`echo real(c);`
`echo integer(c);`
`echo string(c);`
	
	`1.000000`
	`1`
	`1`

e := "1.888";
echo real(e);
echo integer(e);
echo binary(e);
e := "";
echo binary(e);
	
	1.888000
	1
	1
	
	0

3.6 String operations

Especially for displaying strings or numbers with the echo function there are string operations to concatenate and format strings.

Usage:

```
expression + expression                 #concat strings if one expression
                                        #has the type string

format( formatString, expression )      #converts a number into a
                                        #string using a format string

len( stringExpression )                 #length of a string


type( expression )                      #returns the type of the expression
                                        #as a string
```

expression	expression which is converted to string Cannot be a set expression. Such an expression must be converted to a string expression by a type cast
formatString	a string expression containing format parameters CMPL uses the format parameters of the programming language C++. For further information please consult a C++ manual.

Usage format parameters:

```
%<flags><width><.precision>specifier
```

specifier	
d	integer
f	real
s	string

flags	
-	left-justify
+	Forces the result to be preceded by a plus or minus sign (+ or -) even for positive numbers. By default only negative numbers are preceded with a - sign.
width	
(number)	Minimum number of characters to be printed. If the value to be printed is shorter than this number, the result is padded with blank spaces. The value is not truncated even if the result is larger.
*	The *width* is not specified in the *format* string, but as an additional integer value argument preceding the argument that has to be formatted.
.precision	
.*number*	For integer specifiers d: precision specifies the minimum number of digits to be written. If the value to be written is shorter than this number, the result is padded with leading zeros. The value is not truncated even if the result is longer. A precision of 0 means that no character is written for the value 0. For f: this is the number of digits to be printed after the decimal point. For s: this is the maximum number of characters to be printed. By default all characters are printed until the ending null character is encountered. When no precision is specified, the default is 1. If the period is specified without an explicit value for precision, 0 is assumed.
.*	The *precision* is not specified in the *format* string, but as an additional integer value argument preceding the argument that has to be formatted.

Examples:

```
a:=66.77777;
echo type(a)+ " " + a + " to string
" + format("%10.2f", a);
```

returns the user message

```
real 66.777770 to string 66.78
```

If you would like to display an entire set concatenating with a string, then you have to use a string cast of your set.

Example:

```
s:= set( 7, "qwe", 6, "fe", 5, 8 );
echo "set is " + string(s);
```

returns the user message

```
set is set( 7, "qwe", 6, "fe", 5, 8 )
```

4 Input and output operations

The CMPL input and output operations can be separated into message function, a function that reads the external data and the include statement that reads external CMPL code.

4.1 Error and user messages

Both kinds of message functions display a string as a message. In contrast to the echo function an error message terminates the CMPL program after displaying the message.

Usage:

```
error expression;           #error message - terminates the CMPL program

echo expression;       #user message
```

expression A message that is to be displayed. If the expression is not a string it will be automatically converted to string.

Examples:

`{a<0: error "negative value"; }`	If `a` is negative an error message is displayed and the CMPL program will be terminated.
`echo "constant definitions finished";`	A user message is displayed.

`{ i:=1(1)3: echo "value:" + i;}`	The following user messages are displayed:
	`value: 1`
	`value: 2`
	`value: 3`

4.2 cmplData files

A cmplData file is a plain text file that contains the definition of parameters, sets with their values in a specific syntax. The parameters and sets can be read into a CMPL model by using the CMPL header argument `%data`.

Usage:

```
%name < numberOrString >                                    # scalar parameter

%name set[[rank]] < setExpression >                         # set definition

%name [set] [= default] [indices] < listOfNumbersOrStrings >
                                                            # parameter array
#text                                                       # comments
```

Excluding comments each cmplData definition starts with `%`.

%name **<** *numberOrString* **>** a scalar parameter `name` is assigned a single string or number

%name **set***[***[***rank***]***]* **<** *setExpression* **>** definition of an *n*-tuple set

A set definition starts with the *name* followed by the keyword **set**. For *n*-tuple sets with *n*>1 the rank of the set is to be specified enclosed by square brackets.

For enumeration sets the entries of the sets are separated by white spaces and imbedded in angle brackets. It is also possible to define algorithmic sets in normal CMPL syntax.

%name ***[****set****]*** *[***=** *default] [****indices****]*
< *listOfNumbersOrStrings* **>**

definition of a parameter array

The specification of a parameter array starts with the name followed by one or more sets, over which the array is defined. If more than one set is used then the sets have to be separated by commas. The set or sets have to be defined before the parameter definition.

If the data entries are specified by their indices (keyword ***indices***) then a default value can be defined.

The data entries can be strings or numbers and have to be separated by white spaces and imbedded in angle brackets.

If the data entries are specified by their indices then each data entry has to start with the indices followed by the value and separated by white spaces.

If not so then the order of the elements are given by the natural order of the set or sets.

Examples:

`%a < 10 >`	Defines a scalar parameter `a` and assigns the number 10.
`%s set < 0..6 >` `%s set < 0..6 >`	`s` is assigned $s \in (0,1,\ldots,6)$
`%s set < 10(-2)4 >`	`s` is assigned $s \in (10,8,6,4)$
`%prod set < bike1 bike2 >` `%prod set < "bike 1"  "bike 2" >`	1-tuple enumeration set of strings
`%a set< 1 a  3  b 5 c >` `%x[a] < 10 20 30 40 50 60 >`	1-tuple enumeration set of strings and integers vector `x` identified by the set `a` is assigned an integer vector

`%data : a set, x[a]`
 	
`parameters:`
`  echo x[1];`
`  echo x["a"];`
`  {i in a: echo x[i];}`
	reads the set `a` and the vector `x` into a CMPL model
	The following user messages are displayed:
	`10`
	`20`
	`10 20 30 40 50 60`

```
%n set < 1..3 >
%m set < 1..3 >

%a[n,m] = 0 indices <   1 1 1
                        2 2 1
                        3 3 1 >
```

defines a 3x3 identity matrix

```
%x set < 1..2 >
%y set < 1..2 >
%z set < 1..2 >

%cube[x,y,z] < 1 2 3 4 5 6 7 8 >
```

definition of a data cube with the dimension `x,y,z`

x	*y*	*z*	*value*
1	1	1	1
1	1	2	2
1	2	1	3
1	2	2	4
2	1	1	5
2	1	2	6
2	2	1	7
2	2	2	8

```
%data : x set, y set, z set, cube[x,y,z]


parameters:
  {i in x, j in y, k in z:
      echo i+","+j+","+k+":"+cube[i,j,k];
  }
```

reads the sets `x,y,z` and the `cube` into a CMPL model

The following user messages are displayed:

```
1,1,1:1
1,1,2:2
1,2,1:3
1,2,2:4
2,1,1:5
2,1,2:6
2,2,1:7
2,2,2:8
```

```
%cube[x,y,z] = 0 indices < 1 1 1 1
                           2 2 2 1 >
```

defines the following data cube

x	*y*	*z*	*value*
1	1	1	1
1	1	2	0
1	2	1	0
1	2	2	0
2	1	1	0
2	1	2	0
2	2	1	0
2	2	2	1

```
%x set[3] <  1 1 1
             1 1 2
             1 2 1
             1 2 2
             2 1 1
             2 1 2
             2 2 1
             2 2 2 >

%cube[x] < 1 2 3 4 5 6 7 8 >
```

cube defined over a 3-tuple set

x	*y*	*z*	*value*
1	1	1	1
1	1	2	2
1	2	1	3
1	2	2	4
2	1	1	5
2	1	2	6
2	2	1	7
2	2	2	8

```
%data : x set[3], cube[x]

parameters:
   {i in x:  echo i +":"+cube[i]; }
```

reads the 3-tuple set `x` and `cube`

The following user messages are displayed:

```
[1, 1, 1]:1
[1, 1, 2]:2
[1, 2, 1]:3
[1, 2, 2]:4
[2, 1, 1]:5
[2, 1, 2]:6
[2, 2, 1]:7
[2, 2, 2]:8
```

```
%x set[3] <  1 1 1   1 1 2   1 2 1   1 2 2
             2 1 1   2 1 2   2 2 1   2 2 2 >

%cube[x] = 0 indices <      1 1 1 1
                            2 2 2 1 >
```

data `cube` defined over `x`

x	*y*	*z*	*value*
1	1	1	1
1	1	2	0
1	2	1	0
1	2	2	0
2	1	1	0
2	1	2	0
2	2	1	0
2	2	2	1

```
%routes set[2] <  p1 c1
                  p1 c2
                  p1 c4
                  p2 c2
                  p2 c3
                  p2 c4
                  p3 c1
                  p3 c3  >
%c[routes]  < 3  2  6  5  2  3  2  4 >
```

defines a 2-tuple set `routes` and a matrix `c` that is defined over `routes`

`%data : routes set[2], c[routes]`
 	
`parameters:`
`  {i in routes: echo i + " : "+ c[i];}`
	reads the 2-tuple set `routes` and the matrix `c` into a CMPL model
	The following user messages are displayed:
	`["p1", "c1"] : 3`
	`["p1", "c2"] : 2`
	`["p1", "c4"] : 6`
	`["p2", "c2"] : 5`
	`["p2", "c3"] : 2`
	`["p2", "c4"] : 3`
	`["p3", "c1"] : 2`
	`["p3", "c3"] : 4`

4.3 Readcsv and readstdin

CMPL has two additional functions that enable a user to read external data. The function `readstdin` is designed to read a user's numerical input and assign it to a parameter. The function `readcsv` reads numerical data from a CSV file and assigns it to a vector or matrix of parameters.

Usage:

```
readstdin(message);                 #returns a user numerical input

readcsv(fileName);                  #reads numerical data from a csv file
                                    #for assigning these data to an array
```

message string expression for the message that is to be displayed

fileName string expression for the file name of the CSV file (relative to the directory in which the current CMPL file resides)
In CMPL CSV files that use a comma or semicolon to separate values are permitted.

Example:

`a := readstdin("give me a number");`	reads a value from `stdin` to be used as value for `a`. Only recommended when using CMPL as a command line interpreter.

The following example uses three CSV files:

`1;2;3`	c.csv
`5.6;7.7;10.5` `9.8;4.2;11.1`	a.csv
`15;20`	b.csv
`parameters:` `  c[] := readcsv("c.csv");`	Using `readcsv` CMPL generates the following model:

```
      b[] := readcsv("b.csv");
      A[,] := readcsv("a.csv");
variables:
      x[defset(c[])]: real[0..];
objectives:
      c[]T * x[]->max;
constraints:
      A[,] * x[] <= b[];
```

$$1 \cdot x_1 + 2 \cdot x_2 + 3 \cdot x_3 \rightarrow max!$$
$$s.t.$$
$$5.6 \cdot x_1 + 7.7 \cdot x_2 + 10.5 \cdot x_3 \leq 15$$
$$9.8 \cdot x_1 + 4.2 \cdot x_2 + 11.1 \cdot x_3 \leq 20$$
$$x_j \geq 0; j = 1(1)3$$

4.4 Include

Using the `include` directive it is possible to read external CMPL code in a CMPL program. The CMPL code in the external CMPL file can be used by several CMPL programs. This makes sense for sharing basic data in a couple of CMPL programs or for the multiple use of specific CMPL statements in several CMPL programs. The `include` directive can stand in any position in a CMPL file. The content of the included file is inserted at this position before parsing the CMPL code. Because `include` is not a statement it is not closed with a semicolon.

Usage:

```
include "fileName"          #include external CMPL code
```

fileName — file name of the CMPL file (relative to the directory in which the current CMPL file resides)

Note that *fileName* can only be a literal string value. It cannot be a string expression or a string parameter.

The following CMPL file "const-def.gen" is used for the definition of a couple of parameters:

```
c[] := ( 1, 2, 3 );
b[] := ( 15, 20 );
A[,] := ( ( 5.6, 7.7, 10.5 ),
        ( 9.8,4.2,11.1) );
```

const-def.gen

```
parameters:
    include "const-def.cmpl"

variables:
    x[defset(c[])]: real[0..];

objectives:
    c[]T * x[] -> max;
constraints:
    A[,] * x[] <= b[];
```

Using the `include` statement CMPL generates the following model:

$$1 \cdot x_1 + 2 \cdot x_2 + 3 \cdot x_3 \rightarrow max!$$
$$s.t.$$
$$5.6 \cdot x_1 + 7.7 \cdot x_2 + 10.5 \cdot x_3 \leq 15$$
$$9.8 \cdot x_1 + 4.2 \cdot x_2 + 11.1 \cdot x_3 \leq 20$$
$$x_j \geq 0; j = 1(1)3$$

5 Statements

As mentioned earlier, every CMPL program consists of at least one of the following sections: `parameters:`, `variables:`, `objectives:` and `constraints:`. Each section can be inserted several times and mixed in a different order. Every section can contain special statements. Every statement finishes with a semicolon.

5.1 `parameters` and `variables` section

Statements in the `parameters` section are assignments to parameters. These assignments define parameters or reassign a new value to already defined parameters. Statements in the `variables` sections are definitions of model variables.

All the syntactic and semantic requirements are described in the chapters above.

5.2 `objectives` and `constraints` section

In the `objectives` and `constraints` sections a user has to define the content of the decision model in linear terms. In general, an objective function of a linear optimization model has the form:

$$c_1 \cdot x_1 + c_2 \cdot x_2 + \ldots + c_n \cdot x_n \;\rightarrow\; max\,! \quad (\text{or } min\,!)$$

with the objective function coefficient c_j and model variables x_j . Constraints in general have the form:

$$\begin{aligned} k_{11} \cdot x_1 + k_{12} \cdot x_2 + \ldots + k_{1n} \cdot x_n &\le b_1 \\ k_{21} \cdot x_1 + k_{22} \cdot x_2 + \ldots + k_{2n} \cdot x_n &\le b_2 \\ &\vdots \\ k_{m1} \cdot x_1 + k_{m2} \cdot x_2 + \ldots + k_{mn} \cdot x_n &\le b_m \end{aligned}$$

with constraint coefficients k_{ij} and model variables x_j .

An objective or constraint definition in CMPL must use exactly this form or a sum loop that expresses this form. A coefficient can be an arbitrary numerical expression, but the model variables cannot stand in expressions that are different from the general form formulated. The rule that model variables cannot stand in bracketed expressions serves to enforce this.

Please note, it is not permissible to put model variables in brackets!

The example (`a` and `b` are parameters, `x` and `y` model variables)

```
a*x + a*y + b*x + b*y
```

can be written alternatively (with parameters in brackets) as:

```
(a + b)*x + (a + b)*y
```

but not (with model variables in brackets) as:

```
a*(x + y) + b*(x + y)
```

For the definition of the objective sense in the `objectives` section the syntactic elements `->max` or `->min` are used. A line name is permitted and the definition of the objective function has to have a linear form.

Usage of an objective function:

```
objectives:
            [lineName:] linearTerm ->max|->min;
```

lineName	optional element description of objective
linearTerm	definition of linear objective function

The definition of a constraint has to consist of a linear definition of the use of the constraint and one or two relative comparisons. Line names are permitted.

Usage of a constraint:

```
constraints:
            [lineName:] linearTerm <=|>=|= linearTerm  [<=|>=|= linearTerm];
```

lineName	optional element description of objective
linearTerm	linear definition of the left-hand side or the right-hand side of a constraint

6 Control structure

6.1 Overview

A control structure is imbedded in `{ }` and defined by a header followed by a body separated off by `:`.

General usage of a control structure:

```
     [controlName]|[sum|set] { controlHeader : controlBody }
```

A control structure can be started with an optional name for the control structure. In the `objectives` and in the `constraints` section this name is also used as the line name.

It is possible to define different kinds of control structures based on different headers, control statements and special syntactical elements. Thus the control structure can used for for loops, while loops, if-then-else clauses and switch clauses. Control structures can be used in all sections.

A control structure can be used for the definition of statements. In this case the control body contains one or more statements which are permissible in this section.

It is also possible to use control structures for `sum` and `set` as expressions. Then the body contains a single expression. A control structure as an expression cannot have a name because this place is taken by the keyword `sum` or `set`. Moreover a control structure as an expression cannot use control statements because the body is an expression and not a statement.

6.2 Control header

A control header consists of one or more control headers. Where there is more than one header, the headers must be separated by commas. Control headers can be divided into iteration headers, condition headers, local assignments and empty headers.

6.2.1 Iteration headers

Iteration headers define how many repeats are to be executed in the control body. Iteration headers are based on sets.

Usage:

```
    localParam in set       # iteration over a set
```

localParam	name of the local parameter
set	The defined local parameter iterates over the elements of the set and the body is executed for every element in the set.

Examples:

`s1 := set( "a","b","c","d");` `{k in s1:  … }`	`k` is iterated over all elements of the set `s1`
`s2 := 1(1)10;` `{k in s2:  … }`	`k` is iterated over the set $k \in \{1,2,\ldots,10\}$
`s3 := 2..6;` `{k := s3:  …  }`	`k` is iterated over the set $k \in \{2,3,\ldots,6\}$

`a := set( [1,1],[1,2],[2,2],[3,2] );`
`{ k in a : … }`
 	
`a := set( [1,1],[1,2],[2,2],[3,2] );`
`{ [i,j] in a : … }`
	`k` is iterated over the 2-tuple set `a`
	
	2-tuple index `[i,j` is iterated over the 2-tuple set `a`

6.2.2 Condition headers

A condition returns `1(True)` or `0(False)` subject to the result of a comparison or the properties of a parameter or a set. If the condition returns `1(True)` the body is executed once or else the body is skipped.

Comparison operators for parameters:

`=, ==`	equality
`<>, !=`	inequality
`<`	less than
`>`	greater than
`<=`	equal to or less than
`>=`	equal to or greater than

Comparison operators for sets:

`=`	equality
`==`	tests whether the iteration order of two sets is equal
`<>`	inequality
`!=`	tests whether the iteration order of two sets is not equal
`<`	subset or not equal (only for 1-tuple sets)
`>`	greater than (only for 1-tuple sets)
`<=`	subset or equal (only for 1-tuple sets)
`>=`	equal to or greater than (only for 1-tuple sets)

Logical operators:

`&&`	AND
`||`	OR
`!`	NOT

If a real or integer parameter is assigned 0, the condition returns `0 (false)`. Alternatively if the parameter is assigned `1` the condition returns `1 (true)`.

Examples:

`i:=1;`	
`j:=2;`	
`{i>j : … }`	condition is false
`{!(i>j) : … }`	condition is true
`{!i || j=2 : … }`	condition is true
`{!i && j=2 : … }`	condition is false (`!i` is false, because `i` is not 0)

6.2.3 Local assignments

A local assignment as control header is useful if a user wishes to make several calculations in a local environment. Assigning expression to a parameter within the `constraints` section is generally not allowed with the exception of a local assignment within a control structure. The body will be executed once.

Usage:

```
    localParam := expression            # assignment to a local parameter
```

localParam	Defines a local parameter with this name.
expression	Expression which is assigned to the local parameter.

Examples:

`constraints:` `  { k:=1 :  … }`	`k` is assigned `1` and used as local parameter within the control structure.

6.3 Alternative bodies

If a control header consists of at least one condition, it is possible to define alternative bodies. Structures like that make sense e.g. if a user wishes to combine a for loop with an if-then clause.

The first defined body after the headers is the main body of the control structure. Subsequent bodies must be separated by the syntactic element `|`. Alternative bodies are only executed if the main body is skipped.

Usage:

```
    { controlHeader: mainBody [ | condition1: alternativeBody1 ]
          [ | ... ] [ | default: alternativeDefaultBody ] }
```

controlHeader	header of the control structure including at least one condition The alternative bodies belong to last header of control header. This header cannot be an assignment of a local parameter, because in this case the main body is never skipped.
mainBody	main body of control structure
condition1	Will be evaluated if alternative body is executed.
alternativeBody1	The first alternative body with a condition that evaluates to true is executed. The remaining alternative bodies are skipped without checking the conditions.
alternativeDefaultBody	If no condition evaluates to true then the alternative default body is executed. If the control structure has no alternative default body, then no body is executed.

6.4 Control statements

It is possible to change or interrupt the execution of a control structure using the keywords `continue`, `break` and `repeat`. A `continue` stops the execution of the specified loop, jumps to the loop header and executes the next iteration. A `break` only interrupts the execution of the specified loop. The keyword `repeat` starts the execution again with the referenced header.

Every control statement references one control header. If no reference is given, it references the innermost header. Possible references are the name of the local parameter which is defined in this head, or the name of the control structure. The name of the control structure belongs to the first head in this control structure.

Usage:

```
continue [reference];
break [reference];
repeat [reference];
```

reference — a reference to a control header specified by a name or a local parameter

break *[reference]* — The execution of the body of the referenced head is cancelled. Remaining statements are skipped.

If the referenced header contains iteration over a set, the execution for the remaining elements of the set is skipped.

continue *[reference]* — The execution of the body of the referenced head is cancelled. Remaining statements are skipped.

If the referenced header contains iteration over a set, the execution is continued with the next element of the set. For other kinds of headers `continue` is equivalent to `break`.

repeat *[reference]* — The execution of the body of the referenced header is cancelled. Remaining statements are skipped.

The execution starts again with the referenced header. The expression in this header is to be evaluated again. If the header contains iteration over a set, the execution starts with the first element. If this header is an assignment to a local parameter, the assignment is executed again. If the header is a condition, the expression is to be checked prior to execution or skipping the body.

6.5 Specific control structures

6.5.1 For loop

A for loop is imbedded in `{ }` and defined by at least one iteration header followed by a loop body separated off by `:`. The loop body contains user-defined instructions which are repeatedly carried out. The number of repeats is based on the iteration header definition.

Usage:

```
{ iterationHeader [, iterationHeader1] [, ...]  : controlBody }
```

iterationHeader *iterationHeader1*	defined iteration headers
controlBody	CMPL statements that are executed in every iteration

Examples:

`{ i in 1(1)3 : ... }`	loop counter `i` with a start value of 1, an increment of 1 and an end condition of 3
`{ i in 1..3 : ... }`	alternative definition of a loop counter; loop counter `i` with a start value of 1 and an end condition of 3. (The increment is automatically defined as 1)

`products:= set( "p1", "p2", "p3");`
`hours[products]:=(20,55,10);`
`{i in products:`
`  echo "hours of product " +`
`  i + " : "+ hours[i];`
`}`
	for loop using the set `products` returns
	user messages `hours of product: p1 : 20`
	`hours of product: p2 : 55`
	`hours of product: p3 : 10`

`{i in 1(1)2:`
`  {j in 2(2)4:  A[i,j] := i + j; }`
`}`
	defines `A[1,2] = 3`, `A[1,4] = 5`, `A[2,2] = 4` and `A[2,4] = 6`

`a := set([1,1],[1,2],[2,2],[3,2]);`
`b[a] := ( 10, 20, 30 , 40);`
 	
`{ k in a : echo k + ":"+ b[k] ;}`
	`k` is iterated over the 2-tuple set `a`
	
	The following user messages are displayed:
	`[1, 1]:10`
	`[1, 2]:20`
	`[2, 2]:30`
	`[3, 2]:40`

Several loop heads can be combined. The above example can thus be abbreviated to:

`{i in 1(1)2, j in 2(2)4:`
`  A[i,j] := i + j;`
`}`
	defines `A[1,2] = 3, A[1,4] = 5, A[2,2] = 4` and `A[2,4] = 6`

`{i in 1(1)5, j in 1(1)i:`
`  A[i,j] := i + j;`
`}`
	definition of a triangular matrix

6.5.2 If-then clause

An if-then consists of one condition as control header and user-defined expressions which are executed if the if condition or conditions are fulfilled. Using an alternative default body the if-then clause can be extended to an if-then-else clause.

Usage:

```
{ condition: thenBody [| default: elseBody ]}
```

condition	If the evaluated condition is true, the code within the body is executed.
thenBody	This body is executed if the *condition* is true.
elseBody	This body is executed if the *condition* is false.

Examples:

`{i := 1(1)5, j := 1(1)5:`
`  {i = j:  A[i,j] := 1; }`
`  {i != j: A[i,j] := 0; }`
`}`
	definition of the identity matrix with combined loops and two if-then clauses

`{i := 1(1)5, j := 1(1)5:`
`  {i = j:  A[i,j] := 1; |`
`  default: A[i,j] := 0; }`
`}`
	same example, but with one if-then-else clause

`i:=10;`
`{ i<10: echo "i less than 10";`
`  | default: echo "i greater than 9";`
`}`
	example of an if-then-else clause
	returns user message `i greater than 9`

`sum{ i = j : 1 | default: 2 }`	conditional expression, evaluates to 1 if `i = j`, otherwise to 2

6.5.3 Switch clause

Using more than one alternative body the if-then clause can be extended to a switch clause.

Usage:

```
{ condition1: body1 [| condition2: body2>] [| ... ] [| default: defaultBody ]}
```

If the first condition returns TRUE, only *body1* will be executed. Otherwise the next condition *condition1* will be verified. *body2* is executed if all of the previous conditions are not fulfilled. If no condition returns true, then the *defaultBody* is executed.

Example:

```
i:=2;
{   i=1: echo "i equals 1";
  | i=2: echo "i equals 2";
  | i=3: echo "i equals 3";
  | default: echo "any other value";
}
```

example of a switch clause
returns user message `i equals 2`

6.5.4 While loop

A while loop is imbedded in `{ }` and defined by a condition header followed by a loop body separated off by `:` and finished by the keyword `repeat`. The loop body contains user-defined instructions which are repeatedly carried out until the condition in the loop header is false.

Usage:

```
{ condition : statements repeat; }
```

condition	If the evaluated condition is true, the code within the body is executed. This repeats until the condition becomes false.
statements	one or more user-defined CMPL instructions To prevent an infinite loop the statements in the control body must have an impact on the *condition*.

Examples:

```
i:=2;
{i<=4:
      A[i] := i;
      i := i+1;
      repeat;
}
```

while loop with a global parameter

Can only be used in the `parameters` section, because the assignment to a global parameter is not permitted in other sections.

defines `A[2] = 2`, `A[3] = 3` and `A[4] = 4`

{a := 1, a < 5:
echo a;
a := a + 1;
repeat;
}
	while loop using a local parameter
	returns user messages 1
	2
	3
	4

{a:=1:
xx {:
echo a;
a := a + 1;
{a>=4: break xx;}
repeat;
}
}
	Alternative formulation:
	The outer control structure defines the local parameter a. This control structure is used as a loop with a defined name and an empty header. The name is necessary, because it is needed as reference for the break statement in the inner control structure. (Without this reference the break statement would refer to the condition a>=4)

6.6 Set and sum control structure as expression

Starting with the keyword sum or the keyword set a control structure returns an expression. Only expressions are permitted in the body of the control structure. Control statements are not allowed, because the body cannot contain a statement. It is possible to define alternative bodies.

Usage:

```
sum { controlHeader : bodyExpressions }
set { controlHeader : bodyExpressions }
```

controlHeader	header of the control structure The header of a sum or a set control structure is usually an iteration header, but all kinds of control header can be used.
bodyExpressions	user-defined expressions

A sum expression repeatedly summarises the user-defined expressions in the *bodyExpressions*. If the body is never executed, it evaluates to 0. A set expression returns a set subject to the *controlHeader* and the *bodyExpressions*. The element type included in *bodyExpressions* must be integer or string. Please note that the set expression only works for 1-tuple sets.

Examples:

x[1..3] := (2, 4, 6); a := sum{i := 1(1)3 : x[i] };	a is assigned 12

products:= set("p1", "p2", "p3");
hours[products]:=(20,55,10);
totalHours:= sum{i in products: hours[i] };
	totalHours is assigned 85

x[1..3,1..2]:=((1,2),(3,4),(5,6)); b:= sum{i := 1(1)3, j := 1(1)2: x[i,j] };	sum with more than one control header b is assigned 21.

`s:=set();` `d:= sum{i in s: i |default: -1 };`	sums up all elements in the set `s`. Since `s` is an empty set, `d` is assigned to the alternative default value `-1`.

`a := set( [1,1],[1,2],[2,2],[3,2] );`
`b[a] := ( 10, 20, 30 , 40);`
 	
`c := sum{ k in a : b[k]};`
	calculates a sum over all elements in b which is defined over the 2-tuple set `a`.
	`c` is assigned `100`.

`e:= set{i:= 1..10: i^2 };`	e is assigned the set `(1, 4, 9, 16, 25, 36, 49, 64, 81, 100)`
`f:= set{i:= 1..100, round(sqrt(i))^2 = i: i };`	f is assigned the set `(1, 4, 9, 16, 25, 36, 49, 64, 81, 100)`

The `sum` expression can also be used in linear terms for the definition of objectives and constraints. In this case the body of the control structure can contain model variables.

Examples:

```
parameters:
      a[1..2,1..3] :=((1,2,3),(4,5,6));
      b[1..2] := (100,100);
      c[1..3] := (20,10,10);


variables:
      x[1..3]: real[0..];


objectives:
      sum{j:=1..3: c[j] *x[j]}->max;

constraints:
      { i:=1..2:
          sum{j:=1..3: a[i,j] * x[j]}<= b[i];
      }
```

objective definition using a sum

$$20 \cdot x_1 + 10 \cdot x_2 + 10 \cdot x_3 \rightarrow max!$$

constraints definition using a sum

$$1 \cdot x_1 + 2 \cdot x_2 + 3 \cdot x_3 \leq 100$$
$$4 \cdot x_1 + 5 \cdot x_2 + 6 \cdot x_3 \leq 100$$

7 Matrix-Vector notations

CMPL allows users to define objectives and constraints in a matrix-vector notation (e.g. matrix vector multiplication). CMPL generates all required rows and columns automatically by implicit loops.

Implicit loops are formed by matrices and vectors, which are defined by the use of free indices. A free index is an index which is not specified by a position in an array. It can be specified by an entire set or without any specification. But the separating commas between indices must in any case be specified. A multidimensional array with one free index is always treated as a column vector, regardless of where the free index stands. A column vector can be transposed to a row vector with `T`. A multidimensional array with two free indices is al-

ways treated as a matrix. The first free index is the row, the second the column. Implicit loops are only possible in the `objectives` section and the `constraints` section.

Please note that matrix-vector notations only works for arrays which are defined over 1-tuple sets.

Usage:

```
vector[set]                     #column vector
vector[set]T                    #transpose of column vector  - row vector

matrix[index, set]              #column vector
matrix[set, index]              #also column vector

matrix[index, set]T             #transpose of column vector  - row vector
matrix[set, index]T             #transpose of column vector  - row vector

matrix[set1, set2]              #matrix
```

vector, matrix	name of a vector or matrix
index	a certain index value
[set]	optional specification of a set for the free index

Examples:

`x[]`	vector with free index across the entire defined area
`x[2..5]`	vector with free index in the range 2 – 5
`A[,]`	matrix with two free indices
`A[1,]`	matrix with one fixed and one free index; this is a column vector.
`A[,1]`	matrix with one fixed and one free index; this is also a column vector.

The most important ways to define objectives and constraints with implicit loops are vector-vector multiplication and matrix-vector multiplication. A vector-vector multiplication defines a row of the model (e.g. an objective or one constraint). A matrix-vector multiplication can be used for the formulation of more than one row of the model.

Usage of multiplication using implicit loops :

```
paramVector[set]T * varVector[set]  #vector-vector multiplication
varVector[set]T * paramVector[set]  #vector-vector multiplication

paramMatrix[set1,set2] * varVector[set2]
                                    #matrix-vector multiplication
varVector[set1]T * paramMatrix[set1,set2]
                                    #matrix-vector multiplication
```

paramVector	name of a vector of parameters
varVector	name of a vector of model variables
paramMatrix	name of a matrix of parameters
T	syntactic element for transposing a vector

Examples:

```
parameters:
      a[1..2,1..3] :=(  (1,2,3),
                        (4,5,6));
      b[1..2] := (100,100);
      c[1..3] := (20,10,10);
variables:
      x[1..3]: real[0..];
objectives:
      c[]T * x[] ->max;

constraints:
      a[, ] * x[] <=b[];
```

objective definition using implicit loops

$$20 \cdot x_1 + 10 \cdot x_2 + 10 \cdot x_3 \rightarrow max\ !$$

constraint definition using implicit loops

$$1 \cdot x_1 + 2 \cdot x_2 + 3 \cdot x_3 \leq 100$$
$$4 \cdot x_1 + 5 \cdot x_2 + 6 \cdot x_3 \leq 100$$

Aside from vector-vector multiplication and matrix-vector multiplication vector subtractions or additions are also useful for the definition of constraints. The addition or subtraction of a variable vector adds new columns to the constraints. The addition or subtraction of a constant vector changes the right side of the constraints.

Usage of additions or subtractions using implicit loops:

```
  linearTerms + varVector[set]          #variable vector addition
  linearTerms - varVector[set]          #variable vector subtraction

  linearTerms + paramVector[set]        #parameter vector addition
  linearTerms - paramVector[set]        #parameter vector subtraction
```

linearTerms	other linear terms in an objective or constraint

Examples:

```
parameters:
      a[1..2,1..3] :=(  (1,2,3),
                        (4,5,6));
      b[1..2] := (100,100);
      d[1..2] := (10,10);
      c[1..3] := (20,10,10);
variables:
      x[1..3]: real[0..];
```

```
objectives:
      c[]T * x[] ->max;
```

`constraints:` `  a[,] * x[] + d[] <=b[];`	constraints definition using implicit loops $1 \cdot x_1 + 2 \cdot x_2 + 3 \cdot x_3 \leq 90$ $4 \cdot x_1 + 5 \cdot x_2 + 6 \cdot x_3 \leq 90$ equivalent to `a[,] * x[]  <=b[] - d[];`
`0 <= x[1..3]+y[1..3]+z[2]<= b[1..3];`	implicit loops for a column vector

`0 <= x[1] + y[1] + z[2] <= b[1];`
`0 <= x[2] + y[2] + z[2] <= b[2];`
`0 <= x[3] + y[3] + z[2] <= b[3];`
	equivalent formulation

`parameters:`
`  a[1..2,1..3] :=(  (1,2,3),`
`  (4,5,6));`
`  b[1..2] := (100,100);`
`  d[1..2] := (10,10);`
`  c[1..3] := (20,10,10);`
`variables:`
`  x[1..3]: real[0..];`
`  z[1..2]: real[0..];`	

`objectives:` `  c[]T * x[] ->max;`	
`constraints:` `  a[,] * x[] + z[] <=b[];`	constraints definition using implicit loops $1 \cdot x_1 + 2 \cdot x_2 + 3 \cdot x_3 + z_1 \leq 90$ $4 \cdot x_1 + 5 \cdot x_2 + 6 \cdot x_3 + z_2 \leq 90$

8 Automatic model reformulations

8.1 Overview

CMPL includes two types of automatic code generation which release the user from additional modelling work. CMPL automatically optimizes the generated model by means of matrix reductions. The second type of automatic code reformulations is the equivalent transformation of variable products.

8.2 Matrix reductions

Matrix reductions are subject to constraints of a specific form.

a) If a constraint contains only one variable or only one of the variables with a coefficient not equal to 0, then the constraint is taken as a lower or upper bound.

For the following summation (`x[]` is a variable vector)

```
sum{i:=1(1)2: (i-1) * x[i]} <= 10;
```

no matrix line is generated; rather `x[2]` has an upper bound of 10.

b) If there is a constraint in the coefficients of all variables proportional to another constraint, only the more strongly limiting constraint is retained.

Only the second of the two constraints (`x[]` is a variable vector)

```
2*x[1] + 3*x[2] <= 20;
10*x[1] + 15*x[2] <= 50;
```

is used in generating a model line.

Matrix reductions are switched off by default, but can be enabled by the command line argument `-gn`.

8.3 Equivalent transformations of Variable Products

A product of variables cannot be a part of an LP or MIP model, because such a variable product is a non-linear term. But if one factor of the product is an integer variable then it is possible to formulate an equivalent transformation using a set of specific linear inequations. [cf. Rogge/Steglich (2007)]

The automatic generation of an equivalent transformation of a variable product is a unique characteristic of CMPL.

8.3.1 Variable Products with at least one binary variable

A product of variables with at least one binary variable can be transformed equivalently in a system of linear inequations as follows (Rogge and Steglich 2007, p. 25ff.) :

$w := u \cdot v, \; \underline{u} \le u \le \bar{u} \;\; (u \text{ real or integer}), v \in \{0,1\}$
is equivalent to

u real or integer, $v \in \{0,1\}$ and
$\underline{u} \cdot v \le w \le \bar{u} \cdot v$
$\underline{u} \cdot (1-v) \le u - w \le \bar{u} \cdot (1-v)$

CMPL is able to perform these transformations automatically. For the following given variables

```
variables:  x: binary;
            y: real[YU..YO];
```

each occurrence of the term `x*y` in the CMPL model description is replaced by an implicit newly-defined variable `x_y`, and the following additional statements are generated automatically:

```
constraints:
      min(YU, 0) <= x_y <= max(YO, 0);
      {YU < 0: x_y - YU*x >= 0; }
      {YO > 0: x_y - YO*x <= 0; }
      y - x_y + YU*x >= YU;
      y - x_y + YO*x <= YO;
```

8.3.2 Variable Product with at least one integer variable

Also for products of variables with at least one integer variable it is possible to formulate an equivalent system of linear inequation [Rogge/Steglich (2007), p. 28ff.] :

$w := u \cdot v$,
$\underline{u} \le u \le \overline{u}$, ($u$ real or integer, if u integer then $\underline{v} - \overline{v} \le \underline{u} - \overline{u}$),
$\underline{v} \le v \le \overline{v}$ (v integer)
is equivalent to

u real or integer and

$$v = \underline{v} + \sum_{j=0}^{d} 2^j \cdot y_j,\ v \le \overline{v},\ \text{with } d = \lceil ld(\overline{v} - \underline{v} + 1) \rceil - 1$$

$$w = u \cdot \underline{v} + \sum_{j=0}^{d} 2^j \cdot w_j$$

$$\underline{u} \cdot y_j \le w_j \le \overline{u} \cdot y_j$$

$$\underline{u} \cdot (1 - y_j) \le u - w_j \le \overline{u} \cdot (1 - y_j)$$

$$y_j \in \{0,1\},\ j = 0(1)d$$

CMPL is able to perform these transformations automatically as described above. For the following given variables

```
variables:  x: integer[XU..XO];
            y: real[YU..YO];
```

each occurrence of the term `x*y` in the CMPL model description is replaced by an implicit newly-defined variable `x_y`, and the following additional statements are generated automatically (here `d` stands for the number of binary positions needed for `XO-XU+1`):

```
variables:
      _x[1..d]: binary;
      _x_y[1..d]: real;

constraints:
      min(XU*YU,XU*YO,XO*YU,XO*YO) <= x_y <= max(XU*YU,XU*YO,XO*YU,XO*YO);

      x = XU + sum{i=1(1)d: (2^(i-1))*_x[i]};
      x_y = XU*y + sum{i=1(1)d: (2^(i-1))*_x_y[i]};

      {i = 1(1)d:
            min(YU, 0) <= _x_y[i] <= max(YO, 0);
            {YU < 0: _x_y[i] - YU*_x[i] >= 0; }
            {YO > 0: _x_y[i] - YO*_x[i] <= 0; }
            y - _x_y[i] + YU*_x[i] >= YU;
            y - _x_y[i] + YO*_x[i] <= YO;
      }
```

9 CMPL as command line tool

9.1 Usage

The CMPL command line tool can be used in two modes. Using the solver mode, an LP or MIP can be formulated, solved and analysed. In this mode, OSSolverService, GLPK or Gurobi is invoked. In the model mode it is possible to transform the mathematical problem into MPS, Free-MPS or OSiL files that can be used by certain alternative LP or MIP solvers.

```
cmpl [<options>] <cmplFile>
```

Usage: cmpl [options] [<cmplFile>]

Model mode:

-i <cmplFile>	: input file
-data <cmplDataFile>	: reads a cmplDataFile
-m [<File>]	: export model in MPS format in a file or stdout
-fm [<File>]	: export model in Free-MPS format in a file or stdout
-x [<File>]	: export model in OSiL XML format in a file or stdout
-syntax	: checks the syntax of the CMPL model w/o generating of a MPS or OSiL file
-noOutput	: no generating of a MPS or OSiL file

Solver mode:

-solver <solver>	: name of the solver you want to use possible options: glpk, cbc, scip, gurobi, cplex
-solverUrl <url>	: URL of the solver service w/o a defined remote solver service, a local solver is used
-solution [<File>]	: optimization results in CmplSolution XML format
-solutionCsv [<File>]	: optimization results in CSV format
-solutionAscii [<File>]	: optimization results in ASCII format
-obj <objName>	: name of the objective function
-objSense <max/min>	: objective sense
-maxDecimals <x>	: maximal number of decimals in the solution report (max 12)
-zeroPrecision <x>	: Precision of zero values in the solution report (default 1e-9)
-ignoreZeros	: display only variables and constraints with non-zero values in the solution report

-dontRemoveTmpFiles : Don't remove temporary files (mps,osil,osrl,gsol)

-alias <alias> : uses an alias name for the cmpl model

General options:

-e [<File>] : output for error messages and warnings
-e simple output to stderr (default)
-e <File> output in CmplMessage XML format to file

-matrix [<File>] : Writes the generated matrix in a file or on stdout.

-l [<File>] : output for replacements for products of variables

-s [<File>] : short statistic info

-p [<File>] : output for protocol

-silent : suppresses CMPL and solver messages

-integerRelaxation : All integer variables are changed to continuous variables.

-gn : matrix reductions

-gf : Generated constraints for products of variables are included at the original position of the product.

-cd : warning at multiple parameter definition

-ci <x> : mode for integer expressions (0 - 3), (default 1)
If the result of an integer operation is outside the range of a long integer then the type of result will change from integer to real. This flag defines the integer range check behaviour.
-ci 0 no range check
-ci 1 default, range check with a type change if necessary
-ci 2 range check with error message if necessary
-ci 3 Each numerical operation returns a real result

-f% <format> : format option for MPS or OSiL files (C++ style - default %f)

-h : get this help

-v : version

Examples - solver mode:

`cmpl test.cmpl`	solves the problem `test.cmpl` locally with the default solver and displays a standard solution report
`cmpl -solver glpk test.cmpl`	solves the problem `test.cmpl` locally using GLPK and displays a standard solution report

`cmpl -solverUrl ↲`
`http://194.95.44.187:8080/ ↲`
`OSServer/services/OSSolverService ↲`
`test.cmpl`
	solves the problem `test.cmpl` remotely with the defined web service and displays a standard solution report

`cmpl -solutionCsv test.cmpl`	solves the problem `test.cmpl` locally with the default solver writes the solution in the CSV-file `test.csv` and displays a standard solution report
`cmpl "/Users/test/Documents/ ↲ Projects/Project 1/test.cmpl"`	If the file name or the path contains blanks then one can enclose the entire file name in double quotes.

Examples - model mode:

`cmpl -i test.cmpl -m test.mps`	reads the file `test.cmpl` and generates the MPS-file `test.mps`.
`cmpl -ff -i test.cmpl -m test.mps`	reads the file `test.cmpl` and generates the Free-MPS-file `test.mps`.
`cmpl -i test.cmpl -x test.osil`	reads the file `test.cmpl` and generates the OSiL-file `test.osil`.

9.2 Syntax checks

Syntax checks can be carried out with or without data.

If the parameters and sets are specified within the `parameter` section it is only necessary to use the command line argument `-syntax` or the CMPL header option `%arg -syntax`. The following CMPL model:

```
%arg -syntax
parameters:
      n := 1..2;
      m := 1..3;
      c[m] := ( 1, 2, 3 );
      b[n] := ( 15, 20 )
      A[m,n] := (( 5.6, 7.7, 10.5 ),( 9.8, 4.2, 11.1 ));
variables:
      x[m]: real[0..];
objectives:
      profit: c[]T * x[] -> max;
constraints:
      machine: A[,] * x[] <= b[];
```

causes the error message

```
CMPL model syntax check - running
error (compiler): file zzz.cmpl line 7: syntax error, unexpected SYMBOL_UNDEF, expecting ';'
error (compiler): file zzz.cmpl line 13: syntax error, unexpected SYMBOL_UNDEF
CMPL syntax check has finished with 2 error(s).
```

because the statement `b[n] := ( 15, 20 )` in line 6 has to be closed by a semicolon.

If a user wants to execute a syntax check without data then a CMPL header entry `%data` has to be defined including a complete specification of the sets and parameters that are necessary for the model. Please note the CMPL header option `%arg -syntax` has to be specified before the `%data` entry.

The following CMPL model:

```
%arg -syntax
%data datafile.cdat : n set, m set, c[m], b[n], A[m,n]

variables:
      x[m]: real[0..]
objectives:
      profit: c[]T * x[] -> max;
constraints:
      machine: A[,] * x[] <= b[];
```

causes the error message

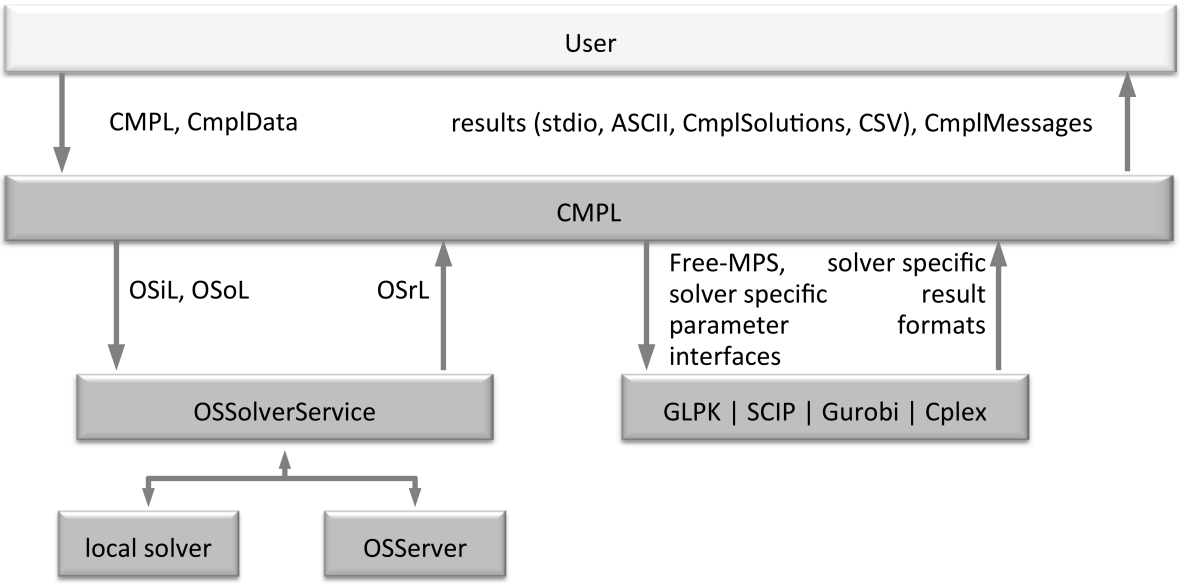
```
CMPL model syntax check - running
error (compiler): file zzz.cmpl line 6: syntax error, unexpected SECT_OBJ, expecting ';'
CMPL syntax check has finished with 1 error(s).
```

because the statement `x[m]: real[0..]` in line 5 has to be closed by a semicolon.

9.3 Input and output file formats

9.3.1 Overview

As shown in the picture below CMPL uses several ASCII files for the communication with the user and the solvers.



CMPL	input file for CMPL - syntax as described above
CmplData	specific data file format for CMPL - syntax as described above
MPS	output file for the generated model in MPS format Can be used with most solvers. This format is very restrictive and therefore not recommended.

Free-MPS	output file for the generated model in Free-MPS format Can be used with most solvers.
OSiL	output file for the generated model in OSiL format The OSiL XML schema is developed by the COIN-OR community (COmputational INfrastructure for Operations Research - open source for the operations research community). Can be used with solvers which are supported by the COIN-OR Optimization Services (OS) Framework.
OSoL	OSoL is an XML-based language for representing options that get passed to an optimization solver or a hosted optimization solver Web service. CMPL creates an OsoL file automatically if CBC is chosen and some CBC options are defined in the CMPL header.
OSrL	Optimization Services result Language OSrL (result) is a format for optimization results, if a COIN-OS solver is used.
GLPK plain text (result) format	GLPK can write the results of an optimization in the form of a plain text file. Only used if GLPK is chosen as solver.
CPLEX solution format	an XML based solution file format
SCIP solution format	a plain text file format for SCIP solutions
CmplSolutions	Solutions can be solved in CMPL's XML based solution file format
CmplMessages	a XML file containing the status and messages of a CMPL model

9.3.2 CMPL

A CMPL file is an ASCII file that includes the user-defined CMPL code with a syntax as described in this manual.

The example

$$1 \cdot x_1 + 2 \cdot x_2 + 3 \cdot x_3 \rightarrow max\ !$$
$$s.t.$$
$$5.6 \cdot x_1 + 7.7 \cdot x_2 + 10.5 \cdot x_3 \leq 15$$
$$9.8 \cdot x_1 + 4.2 \cdot x_2 + 11.1 \cdot x_3 \leq 20$$
$$0 \leq x_n \ \ ; n = 1(1)3$$

can be formulated in CMPL as follows:

```
%opt cbc threads 2

parameters:
      n := 1..2;
      m := 1..3;
      c[m] := ( 1, 2, 3 );
      b[n] := ( 15, 20 );
      A[n,m] := (( 5.6, 7.7, 10.5 ),( 9.8, 4.2, 11.1 ));
```

```
variables:
      x[m]: real[0..];
objectives:
      profit: c[]T * x[] -> max;
constraints:
      res: A[,] * x[] <= b[];
```

9.3.3 MPS

An MPS (Mathematical Programming System) file is a ASCII file for presenting linear programming (LP) and mixed integer programming problems.

MPS is an old format and was the de facto standard for most LP solvers. MPS is column-oriented and is set up for punch cards with defined positions for fields. Owing to these requirements the length of column or row names and the length of a data field are restricted. MPS is very restrictive and therefore not recommended. For more information please see http://en.wikipedia.org/wiki/MPS_(format).

The MPS file for the CMP example given in the section above is generated as follows:

```
* CMPL - MPS - Export
NAME          test.cmpl
ROWS
 N  profit
 L  res[1]
 L  res[2]
COLUMNS
    x[1]      profit               1   res[1]        5.600000
    x[1]      res[2]        9.800000
    x[2]      profit               2   res[1]        7.700000
    x[2]      res[2]        4.200000
    x[3]      profit               3   res[1]       10.500000
    x[3]      res[2]       11.100000
RHS
    RHS       res[1]              15   res[2]              20
RANGES
BOUNDS
 PL BOUND     x[1]
 PL BOUND     x[2]
 PL BOUND     x[3]
ENDATA
```

9.3.4 Free - MPS

The Free-MPS format is an improved version of the MPS format. There is no standard for this format but it is widely accepted. The structure of a Free-MPS file is the same as an MPS file. But most of the restricted MPS format requirements are eliminated, e.g. there are no requirements for the position or length of a field. For more information please visit the project website of the lp_solve project. [http://lpsolve.sourceforge.net]

The Free-MPS file for the given CMP example is generated as follows:

```
* CMPL - Free-MPS - Export
NAME          test.cmpl
ROWS
 N profit
 L res[1]
 L res[2]
COLUMNS
 x[1] profit 1 res[1] 5.600000
 x[1] res[2] 9.800000
 x[2] profit 2 res[1] 7.700000
 x[2] res[2] 4.200000
 x[3] profit 3 res[1] 10.500000
 x[3] res[2] 11.100000
RHS
 RHS res[1] 15 res[2] 20
RANGES
BOUNDS
 PL BOUND x[1]
 PL BOUND x[2]
 PL BOUND x[3]
ENDATA
```

9.3.5 OSiL

OSiL is an XML-based format which can be used for presenting linear programming (LP) and mixed integer programming problems. The OSiL XML schema was developed by the COIN-OR community (COmputational INfrastructure for Operations Research - open source for the operations research community). The format makes it very easy to save and present a model and so is particularly suitable for defining an interface to several solvers. An OSiL file can be used with solvers which are supported by the COIN-OR Optimization Services (OS) Framework. [cf. Gassmann, Ma, Martin, Sheng, 2011, p. 38ff.]

The OSiL file for the given CMP example is generated as follows:

```
<?xml version="1.0" encoding="UTF-8"?>
<osil xmlns="os.optimizationservices.org"
xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
xsi:schemaLocation="os.optimizationservices.org
http://www.optimizationservices.org/schemas/2.0/OSiL.xsd">
      <instanceHeader>
            <name>test.cmpl</name>
            <description>generated by CMPL</description>
      </instanceHeader>
      <instanceData>
            <variables numberOfVariables="3">
                  <var name="x[1]"  type="C" lb="0"/>
                  <var name="x[2]"  type="C" lb="0"/>
```

```
                <var name="x[3]"  type="C" lb="0"/>
            </variables>
            <objectives numberOfObjectives="1">
                <obj name="profit" maxOrMin="max" numberOfObjCoef="3">
                    <coef idx="0">1</coef>
                    <coef idx="1">2</coef>
                    <coef idx="2">3</coef>
                </obj>
            </objectives>
            <constraints numberOfConstraints="2">
                <con name="res[1]" ub="15"/>
                <con name="res[2]" ub="20"/>
            </constraints>
            <linearConstraintCoefficients numberOfValues="6">
                <start>
                    <el>0</el>
                    <el>2</el>
                    <el>4</el>
                    <el>6</el>
                </start>
                <rowIdx>
                    <el>0</el>
                    <el>1</el>
                    <el>0</el>
                    <el>1</el>
                    <el>0</el>
                    <el>1</el>
                </rowIdx>
                <value>
                    <el>5.600000</el>
                    <el>9.800000</el>
                    <el>7.700000</el>
                    <el>4.200000</el>
                    <el>10.500000</el>
                    <el>11.100000</el>
                </value>
            </linearConstraintCoefficients>
        </instanceData>
</osil>
```

9.3.6 OSoL

"OSoL is an XML-based language for representing options that get passed to an optimization solver or a hosted optimization solver Web service. For more information please visit the project website of COIN-OR OS project." [Gassmann/Ma/Martin/Sheng, 2011, p. 41ff.]

The following OSoL-file describes a parameter for the CBC solver if CBC would be chosen as solver.

```
<?xml version="1.0" encoding="UTF-8"?>
<osol xmlns="os.optimizationservices.org"
     xmlns:xs="http://www.w3.org/2001/XMLSchema"
     xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
     xsi:schemaLocation="os.optimizationservices.org
     http://www.optimizationservices.org/schemas/OSoL.xsd">
       <optimization>
          <solverOptions numberOfSolverOptions="1">
          <solverOption name="threads"  solver="cbc"  value="2"  />
       </solverOptions>
   </optimization>
</osol>
```

9.3.7 OSrL

"OSrL is an XML-based language for representing the solution of large-scale optimization problems including linear programs, mixed-integer programs, quadratic programs, and very general nonlinear programs." [Gassmann/Ma/Martin/Sheng, 2011, p. 39ff.]

The following OSrL-file contains the results of the given problem.

```
<?xml version="1.0" encoding="UTF-8"?><?xml-stylesheet type="text/xsl"
    href="http://www.coin-or.org/OS/stylesheets/OSrL.xslt"?>
<osrl xmlns="os.optimizationservices.org"
    xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
    xsi:schemaLocation="os.optimizationservices.org
    http://www.optimizationservices.org/schemas/2.0/OSrL.xsd" >
    <general>
      <generalStatus type="normal">
      </generalStatus>
      <serviceName>

      Optimization Services Solver
      Main Authors: Horand Gassmann, Jun Ma, and Kipp Martin
      Distributed under the Eclipse Public License
      OS Version: 2.6.0
      Build Date: May 25 2013
      SVN Version: 4605

      </serviceName>
      <instanceName>tt.cmpl</instanceName>
      <solverInvoked>COIN-OR clp</solverInvoked>
    </general>
    <job>
      <timingInformation numberOfTimes="1">
        <time type="elapsedTime" unit="second" category="total">
```

```
            4.6300000000000074e-4</time>
      </timingInformation>
    </job>
    <optimization numberOfSolutions="1" numberOfVariables="3"
      numberOfConstraints="2" numberOfObjectives="1">
      <solution targetObjectiveIdx="-1">
        <status type="optimal">
        </status>
        <variables numberOfOtherVariableResults="1">
            <values numberOfVar="3">
                <var idx="0">0</var>
                <var idx="1">0</var>
                <var idx="2">1.4285714285714284</var>
            </values>
            <basisStatus>
                <basic numberOfEl="1"><el>2</el></basic>
                <atLower numberOfEl="2"><el>0</el><el>1</el></atLower>
            </basisStatus>
            <other numberOfVar="3" name="reduced costs"
                description="the variable reduced costs">
                <var idx="0">-.5999999999999996</var>
                <var idx="1">-.20000000000000012</var>
                <var idx="2">-0</var>
          </other>
        </variables>
        <objectives >
          <values numberOfObj="1">
            <obj idx="-1">4.285714285714285</obj>
          </values>
        </objectives>
        <constraints >
          <dualValues numberOfCon="2">
            <con idx="0">.2857142857142857</con>
            <con idx="1">-0</con>
          </dualValues>
          <basisStatus>
            <basic numberOfEl="1"><el>1</el></basic>
            <atLower numberOfEl="1"><el>0</el></atLower>
          </basisStatus>
        </constraints>
      </solution>
    </optimization>
</osrl>
```

9.3.8 GLPK plain text (result) format

GLPK is able to write the solution of an optimization in the form of a plain text file in a specific structure. Please see for details [GLPK, 2011, p. 105ff.] Despite that Gurobi does not support this format CMPL uses this file format also for Gurobi because the interaction with Gurobi is established by a python script that is able to write the Gurobi optimization results in the GLPK plain text (result) format.

The following GLPK result file describes the solution of the example.

```
3 3
2 2 4.28571428571429
1 4.28571428571429 0
3 15 0.285714285714286
1 15.8571428571429 0
2 0 -0.6
2 0 -0.2
1 1.42857142857143 0
```

9.3.9 CPLEX solution file format

"CPLEX … writes solution files, formatted in XML, for all problem types, for all application programming interfaces (APIs). ... The XML solution file format makes it possible for you to display and view these solution files in most browsers as well as to pass the solution to XML-aware applications." [CPLEX manual → File formats supported by CPLEX → SOL file format: solution files]

CMPL is able to read the CMPL solution file.

The following CPLEX result file describes the solution of the example.

```
<?xml version = "1.0" encoding="UTF-8" standalone="yes"?>
<CPLEXSolution version="1.2">
 <header
   problemName="test.mps"
   objectiveValue="4.28571428571429"
   solutionTypeValue="1"
   solutionTypeString="basic"
   solutionStatusValue="1"
   solutionStatusString="optimal"
   solutionMethodString="dual"
   primalFeasible="1"
   dualFeasible="1"
   simplexIterations="1"
   writeLevel="1"/>
 <quality
   epRHS="1e-06"
   epOpt="1e-06"
   maxPrimalInfeas="0"
   maxDualInfeas="0"
   maxPrimalResidual="1.99840144432528e-15"
```

```
   maxDualResidual="0"
   maxX="1.42857142857143"
   maxPi="0.285714285714286"
   maxSlack="4.14285714285715"
   maxRedCost="0.6"
   kappa="3.83642857142857"/>
 <linearConstraints>
  <constraint name="machine_1" index="0" status="LL" slack="0"
    dual="0.285714285714286"/>
  <constraint name="machine_2" index="1" status="BS" slack="4.14285714285715"
    dual="-0"/>
 </linearConstraints>
 <variables>
  <variable name="x[1]" index="0" status="LL" value="0" reducedCost="-0.6"/>
  <variable name="x[2]" index="1" status="LL" value="0" reducedCost="-0.2"/>
  <variable name="x[3]" index="2" status="BS" value="1.42857142857143"
    reducedCost="-0"/>
 </variables>
</CPLEXSolution>
```

9.3.10 SCIP solution file format

SCIP writes the solution of the variables in the form of a plain text file in a specific structure. Because SCIP is only used for MIPs the result file format does not contain information about reduced costs or shadow prices.

The following SCIP result file describes the solution of the example if the variables defined as integers.

```
solution status: optimal solution found
objective value:                                  3
x[3]                                              1   (obj:3)
```

9.3.11 CmplSolutions

CmplSolutions is an XML-based format for representing the general status and the solution(s) if the problem is feasible and one or more solutions are found. An user can save it by using the command line argument `-solution [<File>]`.

The CmplSolutions file for the given CMP example is generated as follows:

```
<?xml version = "1.0" encoding="UTF-8" standalone="yes"?>
<CmplSolutions version="1.0">
   <general>
       <instanceName>/Users/mike/ttt.cmpl</instanceName>
       <nrOfVariables>3</nrOfVariables>
       <nrOfConstraints>2</nrOfConstraints>
       <objectiveName>profit</objectiveName>
       <objectiveSense>max</objectiveSense>
       <nrOfSolutions>1</nrOfSolutions>
```

```
        <solverName>COIN-OR clp</solverName>
        <variablesDisplayOptions>(all)</variablesDisplayOptions>
        <constraintsDisplayOptions>(all)</constraintsDisplayOptions>
    </general>
    <solution idx="1" status="optimal" value="4.28571">
        <variables>
            <variable idx="0" name="x[1]" type="C" activity="0"
                   lowerBound="0" upperBound="Infinity" marginal="-0.6"/>
            <variable idx="1" name="x[2]" type="C" activity="0"
                   lowerBound="0" upperBound="Infinity" marginal="-0.2"/>
            <variable idx="2" name="x[3]" type="C" activity="1.42857"
                   lowerBound="0" upperBound="Infinity" marginal="0"/>
        </variables>
        <linearConstraints>
            <constraint idx="0" name="res[1]" type="L" activity="15"
                   lowerBound="-Infinity" upperBound="15" marginal="0.285714"/>
             <constraint idx="1" name="res[2]" type="L" activity="15.8571"
                   lowerBound="-Infinity" upperBound="20" marginal="-"/>
        </linearConstraints>
    </solution>
</CmplSolutions>
```

9.3.12 CmplMessages

CmplMessages is an XML-based format for representing the general status and/or errors of the transformation of a CMPL model in one of the described output files. CmplMessages is intended for communication with other software that uses CMPL for modelling linear optimization problems.

An CmplMessages file consists of two major sections. The `<general>` section describes the general status and the name of the model and a general message after the transformation. The `<mplResult>` section consists of one or more messages about specific lines in the CMPL model.

After the transformation of the given CMPL model, CMPL will finish without errors. The general status is represented in the following MPrL file.

```
<?xml version="1.0" encoding="UTF-8"?>
<CmplMessages version="1.1">
        <general>
                <generalStatus>normal</generalStatus>
                <instanceName>test.cmpl</instanceName>
                <message>cmpl finished normal</message>
        </general>
</CmplMessages>
```

If a semicolon is not set in line 7, CMPL will finish with errors that are represented in the following MPrL file.

```
<?xml version="1.0" encoding="UTF-8"?>
<CmplMessages version="1.1">
        <general>
                <generalStatus>error</generalStatus>
                <instanceName>tt.cmpl</instanceName>
                <message>cmpl finished with errors</message>
        </general>
        <messages numberOfMessages="2">
           <message type ="error" file="tt.cmpl" line="8" description="syntax
error, unexpected SYMBOL_UNDEF, expecting &amp;apos;;&amp;apos;"/>
           <message type ="error" file="tt.cmpl" line="14" description="syntax
error, unexpected SYMBOL_UNDEF"/>
        </messages>
</CmplMessages>
```

The MPrL schema is defined as follows:

```
<?xml version="1.0" encoding="UTF-8"?>
<xsd:schema xmlns:xsd="http://www.w3.org/2001/XMLSchema" >
    <xsd:element name="CmplMessages">
      <xsd:complexType>
        <xsd:sequence>
          <xsd:element ref="general" minOccurs="1" maxOccurs="1"/>
          <xsd:element ref="cmplResult" minOccurs="0" maxOccurs="unbounded"/>
        </xsd:sequence>
      </xsd:complexType>
    </xsd:element>
    <xsd:element name="general">
      <xsd:complexType>
        <xsd:sequence>
          <xsd:element ref="generalStatus" minOccurs="1" maxOccurs="1"/>
          <xsd:element name="instanceName" type="xsd:string" minOccurs="1"
                maxOccurs="1"/>
          <xsd:element name="message" type="xsd:string" minOccurs="0"
                maxOccurs="unbounded"/>
        </xsd:sequence>
      </xsd:complexType>
    </xsd:element>
    <xsd:element name="generalStatus">
      <xsd:simpleType>
        <xsd:restriction base="xsd:string">
          <xsd:enumeration value="error"/>
          <xsd:enumeration value="warning"/>
          <xsd:enumeration value="normal"/>
        </xsd:restriction>
      </xsd:simpleType>
    </xsd:element>
```

```
    <xsd:element name="messages">
      <xsd:complexType>
        <xsd:sequence>
          <xsd:element ref="message" minOccurs="0" maxOccurs="unbounded"/>
        </xsd:sequence>
        <xsd:attribute name="numberOfMessages" type="xsd:nonNegativeInteger"
          use="required"/>
      </xsd:complexType>
    </xsd:element>
    <xsd:element name="message">
      <xsd:complexType>
        <xsd:attribute name="type" use="required">
          <xsd:simpleType>
            <xsd:restriction base="xsd:string">
                <xsd:enumeration value="error"/>
                <xsd:enumeration value="warning"/>
            </xsd:restriction>
          </xsd:simpleType>
        </xsd:attribute>
        <xsd:attribute name="file" type="xsd:string" use="required"/>
        <xsd:attribute name="line" type="xsd:nonNegativeInteger"
            use="required"/>
        <xsd:attribute name="description" type="xsd:string" use="required"/>
      </xsd:complexType>
    </xsd:element>
</xsd:schema>
```

9.4 Using CMPL with several solvers

There are two ways to interact with several solvers. It is recommended to use one of the solvers which are directly supported and executed by CMPL. The CMPL installation routine installs a customized version of the COIN-OR OSSolverService (including the COIN-OR solvers CLP, CBC and Symphony) and GLPK. OSSolverService is the default optimization environment. If you have installed Gurobi, CPLEX or SCIP then you can also use these solvers directly.

Because CMPL transforms a CMPL model into an MPS, a Free-MPS or an OSiL file, the generated model instance can be solved by using most of the free or commercial solvers.

9.4.1 COIN-OR OSSolverService

"The objective of Optimization Services (OS) is to provide a general framework consisting of a set of standards for representing optimization instances, results, solver options, and communication between clients and solvers in a distributed environment using Web Services. … A command line executable OSSolverService for

reading problem instances (OSiL format, AMPL nl format, MPS format) and calling a solver either locally or on a remote server." [Gassmann/Ma/Martin/Sheng, 2011, p. 4.]

For more information please visit https://projects.coin-or.org/OS.

The CMPL distribution contains the OSSolverService binary including the COIN-OR solvers CLP, CBC and Symphony. OSSolverService is the default solver environment for CMPL. It is possible but not necessary to specify which solver is to be used. The default solver for LPs is CLP and for MIPs CBC.

OSSolverService can be used in two modes:

```
cmpl <problem>.cmpl            #Solves the problem locally
                               #with Clp (LP) or CBC (MIP)
cmpl <problem>.cmpl ↲
-solverUrl http://<domain>:8080/OSServer/services/OSSolverService

                               #Solves the problem using
                               #OSServer located at <domain>
                               #with Clp (LP) or CBC (MIP)
```

For more information about the OSServer please visit the COIN-OS website: https://projects.coin-or.org/OS.

It is possible to use most of the CBC solver options within the CMPL header. Please see for a list of useful CBC parameters in Appendix 13.1.

Usage of CBC parameters within the CMPL header:

```
%opt cbc solverOption [solverOptionValue]
```

The user has to formulate the CMPL model. CMPL transforms the CMPL model into an OSiL file. If some CBC solver parameters are defined in the CMPL header, then CMPL generates an OSoL file. After generating the OSiL file (and if needed the OSoL file) CMPL executes OSSolverService directly as an external process. OSSolverService executes either a local solver or a remote solver. CMPL waits for the OSSolverService process. After finishing OSSolverService - and if no error occurs - the result file (OSrL) is to be read by CMPL. After that CMPL creates a standard report or exports the solver results in an ASCII or CSV file.

9.4.2 GLPK

The GLPK (GNU Linear Programming Kit) package is intended for solving large-scale linear programming (LP), mixed integer programming (MIP), and other related problems. "The GLPK package includes the program glpsol, which is a stand-alone LP/MIP solver. This program can be invoked from the command line ... to read LP/MIP problem data in any format supported by GLPK, solve the problem, and write the problem solution obtained to an output text file." [GLPK, 2011, p. 212.]. For more information please visit the GLPK project website: http://www.gnu.org/software/glpk.

The CMPL package contains GLPK and it can be used by the following command:

```
cmpl <problem>.cmpl -solver glpk
```

or by the CMPL header flag:

```
%arg -solver glpk
```

Most of the GLPK solver options can be used by defining solver options within the CMPL header. Please see Appendix 13.2 for a list of useful GLPK parameters.

Usage of GLPK parameters within the CMPL header:

```
%opt glpk solverOption [solverOptionValue]
```

9.4.3 Gurobi

"The Gurobi Optimizer is a state-of-the-art solver for linear programming (LP), quadratic programming (QP) and mixed-integer programming (MIP including MILP and MIQP). It was designed from the ground up to exploit modern multi-core processors. For solving LP and QP models, the Gurobi Optimizer includes high-performance implementations of the primal simplex method, the dual simplex method, and a parallel barrier solver. For MILP and MIQP models, the Gurobi Optimizer incorporates the latest methods including cutting planes and powerful solution heuristics." [www.gurobi.com]

If Gurobi is installed on the same computer as CMPL then Gurobi can be executed directly only by using the command

```
cmpl <problem>.cmpl -solver gurobi
```

or by the CMPL header flag:

```
%arg -solver gurobi
```

All Gurobi parameters (excluding NodefileDir, LogFile and ResultFile) described in the Gurobi manual can be used in the CMPL header.

Usage of Gurobi parameters within the CMPL header:

```
%opt gurobi solverOption [solverOptionValue]
```

9.4.4 SCIP

SCIP is a project of the Konrad-Zuse-Zentrum fuer Informationstechnik Berlin (ZIB).

"SCIP is a framework for Constraint Integer Programming oriented towards the needs of Mathematical Programming experts who want to have total control of the solution process and access detailed information down to the guts of the solver. SCIP can also be used as a pure MIP solver or as a framework for branch-cut-and-price. SCIP is implemented as C callable library and provides C++ wrapper classes for user plugins. It can also be used as a standalone program to solve mixed integer programs."
[http://scip.zib.de/whatis.shtml][Achterberg, 2009]

SCIP can be used only for mixed integer programming (MIP) problems. If SCIP is chosen as solver and the problem is an LP then CLP is executed as solver.

If SCIP is installed on the same computer as CMPL then SCIP can be connected to CMPL by changing the entry `ScipFileName` in the file `<cmplhome>/bin/cmpl.opt`.

Examples:

`ScipFileName = /Applications/Scip/scip`	The binary scip is located in the folder /Applications/Scip
`ScipFileName = /Program Files/Scip/scip.exe`	Example for a Windows system. Please keep in mind to use a slash as a path separator.

If this entry is correct then you can execute SCIP directly by using the command

```
cmpl <problem>.cmpl -solver scip
```

or by the CMPL header flag:

```
%arg -solver scip
```

All SCIP parameters described in the SCIP Doxygen Documentation can be used in the CMPL header.
Please see: http://scip.zib.de/doc/html/PARAMETERS.shtml

Usage SCIP parameters within the CMPL header:

```
%opt scip solverOption solverOptionValue
```

Please keep in mind, that in contrast to the SCIP Doxygen Documentation you do not have to use `=` as assignment operator between the *`solverOption`* and the *`solverOptionValue`*.

Examples:

`%opt scip branching/scorefunc p`	CMPL solver parameter description for `the parameter branching score function` which is described in the SCIP Doxygen Documentation as follows:
	`# branching score function ('s'um, 'p'roduct)`
	`# [type: char, range: {sp}, default: p]`
	`branching/scorefunc = p`

`%opt scip lp/checkfeas TRUE`	`# should LP solutions be checked, resolving LP when numerical troubles occur?`
	`# [type: bool, range: {TRUE,FALSE}, default: TRUE]`
	`lp/checkfeas = TRUE`

`%opt scip lp/fastmip 1`	`# which FASTMIP setting of LP solver should be used? 0: off, 1: low`
	`# [type: int, range: [0,1], default: 1]`
	`lp/fastmip = 1`

9.4.5 CPLEX

CPLEX is a part of the IBM ILOG CPLEX Optimization Studio and includes simplex, barrier, and mixed integer optimizers. "IBM ILOG CPLEX Optimization Studio provides the fastest way to build efficient optimization models and state-of-the-art applications for the full range of planning and scheduling problems. With its integrated development environment, descriptive modeling language and built-in tools, it supports the entire model development process." [IBM ILOG CPLEX Optimization Studio manual]

If CPLEX is installed on the same computer as CMPL then CPLEX can be connected to CMPL by changing the entry `CplexFileName` in the file `<cmplhome>/bin/cmpl.opt`.

Example:

`CplexFileName = /Applications/IBM/ILOG/ ↲`
`CPLEX_Studio_Academic124/cplex/ ↲`
`bin/x86-64_darwin9_gcc4.0/cplex`
	The cplex binary is located in the specified folder

Please note that for Windows installations you also have to use slashes as a path separators (instead of the usual backslashes). If this entry is correct then you can execute CPLEX directly by using the command

```
cmpl <problem>.cmpl -solver cplex
```

or by the CMPL header flag:

```
%arg -solver cplex
```

All CPLEX parameters described in the CPLEX manual (Parameters of CPLEX → Parameters Reference Manual) can be used in the CMPL header.

Usage CPLEX parameters within the CMPL header:

```
%opt cplex solverOption solverOptionValue
```

You have to use the parameters for the Interactive Optimizer. The names of sub-parameters of hierarchical parameters are to be separated by slashes.

Examples:

`%opt cplex threads 2`	Sets the default number of parallel threads that will be invoked.
`%opt cplex mip/limits/aggforcut 4`	Limits the number of constraints that can be aggregated for generating flow cover and mixed integer rounding (MIR) cuts to 4.
`%opt cplex ↲ simplex/tolerances/optimality ↲ 1e-8`	Sets the reduced-cost tolerance for optimality to 1e-8.

9.4.6 Other solvers

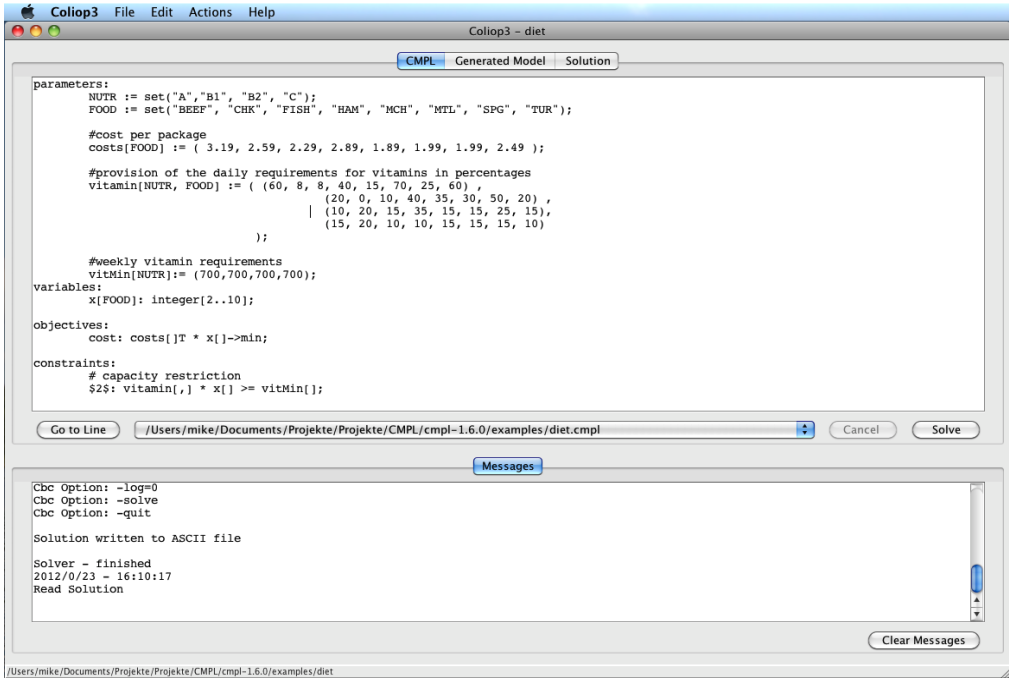
Since CMPL transforms a CMPL model into an MPS, a Free-MPS or an OSiL file, the model can be solved using most free or commercial solvers. To create MPS, Free-MPS or OSiL files please use the following commands:

```
cmpl -m <problemname>.mps <problemname>.cmpl          #MPS export
cmpl -fm <problemname>.mps <problemname>.cmpl         #Free-MPS export
cmpl -x <problemname>.osil <problemname>.cmpl         #OSiL export
```

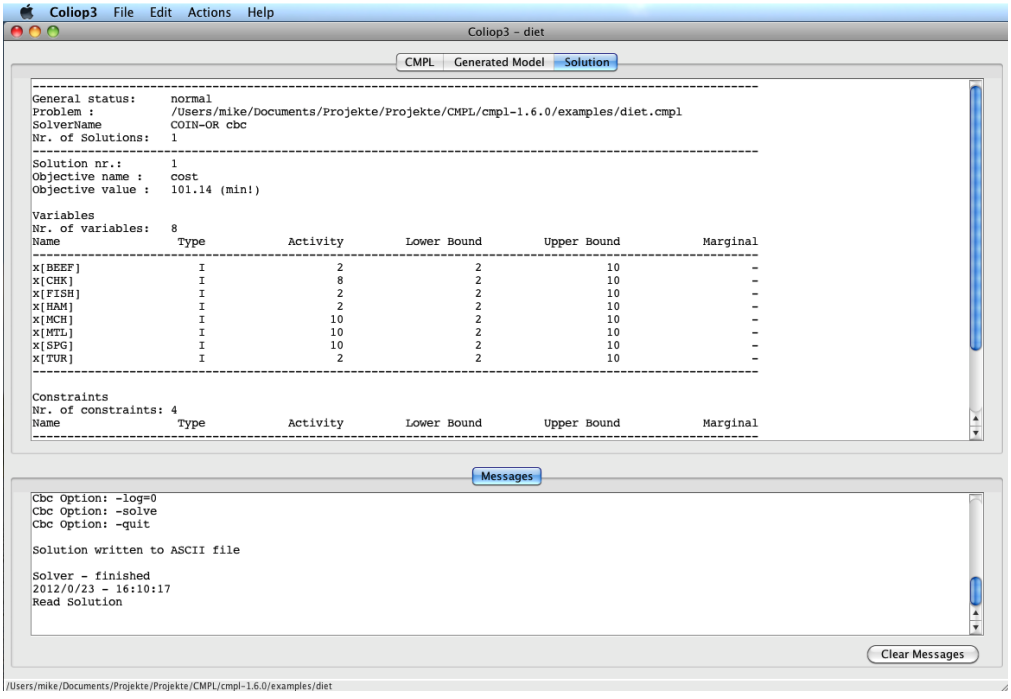
9.5 Using CMPL with Coliop

Coliop is an (simple) IDE (Integrated Development Environment) for CMPL intended to solve linear programming (LP) problems and mixed integer programming (MIP) problems. Coliop is a project of the Technical University of Applied Sciences Wildau and the Institute for Operations Research and Business Management at the Martin Luther University Halle-Wittenberg. Coliop is an open source project licensed under GPL. It is written in Java and is as an integral part of the CMPL distribution available for most of the relevant operating systems (OS X, Linux and Windows). Because Coliop is written in Java it is necessary to install the java runtime environment. Please visit to install java: http://java.com/de/download/index.jsp.

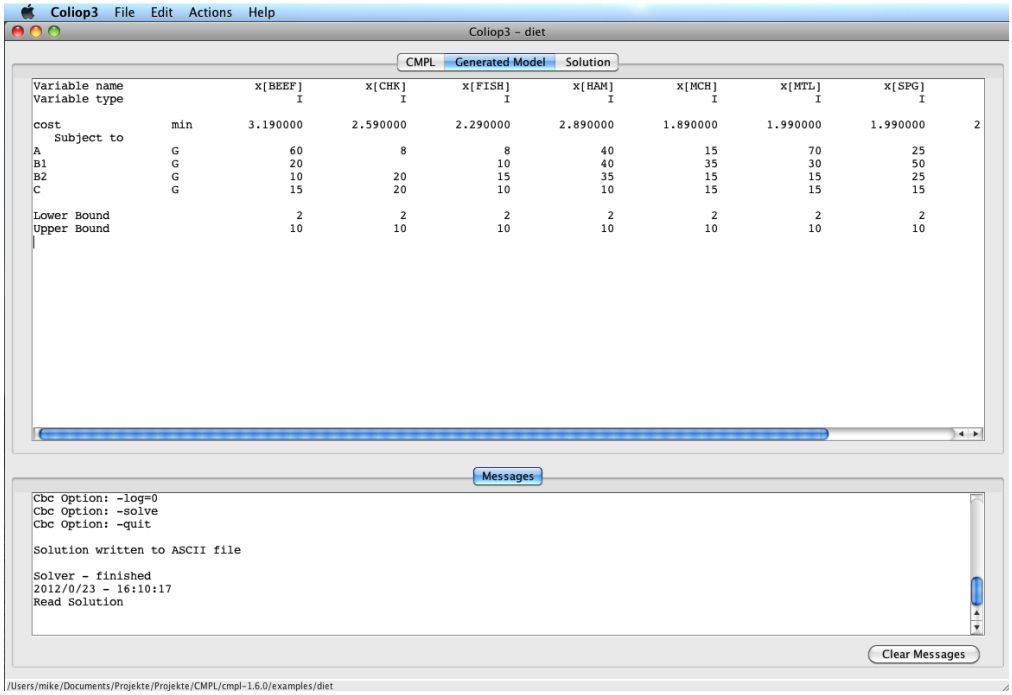
The first working step is to create or to open a CMPL model. By pushing the button <Solve> the model can be solved.



If a syntax error occurs then a user can analyse it by checking the CMPL messages. If CMPL is executed w/o any problems the standard solution report appears.



It is also possible to check the generated model matrix in the tab <Generated Model>.



10 Examples

10.1 Selected decision problems

10.1.1 The diet problem

The goal of the diet problem is to find the cheapest combination of foods that will satisfy all the daily nutritional requirements of a person for a week.

The following data is given (example cf. Fourer/Gay/Kernigham 2003, p. 27ff.) :

food	cost per package	provision of daily vitamin requirements in percentages			
		A	B1	B2	C
BEEF	3.19	60	20	10	15
CHK	2.59	8	2	20	520
FISH	2.29	8	10	15	10
HAM	2.89	40	40	35	10
MCH	1.89	15	35	15	15
MTL	1.99	70	30	15	15
SPG	1.99	25	50	25	15
TUR	2.49	60	20	15	10

The decision is to be made for one week. Therefore the combination of foods has to provide at least 700% of daily vitamin requirements. To promote variety, the weekly food plan must contain between 2 and 10 packages of each food.

The mathematical model can be formulated as follows:

$$3.19 \cdot x_{BEEF} + 2.59 \cdot x_{CHK} + 2.29 \cdot x_{FISH} + 2.89 \cdot x_{HAM} + 1.89 \cdot x_{MCH} + 1.99 \cdot x_{MTL} + 1.99\, x_{SPG} + 2.49 \cdot x_{TUR} \rightarrow min!$$

s.t.

$$60 \cdot x_{BEEF} + 8 \cdot x_{CHK} + 8 \cdot x_{FISH} + 40 \cdot x_{HAM} + 15 \cdot x_{MCH} + 70 \cdot x_{MTL} + 25\, x_{SPG} + 60 \cdot x_{TUR} \leq 700$$
$$20 \cdot x_{BEEF} + 0 \cdot x_{CHK} + 10 \cdot x_{FISH} + 40 \cdot x_{HAM} + 35 \cdot x_{MCH} + 30 \cdot x_{MTL} + 50\, x_{SPG} + 20 \cdot x_{TUR} \leq 700$$
$$10 \cdot x_{BEEF} + 20 \cdot x_{CHK} + 15 \cdot x_{FISH} + 35 \cdot x_{HAM} + 15 \cdot x_{MCH} + 15 \cdot x_{MTL} + 25\, x_{SPG} + 15 \cdot x_{TUR} \leq 700$$
$$15 \cdot x_{BEEF} + 20 \cdot x_{CHK} + 10 \cdot x_{FISH} + 10 \cdot x_{HAM} + 15 \cdot x_{MCH} + 15 \cdot x_{MTL} + 15\, x_{SPG} + 10 \cdot x_{TUR} \leq 700$$

$$x_j \in \{2,3,\ldots,10\} \quad ; j \in \{BEEF, CHK, DISH, HAM, MCH, MTL, SPG, TUR\}$$

The CMPL model `diet.cmpl` can be formulated as follows:

```
parameters:
      NUTR := set("A","B1", "B2", "C");
      FOOD := set("BEEF", "CHK", "FISH", "HAM", "MCH", "MTL", "SPG", "TUR");

      #cost per package
      costs[FOOD] := ( 3.19, 2.59, 2.29, 2.89, 1.89, 1.99, 1.99, 2.49 );
      #provision of the daily requirements for vitamins in percentages
      vitamin[NUTR, FOOD] := ( (60, 8, 8, 40, 15, 70, 25, 60) ,
                               (20, 0, 10, 40, 35, 30, 50, 20) ,
                               (10, 20, 15, 35, 15, 15, 25, 15),
                               (15, 20, 10, 10, 15, 15, 15, 10)
                             );

      #weekly vitamin requirements
      vitMin[NUTR]:= (700,700,700,700);

variables:
      x[FOOD]: integer[2..10];

objectives:
      cost: costs[]T * x[]->min;

constraints:
      # capacity restriction
      $2$: vitamin[,] * x[] >= vitMin[];
```

An alternative formulation is based on the cmplData file `diet-data.cdat` that is formulated as follows:

```
%NUTR set < A B1  B2  C >
%FOOD set < BEEF CHK FISH HAM MCH MTL SPG TUR   >

#cost per package
%costs[FOOD] < 3.19 2.59 2.29 2.89 1.89 1.99 1.99 2.49 >

#provision of the daily requirements for vitamins in percentages
%vitamin[NUTR,FOOD] <   60  8  8  40  15  70  25  60
                        20  0  10  40  35  30  50  20
                        10  20  15  35  15  15  25  15
                        15  20  10  10  15  15  15  10 >

#weekly vitamin requirements
%vitMin[NUTR]  < 700 700 700 700 >
```

Assuming that the corresponding CMPL file `diet-data.cmpl` is in the same working directory the model can be formulated as follows:

```
%data diet-data.cdat: FOOD set, NUTR set, costs[FOOD], vitamin[NUTR,FOOD], vit-
Min[NUTR]

variables:
      x[FOOD]: integer[2..10];

objectives:
      cost: costs[]T * x[]->min;

constraints:
      # capacity restriction
      $2$: vitamin[,] * x[] >= vitMin[];
```

Solving this CMPL model through using the command:

```
cmpl diet-data.cmpl
```

leads to the same solution as for the first formulation:

```
-----------------------------------------------------------------------------------------------------
Problem              diet.cmpl
Nr. of variables     8
Nr. of constraints   4
Objective name       cost
Solver name          COIN-OR cbc
-----------------------------------------------------------------------------------------------------

Objective status     optimal
Objective value      101.14 (min!)
```

```
Variables
Name                 Type            Activity        Lower bound        Upper bound            Marginal
-------------------------------------------------------------------------------------------------------
x[BEEF]                 I                   2                  2                 10                   -
x[CHK]                  I                   8                  2                 10                   -
x[FISH]                 I                   2                  2                 10                   -
x[HAM]                  I                   2                  2                 10                   -
x[MCH]                  I                  10                  2                 10                   -
x[MTL]                  I                  10                  2                 10                   -
x[SPG]                  I                  10                  2                 10                   -
x[TUR]                  I                   2                  2                 10                   -
-------------------------------------------------------------------------------------------------------

Constraints
Name                 Type            Activity        Lower bound        Upper bound            Marginal
-------------------------------------------------------------------------------------------------------
A                       G                1500                700           Infinity                   -
B1                      G                1330                700           Infinity                   -
B2                      G                 860                700           Infinity                   -
C                       G                 700                700           Infinity                   -
-------------------------------------------------------------------------------------------------------
```

10.1.2 Production mix

This model calculates the production mix that maximizes profit subject to available resources. It will identify the mix (number) of each product to produce and any remaining resource.

The example involves three products which are to be produced with two machines. The following data is given:

		P1	P2	P3	upper bounds [h]
upper bound of a product	[units]	250	240	250	
selling price per unit	[€/unit]	500	600	450	
direct costs per unit	[€/unit]	425	520	400	
profit contribution per unit	[€/unit]	75	80	50	
machine hours required per unit					
machine 1	[h/unit]	8	15	12	1,000
machine 2	[h/unit]	15	10	8	1,000

The mathematical model can be formulated as follows:

$$75 \cdot x_1 + 80 \cdot x_2 + 50 \cdot x_3 \rightarrow max\ !$$
$$s.t.$$
$$8 \cdot x_1 + 15 \cdot x_2 + 12 \cdot x_3 \leq 1{,}000$$
$$15 \cdot x_1 + 10 \cdot x_2 + 8 \cdot x_3 \leq 1{,}000$$

$$x_1 \in \{0,1,\ldots,250\}$$
$$x_2 \in \{0,1,\ldots,240\}$$
$$x_3 \in \{0,1,\ldots,250\}$$

The CMPL model `production-mix.cmpl` is formulated as follows:

```
%arg -solver glpk
parameters:
      products := 1..3;
      machines := 1..2;

      price[products] := (500, 600, 450 );
      costs[products] := (425, 520, 400);

      #machine hours required per unit
      a[machines,products] := ((8, 15, 12), (15, 10, 8));

      #upper bounds of the machines
      b[machines] := (1000, 1000);

      #profit contribution per unit
      {j in products:  c[j] := price[j]-costs[j]; }

      #upper bound of the products
      xMax[products] := (250, 240, 250 );

variables:
      x[products]: integer;

objectives:
      profit: c[]T  * x[] ->max;

constraints:
      res: a[,] * x[] <= b[];
      0<=x[]<=xMax[];
```

The model can be formulated alternatively by using the cmplData `prodmix-data.cdat` file.

```
%products set < 1..3 >
%machines set < 1..2 >

%price[products] <500 600 450 >
%costs[products] <425 520 400 >

#machine hours required per unit
%a[machines,products] < 8  15  12  15 10 8 >

#upper bounds of the machines
%b[machines] < 1000 1000 >
```

```
#lower and upper bound of the products
%xMax[products] < 250  240  250>
%xMin[products] < 45 45 45 >

#fixed setup costs
%FC[products] < 500 400 500>
```

The parameter arrays `xMin` and `FC` are not necessary for the given problem and therefore not specified within the `%data` options in the following CMPL file `prodmix-data.cdat`:

```
%arg -solver glpk
%data : products set, machines set, price[products], costs[products]
%data : a[machines,products], b[machines], xMax[products]

parameters:
      #profit contribution per unit
      {j in products:  c[j] := price[j]-costs[j]; }

variables:
      x[products]: integer;

objectives:
      profit: c[]T  * x[] ->max;

constraints:
      res: a[,] * x[] <= b[];
      0<=x[]<=xMax[];
```

The CMPL command

```
cmpl production-mix-data.cmpl
```

leads to the following Solution:

```
-------------------------------------------------------------------------------------------------------------
Problem              production-mix.cmpl
Nr. of variables     3
Nr. of constraints   2
Objective name       profit
Solver name          GLPK
-------------------------------------------------------------------------------------------------------------

Objective status     optimal
Objective value      6395 (max!)

Variables
Name                 Type           Activity        Lower bound        Upper bound           Marginal
-------------------------------------------------------------------------------------------------------------
x[1]                    I                 33                  0                250                  -
x[2]                    I                 49                  0                240                  -
x[3]                    I                  0                  0                250                  -
-------------------------------------------------------------------------------------------------------------

Constraints
Name                 Type           Activity        Lower bound        Upper bound           Marginal
-------------------------------------------------------------------------------------------------------------
res_1                   L                999          -Infinity               1000                  -
res_2                   L                985          -Infinity               1000                  -
-------------------------------------------------------------------------------------------------------------
```

10.1.3 Production mix including thresholds and step-wise fixed costs

This model calculates the production mix that maximizes profit subject to available resources. When a product is produced, there are fixed set-up costs. There is also a threshold for each product. The quantity of a product is zero or greater than the threshold.

The example involves three products which are to be produced with two machines. The following data is given:

		P1	P2	P3	upper bounds [h]
production minimum of a product	[units]	45	45	45	
upper bound of a product	[units]	250	240	250	
selling price per unit	[€/unit]	500	600	450	
direct costs per unit	[€/unit]	425	520	400	
profit contribution per unit	[€/unit]	75	80	50	
set-up costs	[€]	500	400	500	
machine hours required per unit					
machine 1	[h/unit]	8	15	12	1,000
machine 2	[h/unit]	15	10	8	1,000

The mathematical model can be formulated as follows:

$$75 \cdot x_1 + 80 \cdot x_2 + 50 \cdot x_3 - 500 \cdot y_1 - 400 \cdot y_2 - 500 \cdot y_3 \rightarrow max!$$

$$s.t.$$

$$8 \cdot x_1 + 15 \cdot x_2 + 12 \cdot x_3 \leq 1{,}000$$

$$15 \cdot x_1 + 10 \cdot x_2 + 8 \cdot x_3 \leq 1{,}000$$

$$45 \cdot y_1 \leq x_1 \leq 250 \cdot y_1$$

$$45 \cdot y_2 \leq x_2 \leq 240 \cdot y_2$$

$$45 \cdot y_3 \leq x_3 \leq 250 \cdot y_3$$

$$x_1 \in \{0,1,\ldots,250\}$$

$$x_2 \in \{0,1,\ldots,240\}$$

$$x_3 \in \{0,1,\ldots,250\}$$

$$y_j \in \{0,1\} \quad ; j = 1(1)3$$

The CMPL model `production-mix-fixed-costs.cmpl` is formulated as follows:

```
%data production-mix-data.cdat

parameters:
      #profit contribution per unit
      {j in products:  c[j] := price[j]-costs[j]; }
```

```
variables:
      {j in products : x[j]: integer[0..xMax[j]]; }
      y[products] : binary;

objectives:
      profit: c[]T  * x[] - FC[]T * y[] ->max;

constraints:
      res: a[,] * x[] <= b[];
      bounds {j in products: xMin[j] * y[j] <= x[j] <= xMax[j] * y[j]; }
```

CMPL command:

```
cmpl production-mix-fixed-costs.cmpl
```

Solution:

```
-------------------------------------------------------------------------------------------------------------
Problem              production-mix-fixed-costs.cmpl
Nr. of variables     6
Nr. of constraints   8
Objective name       profit
Solver name          COIN-OR cbc
-------------------------------------------------------------------------------------------------------------

Objective status     optimal
Objective value      4880 (max!)

Variables
Name                 Type            Activity        Lower bound        Upper bound            Marginal
-------------------------------------------------------------------------------------------------------------
x[1]                    I                   0                  0                250                   -
x[2]                    I                  66                  0                240                   -
x[3]                    I                   0                  0                250                   -
y[1]                    B                   0                  0                  1                   -
y[2]                    B                   1                  0                  1                   -
y[3]                    B                   0                  0                  1                   -
-------------------------------------------------------------------------------------------------------------

Constraints
Name                 Type            Activity        Lower bound        Upper bound            Marginal
-------------------------------------------------------------------------------------------------------------
res_1                   L                 990          -Infinity               1000                   -
res_2                   L                 660          -Infinity               1000                   -
bounds_1_1              L                   0          -Infinity                  0                   -
bounds_1_2              L                   0          -Infinity                  0                   -
bounds_2_1              L                 -21          -Infinity                  0                   -
bounds_2_2              L                -174          -Infinity                  0                   -
bounds_3_1              L                   0          -Infinity                  0                   -
bounds_3_2              L                   0          -Infinity                  0                   -
-------------------------------------------------------------------------------------------------------------
```

10.1.4 The knapsack problem

Given a set of items with specified weights and values, the problem is to find a combination of items that fills a knapsack (container, room, …) to maximize the value of the knapsack subject to its restricted capacity or to minimize the weight of items in the knapsack subject to a predefined minimum value.

In this example there are 10 boxes, which can be sold on the market at a defined price.

box number	weight [pounds]	price [€/box]
1	100	10
2	80	5
3	50	8
4	150	11
5	55	12
6	20	4
7	40	6
8	50	9
9	200	10
10	100	11

1. What is the optimal combination of boxes if you are seeking to maximize the total sales and are able to carry a maximum of 60 pounds?
2. What is the optimal combination of boxes if you are seeking to minimize the weight of the transported boxes bearing in mind that the minimum total sales must be at least €600 ?

Model 1: maximize the total sales

The mathematical model can be formulated as follows:

$$100 \cdot x_1 + 80 \cdot x_2 + 50 \cdot x_3 + 150 \cdot x_4 + 55 \cdot x_5 + 20 \cdot x_6 + 40 \cdot x_7 + 50 \cdot x_8 + 200 \cdot x_9 + 100 \cdot x_{10} \rightarrow max!$$

$$s.t.$$

$$10 \cdot x_1 + 5 \cdot x_2 + 8 \cdot x_3 + 11 \cdot x_4 + 12 \cdot x_5 + 4 \cdot x_6 + 6 \cdot x_7 + 9 \cdot x_8 + 10 \cdot x_9 + 11 \cdot x_{10} \leq 60$$

$$x_j \in \{0,1\} \quad ; j = 1(1)10$$

The basic data is saved in the CMPL file `knapsack-data.cdat`:

```
%boxes set < 1(1)10 >

#weight of the boxes
%w[boxes] < 10 5 8 11 12 4 6 9 10 11 >

#price per box
%p[boxes] <100 80 50 150 55 20 40 50 200 100 >

#max capacity
%maxWeight <60>

#min sales
%minSales <600>
```

A simple CMPL model `knapsack-max-basic.cmpl` can be formulated as follows:

```
%data knapsack-data.cdat : boxes set, w[boxes], p[boxes], maxWeight, minSales
%display nonZeros

variables:
      x[boxes] : binary;
objectives:
      sales: p[]T * x[] ->max;
constraints:
      weight: w[]T * x[] <= maxWeight;
```

CMPL command:

```
cmpl  knapsack-max-basic.cmpl
```

Solution:

```
--------------------------------------------------------------------------------------------------------------
Problem             knapsack-max-basic.cmpl
Nr. of variables    10
Nr. of constraints  1
Objective name      sales
Solver name         COIN-OR cbc
--------------------------------------------------------------------------------------------------------------

Objective status    optimal
Objective value     700 (max!)

Nonzero variables
Name                Type            Activity         Lower bound         Upper bound            Marginal
--------------------------------------------------------------------------------------------------------------
x[1]                   B                   1                   0                   1                   -
x[2]                   B                   1                   0                   1                   -
x[4]                   B                   1                   0                   1                   -
x[6]                   B                   1                   0                   1                   -
x[8]                   B                   1                   0                   1                   -
x[9]                   B                   1                   0                   1                   -
x[10]                  B                   1                   0                   1                   -
--------------------------------------------------------------------------------------------------------------

Nonzero constraints
Name                Type            Activity         Lower bound         Upper bound            Marginal
--------------------------------------------------------------------------------------------------------------
weight                 L                  60           -Infinity                  60                   -
--------------------------------------------------------------------------------------------------------------
```

Model 2: minimize the weight

The mathematical model can be formulated as follows:

$$10 \cdot x_1 + 5 \cdot x_2 + 8 \cdot x_3 + 11 \cdot x_4 + 12 \cdot x_5 + 4 \cdot x_6 + 6 \cdot x_7 + 9 \cdot x_8 + 10 \cdot x_9 + 11 \cdot x_{10} \rightarrow min!$$

$$s.t.$$

$$100 \cdot x_1 + 80 \cdot x_2 + 50 \cdot x_3 + 150 \cdot x_4 + 55 \cdot x_5 + 20 \cdot x_6 + 40 \cdot x_7 + 50 \cdot x_8 + 200 \cdot x_9 + 100 \cdot x_{10} \geq 600$$

$$x_j \in \{0,1\} \quad ; j = 1(1)10$$

A simple CMPL model `knapsack-min-basic.cmpl` can be formulated as follows:

```
%data knapsack-data.cdat
%display nonZeros

variables:
      x[boxes] : binary;
objectives:
      weight: w[]T * x[] ->min;
constraints:
      sales: p[]T * x[] >= minSales;
```

CMPL command:

```
cmpl  knapsack-min-basic.cmpl
```

Solution:

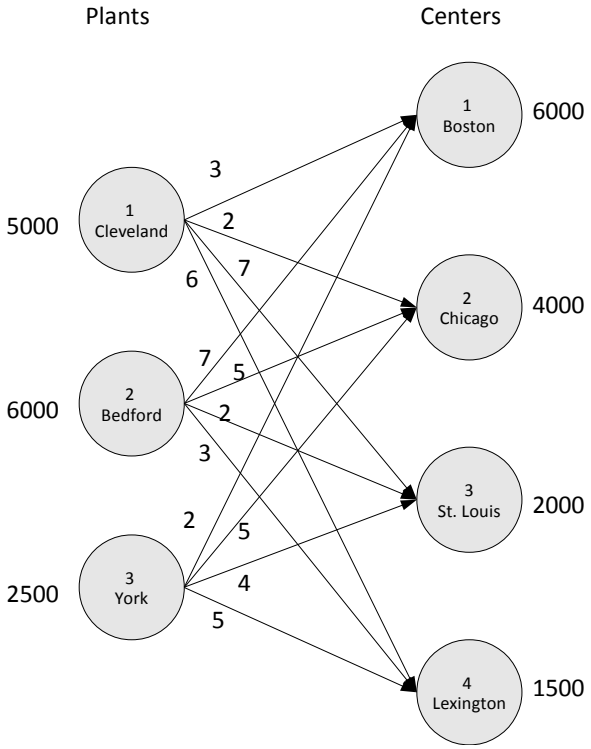
```
--------------------------------------------------------------------------------------------------------
Problem              knapsack-min-basic.cmpl
Nr. of variables     10
Nr. of constraints   1
Objective name       weight
Solver name          COIN-OR cbc
--------------------------------------------------------------------------------------------------------

Objective status     optimal
Objective value      47 (min!)

Nonzero variables
Name                 Type            Activity         Lower bound         Upper bound            Marginal
--------------------------------------------------------------------------------------------------------
x[1]                    B                   1                   0                   1                   -
x[2]                    B                   1                   0                   1                   -
x[4]                    B                   1                   0                   1                   -
x[9]                    B                   1                   0                   1                   -
x[10]                   B                   1                   0                   1                   -
--------------------------------------------------------------------------------------------------------

Nonzero constraints
Name                 Type            Activity         Lower bound         Upper bound            Marginal
--------------------------------------------------------------------------------------------------------
sales                   G                 630                 600            Infinity                   -
--------------------------------------------------------------------------------------------------------
```

10.1.5 Transportation problem using 1-tuple sets

A transportation problem is a special kind of linear programming problem which seeks to minimize the total shipping costs of transporting goods from several supply locations (origins or sources) to several demand locations (destinations).

The following example is taken from (Anderson/Sweeney/Williams/Martin, 2008, p. 261ff). This problem involves the transportation of a product from three plants to four distribution centers. Foster Generators operates plants in Cleveland, Ohio; Bedford, Indiana; and York, Pennsylvania. The supplies are defined by the production capacities over the next three-month planning period for one particular type of generator.

The company distributes its generators through four regional distribution centers located in Boston, Chicago, St. Louis, and Lexington. It is to decide how much of its products should be shipped from each plant to each distribution center. The objective is to minimize the transportation costs.



The problem can be formulated in the form of the general linear program below:

$$\sum_{i=1}^{m}\sum_{j=1}^{n} c_{ij} \cdot x_{ij} \quad \rightarrow \min!$$

$$s.t.$$

$$\sum_{j=1}^{n} x_{ij} = s_i \qquad ; i = 1(1)m$$

$$\sum_{i=1}^{m} x_{ij} = d_j \qquad ; j = 1(1)n$$

$$x_{ij} \geq 0 \qquad ; i = 1(1)m\,,\, j = 1(1)n$$

x_{ij} – number of units shipped from plant i to center j
c_{ij} – cost per unit of shipping from plant i to center j
s_i – supply in units at plant i
d_j – demand in units at desitination j

The CMPL model `transportation.cmpl` can be formulated as follows:

```
%display nonZeros

parameters:
      plants  := 1(1)3;
      centers := 1(1)4;
```

```
      s[plants]  := (5000,6000,2500);
      d[centers] := (6000,4000,2000,1500);
      c[plants,centers] := ( (3,2,7,6), (7,5,2,3),(2,5,4,5) );

variables:
      x[plants,centers]: real[0..];

objectives:
      costs: sum{i in plants, j in centers : c[i,j] * x[i,j] } ->min;

constraints:
      supplies {i in plants  : sum{j in centers: x[i,j]} = s[i];}
      demands  {j in centers : sum{i in plants : x[i,j]} =  d[j];}
```

or by using an additional cmplData file `transportation-data.cdat`

```
%plants set < 1..3 >
%centers set < 1..4 >

%s[plants] <  5000 6000 2500 >
%d[centers] < 6000 4000 2000 1500 >

%c[plants, centers]  <  3 2 7 6
                        7 5 2 3
                        2 5 4 5 >
```

and the coresponding CMPL model:

```
%data transportation-data.cdat
%display nonZeros

variables:
      x[plants,centers]: real[0..];

objectives:
      costs: sum{i in plants, j in centers : c[i,j] * x[i,j] } ->min;

constraints:
      supplies {i in plants  : sum{j in centers: x[i,j]} = s[i];}
      demands  {j in centers : sum{i in plants : x[i,j]} =  d[j];}
```

CMPL command:

```
cmpl  transportation.cmpl
```

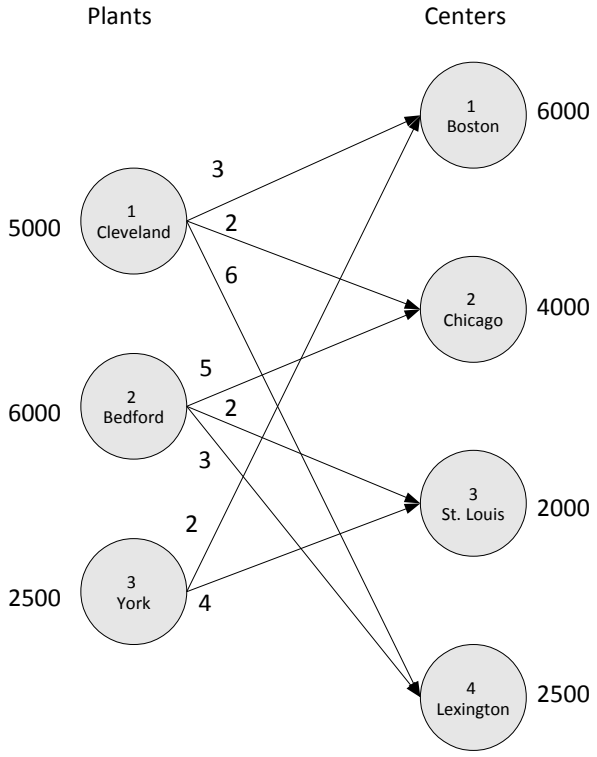
Solution:

```
-----------------------------------------------------------------------------------------------------
Problem             transportation.cmpl
Nr. of variables    12
Nr. of constraints  7
```

```
Objective name       costs
Solver name          COIN-OR clp
-----------------------------------------------------------------------------------------------------
Objective status     optimal
Objective value      39500 (min!)

Nonzero variables
Name                 Type            Activity        Lower bound        Upper bound            Marginal
-----------------------------------------------------------------------------------------------------
x[1,1]                  C                3500                  0           Infinity                   0
x[1,2]                  C                1500                  0           Infinity                   0
x[2,2]                  C                2500                  0           Infinity                   0
x[2,3]                  C                2000                  0           Infinity                   0
x[2,4]                  C                1500                  0           Infinity                   0
x[3,1]                  C                2500                  0           Infinity                   0
-----------------------------------------------------------------------------------------------------

Nonzero constraints
Name                 Type            Activity        Lower bound        Upper bound            Marginal
-----------------------------------------------------------------------------------------------------
supplies_1              E                5000                5000               5000                   1
supplies_2              E                6000                6000               6000                   4
supplies_3              E                2500                2500               2500                   -
demands_1               E                6000                6000               6000                   2
demands_2               E                4000                4000               4000                   1
demands_3               E                2000                2000               2000                  -2
demands_4               E                1500                1500               1500                  -1
-----------------------------------------------------------------------------------------------------
```

10.1.6 Transportation problem using multidimensional sets (2-tuple sets)

In the case that not all of the connections are possible for technological or commercial reasons (e.g. as in the picture below) then an alternative model to the model above has to be formulated. Additionally is assumed that the total demand is greater than the supplies.



The mathematical model is based on the 2-tuple set routes that contains only the valid connections between the plants and the centers.

$$\sum_{(i,j)\in routes} c_{ij}\cdot x_{ij} \qquad \rightarrow \min!$$

$$s.t.$$

$$\sum_{\substack{(k,j)\in routes \\ k=i}} x_{kj} = s_i \qquad ; i=1(1)m$$

$$\sum_{\substack{(i,l)\in routes \\ l=j}} x_{il} \le d_j \qquad ; j=1(1)n$$

$$x_{ij} \ge 0 \qquad ;(i,j)\in routes$$

Die sets and parameters are specified in `transportation-tuple-data.cdat`

```
%routes  set[2]  <      1 1
                        1 2
                        1 4
                        2 2 2 3 2 4
                        3 1 3 3  >
%plants  set < 1(1)3 >
%centers  set < 1..4 >


%s[plants] <  5000 6000 2500 >
%d[centers] < 6000 4000 2000 2500 >
%c[routes]  < 3  2  6  5  2  3  2  4 >
```

that is connected to the CMPL model `transportation-tuple-data.cmpl`:

```
%data : plants set, centers set[1], routes set[2]
%data : c[routes] , s[plants] , d[centers]
%display nonZeros

variables:
   x[routes]: real[0..];
objectives:
   costs: sum{ [i,j] in routes : c[i,j]*x[i,j] } ->min;
constraints:
   supplies {i in plants : sum{j in routes *> [i,*] : x[i,j]} = s[i];}
   demands  {j in centers: sum{i in routes *> [*,j] : x[i,j]} <= d[j];}
```

Solution:

```
-------------------------------------------------------------------------------------------------------------
Problem              transportation-tuple-data.cmpl
Nr. of variables     8
Nr. of constraints   7
Objective name       costs
Solver name          COIN-OR clp
-------------------------------------------------------------------------------------------------------------

Objective status     optimal
Objective value      36500 (min!)

Nonzero variables
Name                 Type            Activity         Lower bound         Upper bound            Marginal
-------------------------------------------------------------------------------------------------------------
x[1,1]                  C                2500                   0            Infinity                   0
x[1,2]                  C                2500                   0            Infinity                   0
x[2,2]                  C                1500                   0            Infinity                   0
x[2,3]                  C                2000                   0            Infinity                   0
x[2,4]                  C                2500                   0            Infinity                   0
x[3,1]                  C                2500                   0            Infinity                   0
-------------------------------------------------------------------------------------------------------------

Nonzero constraints
Name                 Type            Activity         Lower bound         Upper bound            Marginal
-------------------------------------------------------------------------------------------------------------
supplies_1              E                5000                5000                5000                   3
supplies_2              E                6000                6000                6000                   6
supplies_3              E                2500                2500                2500                   2
demands_1               L                5000           -Infinity                6000                   -
demands_2               L                4000           -Infinity                4000                  -1
demands_3               L                2000           -Infinity                2000                  -4
demands_4               L                2500           -Infinity                2500                  -3
-------------------------------------------------------------------------------------------------------------
```

10.1.7 Quadratic assignment problem

Assignment problems are special types of linear programming problems which assign assignees to tasks or locations. The goal of this quadratic assignment problem is to find the cheapest assignments of *n* machines to *n* locations. The transport costs are influenced by

- the distance d_{jk} between location *j* and location *k* and
- the quantity t_{hi} between machine h and machine i, which is to be transported.

The assignment of a machine *h* to a location *j* can be formulated with the Boolean variables

$$x_{hj} = \begin{cases} 1 \text{ , if machine } h \text{ is assigned to location } j \\ 0 \text{ , if not} \end{cases}$$

The general model can be formulated as follows:

$$\sum_{h=1}^{n}\sum_{\substack{i=1\\ i\neq h}}^{n}\sum_{j=1}^{n}\sum_{\substack{k=1\\ i\neq j}}^{n} t_{hi}\cdot d_{jk}\cdot x_{hj}\cdot x_{ik}\rightarrow min!$$

$$s.t.$$

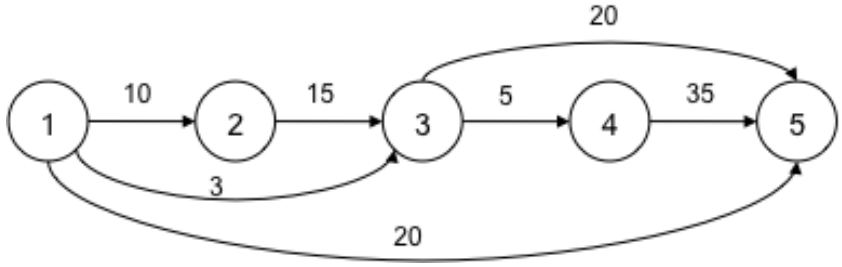
$$\sum_{j=1}^{n} x_{hj}=1 \quad ;h=1(1)n$$

$$\sum_{h=1}^{n} x_{hj}=1 \quad ;j=1(1)n$$

$$x_{hj}\in\{0,1\} \quad ;h=1(1)n\,,\,j=1(1)n$$

Because of the product $x_{hj}\cdot x_{ik}$ in the objective function the model is not a linear model. But it is possible to use a set of inequations to make an equivalent transformation of such multiplications of variables. This transformation is implemented in CMPL and the set of inequations will be generated automatically.

Consider the following case: There are 5 machines and 5 locations in the given factory. The quantities of goods which are to be transported between the machines are indicated in the figure below.



The distances between the locations are given in the following table:

from/to	1	2	3	4	5
1	M	1	2	3	4
2	2	M	1	2	3
3	3	1	M	1	2
4	2	3	1	M	1
5	5	3	2	1	M

The CMPL model `quadratic-assignment.cmpl` can be formulated as follows:

```
%arg -solver cplex
%arg -ignoreZeros
%display var x[*

parameters:
      n:=5;
      M:=1000;
```

```
      d[,]:= (    ( M, 1, 2, 3, 4),
                  ( 2, M, 1, 2, 3),
                  ( 3, 1, M, 1, 2),
                  ( 2, 3, 1, M, 1),
                  ( 5, 3, 1, 1, M) );

      t[,]:= (    ( 0, 10, 10, 0, 20),
                  ( 0, 0,  15, 0, 0 ),
                  ( 0, 0,  0,  5, 20),
                  ( 0, 0,  0,  0, 35),
                  ( 0, 0,  0,  0, 0 ) );
variables:
      x[1..n,1..n]: binary;
      #dummy variables to store the products x_hj * x_ik
      w[1..n,1..n,1..n,1..n]: real[0..1];

objectives:
      costs: sum{  h:=1(1)n, i:=1(1)n, j:=1(1)n, k:=1(1)n :
                  t[h,i]*d[j,k]*w[h,j,i,k] } ->min;
constraints:
      { h:=1(1)n, i:=1(1)n, j:=1(1)n, k:=1(1)n:
                  { t[h,i] = 0:  w[h,j,i,k] = 0; |
                    # definition of the products x_hj * x_ik
                    default: w[h,j,i,k] = x[h,j] * x[i,k]; }
      }
      sos1 { h:=1(1)n: sum{ j:=1(1)n: x[h,j] } = 1; }
      sos2 { j:=1(1)n: sum{ h:=1(1)n: x[h,j] } = 1; }
```

CMPL command:

```
cmpl  quadratic-assignment.cmpl
```

Solution:

```
-----------------------------------------------------------------------------------------------------------
Problem              quadratic-assignment.cmpl
Nr. of variables     375
Nr. of constraints   710
Objective name       costs
Solver name          COIN-OR cbc
-----------------------------------------------------------------------------------------------------------

Objective status     optimal
Objective value      155 (min!)

Nonzero variables (x[*)
Name                 Type           Activity        Lower bound        Upper bound           Marginal
-----------------------------------------------------------------------------------------------------------
x[1,4]                  B                  1                  0                  1                  -
x[2,1]                  B                  1                  0                  1                  -
x[3,2]                  B                  1                  0                  1                  -
x[4,5]                  B                  1                  0                  1                  -
x[5,3]                  B                  1                  0                  1                  -
-----------------------------------------------------------------------------------------------------------
```

The optimal assignments of machines to locations are given in the the table below:

machines \ locations	1	2	3	4	5
1				x	
2	x				
3		x			
4					x
5			x		

10.1.8 Quadratic assignment problem using the solutionPool option

It is for several reasons interesting to catch the feasible integer solutions found during a MIP optimization. Gurobi and Cplex are able to generate and store multiple solutions to a mixed integer programming (MIP) problem. With the display option `solutionPool` these feasible integer solutions can be shown in the solution report. It is recommended to control the behaviour of the solution pool by setting the particular Gurobi or Cplex solver options.

If the CMPL model for quadratic assignment problem above is extended by the following CMPL header entries, then all feasible integer solutions found by Cplex with an objective function value that is maximally 10% less than the incumbent solution.

```
%display solutionPool
%opt cplex mip/pool/relgap 0.1
```

Solution:

```
-------------------------------------------------------------------------------------------------------------
Problem              quadratic-assignment.cmpl
Nr. of variables     375
Nr. of constraints   710
Objective name       costs
Nr. of solutions     3
Solver name          CPLEX
-------------------------------------------------------------------------------------------------------------

Solution nr.         1
Objective status     integer optimal solution
Objective value      155 (min!)

Nonzero variables (x[*)
Name                 Type            Activity         Lower bound         Upper bound            Marginal
-------------------------------------------------------------------------------------------------------------
x[1,4]                  B                   1                   0                   1                   -
x[2,1]                  B                   1                   0                   1                   -
x[3,2]                  B                   1                   0                   1                   -
x[4,5]                  B                   1                   0                   1                   -
x[5,3]                  B                   1                   0                   1                   -
-------------------------------------------------------------------------------------------------------------

Solution nr.         2
Objective status     integer feasible solution
Objective value      155 (min!)
```

```
Nonzero variables (x[*)
Name                 Type            Activity         Lower bound         Upper bound            Marginal
---------------------------------------------------------------------------------------------------------
x[1,4]                  B                   1                   0                   1                   -
x[2,1]                  B                   1                   0                   1                   -
x[3,2]                  B                   1                   0                   1                   -
x[4,5]                  B                   1                   0                   1                   -
x[5,3]                  B                   1                   0                   1                   -
---------------------------------------------------------------------------------------------------------

Solution nr.         3
Objective status     integer feasible solution
Objective value      165 (min!)

Nonzero variables (x[*)
Name                 Type            Activity         Lower bound         Upper bound            Marginal
---------------------------------------------------------------------------------------------------------
x[1,2]                  B                   1                   0                   1                   -
x[2,1]                  B                   1                   0                   1                   -
x[3,3]                  B                   1                   0                   1                   -
x[4,5]                  B                   1                   0                   1                   -
x[5,4]                  B                   1                   0                   1                   -
---------------------------------------------------------------------------------------------------------
```

10.1.9 Generic travelling salesman problem

The travelling salesman problem is well known and often described. In the following CMPL model the (x,y) coordinates of the cities are defined by random numbers and the distances are calculated by the euclidian distance of the (x.y) coordinates. The CMPL model `tsp.cmpl` can be formulated as follows:

```
%arg -solver cbc
%arg -ignoreZeros
%opt cbc threads 4
%display var x*

parameters:
      seed:=srand(100);
      M:=10000;

      nrOfCities:=10;
      cities:=1..nrOfCities;

      {i in cities:
              xp[i]:=rand(100);
              yp[i]:=rand(100);
      }

      {i in cities, j in cities:
          {i==j:
            dist[i,j]:=M; |
          default:
            dist[i,j]:= sqrt( (xp[i]-xp[j])^2 + (yp[i]-yp[j])^2 );
            dist[j,i]:= dist[i,j]+rand(10)-rand(10);
```

```
          }
      }

variables:
      x[cities,cities]: binary;
      u[cities]: real[0..];

objectives:
      distance: sum{i in cities, j in cities: dist[i,j]* x[i,j]} ->min;

constraints:
      sos_i {j in cities:  sum{i in cities: x[i,j]}=1; }
      sos_j {i in cities:  sum{j in cities: x[i,j]}=1; }

      noSubs {i:=2..nrOfCities, j:=2..nrOfCities, i<>j: u[i] - u[j] +
                  nrOfCities * x[i,j] <= nrOfCities-1; }
```

CMPL command:

```
cmpl  tsp.cmpl
```

Solution:

```
-------------------------------------------------------------------------------------------------------------
Problem              tsp.cmpl
Nr. of variables     109
Nr. of constraints   92
Objective name       distance
Solver name          COIN-OR cbc
-------------------------------------------------------------------------------------------------------------

Objective status     optimal
Objective value      321.319 (min!)

Nonzero variables (x*)
Name                 Type            Activity         Lower bound         Upper bound            Marginal
-------------------------------------------------------------------------------------------------------------
x[1,4]                  B                   1                   0                   1                   -
x[2,1]                  B                   1                   0                   1                   -
x[3,6]                  B                   1                   0                   1                   -
x[4,10]                 B                   1                   0                   1                   -
x[5,8]                  B                   1                   0                   1                   -
x[6,9]                  B                   1                   0                   1                   -
x[7,2]                  B                   1                   0                   1                   -
x[8,7]                  B                   1                   0                   1                   -
x[9,5]                  B                   1                   0                   1                   -
x[10,3]                 B                   1                   0                   1                   -
-------------------------------------------------------------------------------------------------------------
```

The tour is optimal as follows:

1→4→10→3→6→9→5→8→7→2→1

10.2 Using CMPL as a pre-solver

CMPL is not only intended to generate models in the MPS or OSIL format. CMPL can also be used as a pre-solver or simple solver. In this way it is possible to find a preliminary solution of a problem as a basis for the model which is to be generated.

10.2.1 Solving the knapsack problem

The knapsack problem is a very simple problem that does not necessarily have to be solved by an MIP solver. CMPL can be used as a simple solver for knapsack problems to approximate the optimal solution.

The idea of the following models is to evaluate each item using the relation between the value per item and weight per item. The knapsack will be filled with the items sorted in descending order until the capacity limit or the minimum value is reached. Using the data from the examples in section10.1.4a CMPL model to maximize the total sales relative to capacity can be formulated as follows.

Model 1: maximize the total sales `knapsack-max-presolved.cmpl`

```
include "knapsack-data.cmpl"

#calculating the relative value of each box
{j in boxes: val[j]:= p[j]/w[j]; }
sumSales:=0;
sumWeight:=0;
#initial solution
x[]:=(0,0,0,0,0,0,0,0,0,0);

{ i in boxes:
      maxVal:=max(val[]);
      {j in boxes:
            { maxVal=val[j] :
                        { sumWeight+w[j] <= maxWeight:
                                    x[j]:=1;
                                    sumSales:=sumSales + p[j];
                                    sumWeight:=sumWeight + w[j];
                        }
                        val[j]:=0;
                        break j;
            }
      }
}

echo "Solution found";
echo "Optimal total sales: "+ sumSales;
echo "Total weight : " + sumWeight;
{j in boxes: echo "x_"+ j + ": " + x[j]; }
```

CMPL command:

```
cmpl knapsack-max-presolved.cmpl -noOutput -cd
```

Solution:

```
Solution found
Optimal total sales: 690
Total weight : 57
x_1: 1
x_2: 1
x_3: 0
x_4: 1
x_5: 0
x_6: 1
x_7: 1
x_8: 0
x_9: 1
x_10: 1
```

This solution is not identical to the optimal solution on page 76 but good enough as an approximate solution.

Model 2: minimize the total weight `knapsack-min-presolved.cmpl`

```
include "knapsack-data.cmpl"
#calculating the relative value of each box
{j in boxes: val[j]:= w[j]/p[j]; }

M:=10000;
sumSales:=0;
sumWeight:=0;
#initial solution
x[]:=(0,0,0,0,0,0,0,0,0,0);
{sumSales < minSales:
      maxVal:=min(val[]);
      {j in boxes:
            { maxVal=val[j] :
                        { sumSales < minSales:
                                    x[j]:=1;
                                    sumSales:=sumSales + p[j];
                                    sumWeight:=sumWeight + w[j];
                        }

                        val[j]:=M;
                        break j;
            }
      }
      repeat;
}
echo "Solution found";
echo "Optimal total weight : " + sumWeight;
echo "Total sales: "+ sumSales;
{j in boxes: echo "x_"+ j + ": " + x[j]; }
```

CMPL command:

```
cmpl knapsack-min-presolved.cmpl -noOutput -cd
```

Solution:

```
Optimal total weight : 47
Total sales: 630
x_1: 1
x_2: 1
x_3: 0
x_4: 1
x_5: 0
x_6: 0
x_7: 0
x_8: 0
x_9: 1
x_10: 1
```

This solution is identical to the optimal solution in section 10.1.4.

10.2.2 Finding the maximum of a concave function using the bisection method

One of the alternative methods for finding the maximum of a negative convex function is the bisection method. [cf. Hillier/Liebermann (2010), p. 554f.] A CMPL program to find the maximum of $f(x)=12\cdot x-3\cdot x^4-2\cdot x^6$ can be formulated as follows (`bisection.cmpl`):

```
parameters:
      #distance epsilon
      e:=0.02;
      #initial solution
      xl:= 0;
      xo:= 2;
      xn:= (xl+xo)/2;
      { (xo-xl) > e :
            fd:= 12 - 12 * xn^3 - 12 * xn^5;
            { fd >= 0 : xl:=xn; |
              fd <= 0 : xo:=xn ;}
              xn:= (xl+xo)/2;

            fx := 12 * xn -3 * xn^4 - 2 * xn^6;
            echo "f'(xn): " + format("%10.4f",fd) + " xl: " +
                  format("%6.4f",xl) +
                  " xo: " + format("%6.4f",xo) + " xn: " + format("%6.4f",xn) +
                  " f(xn): " + format("%6.4f",fx);
            repeat;
      }
```

```
      echo "Optimal solution found";
      x:=xn;
      echo "x: "+ format("%2.3f",x);
      echo "function value: " + (12 * x -3 * x^4 - 2 * x^6);
```

CMPL command:

```
cmpl bisection.cmpl -noOutput -cd
```

Solution:

```
f'(xn):   -12.0000 xl: 0.0000 xo: 1.0000 xn: 0.5000 f(xn): 5.7812
f'(xn):    10.1250 xl: 0.5000 xo: 1.0000 xn: 0.7500 f(xn): 7.6948
f'(xn):     4.0898 xl: 0.7500 xo: 1.0000 xn: 0.8750 f(xn): 7.8439
f'(xn):    -2.1940 xl: 0.7500 xo: 0.8750 xn: 0.8125 f(xn): 7.8672
f'(xn):     1.3144 xl: 0.8125 xo: 0.8750 xn: 0.8438 f(xn): 7.8829
f'(xn):    -0.3397 xl: 0.8125 xo: 0.8438 xn: 0.8281 f(xn): 7.8815
f'(xn):     0.5113 xl: 0.8281 xo: 0.8438 xn: 0.8359 f(xn): 7.8839
Optimal solution found
x: 0.836
function value: 7.883868
```

11 pyCMPL and CMPLServer

Since the release of version 1.8, the CMPL package contains also pyCMPL and CMPLServer.

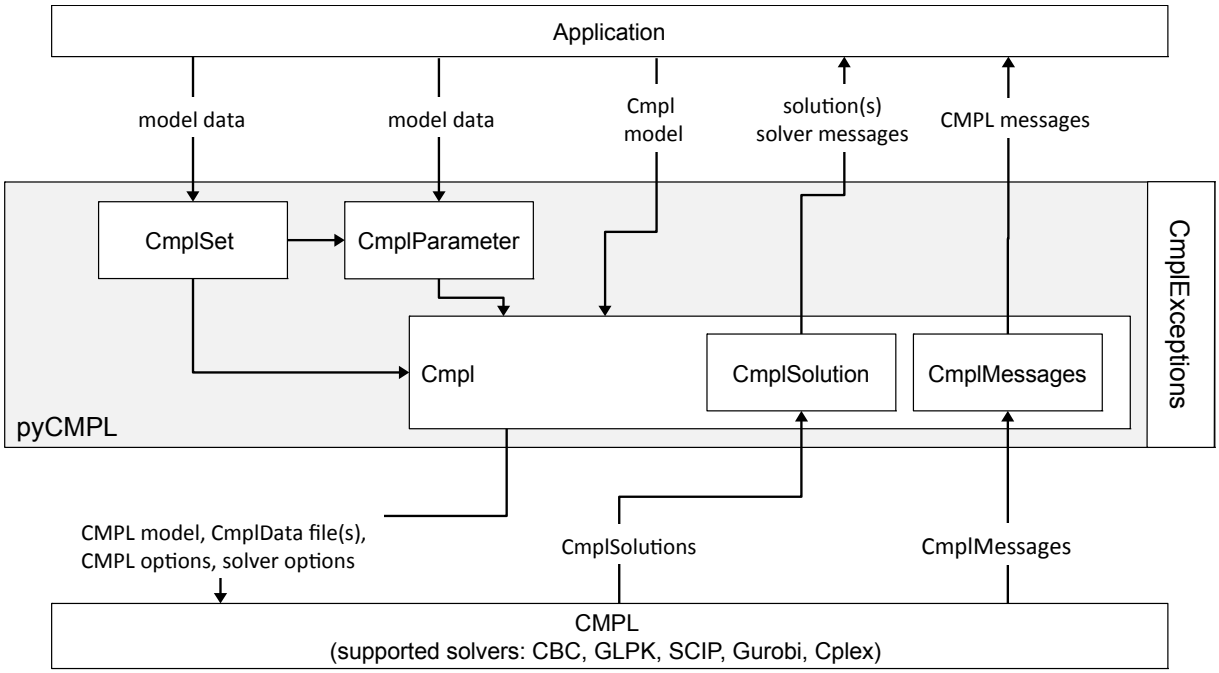
pyCMPL is the CMPL API for Python and an interactive shell. The main idea of this API is to define sets and parameters within the user application, to start and control the solving process and to read the solution(s) into the application if the problem is feasible. All variables, objective functions and constraints are defined in CMPL. These functionalities can be used with a local CMPL installation or a CMPLServer.

CMPLServer is an XML-RPC-based web service for distributed optimization. It is reasonable to solve large models remotely on the CMPLServer that is installed on a high performance system. pyCMPL provides a client API for CMPLServer. CMPL provides three XML-based file formats for the communication between a CMPLServer and its clients. (`CmplInstance`, `CmplSolutions`, `CmplMessages`)

11.1 Creating pyCMPL scripts with a local CMPL installation

The pyCmpl API contains a couple of Python classes to connect a Python application with CMPL as shown in the figure below.

The classes `CmplSet` and `CmplParameter` are intended to define sets and parameters that can be used with several `Cmpl` objects. With the `Cmpl` class it is possible to define a CMPL model, to commit sets and parameters to this model, to start and control the solving process and to read the CMPL and solver messages and to have access to the solution(s) via `CmplMessages` and `CmplSolutions` objects.



To illustrate the formulation of a pyCmpl script an example taken from (Hillier/Liebermann 2010, p. 334f.) is used. Consider a simple assignment problem that deals with the assignment of three machines to four possible locations. There is no work flow between the machines. The total material handling costs are to be minimized. The hourly material handling costs per machine and location are given in the following table.

		Locations			
		1	2	3	4
Machines	1	13	16	12	11
	2	15	-	13	20
	3	5	7	10	6

The mathematical model

$$\sum_{(i,j)\in A} c_{ij} \cdot x_{ij} \quad \rightarrow \min!$$

$$s.t.$$

$$\sum_{\substack{(k,j)\in A \\ k=i}} x_{kj} = 1 \quad ; i = 1(1)m$$

$$\sum_{\substack{(i,l)\in A \\ l=j}} x_{il} \leq 1 \quad ; j = 1(1)n$$

$$x_{ij} \in \{0,1\} \quad ;(i,j)\in A$$

with

Parameters

A	- set of the possible combination of machines and locations
m	- number of machines
n	- number of locations
c_{ij}	- hourly material handling costs of machine i at location j

Variables

x_{ij}	- assignment variable of machine i at location j

can be formulated in CMPL as follows:

```
%data : machines set, locations set, A set[2], c[A]

variables:
      x[A]: binary;

objectives:
      costs: sum{ [i,j] in A : c[i,j]*x[i,j] } -> min ;

constraints:
      sos_m { i in machines:  sum{ j in (A *> [i,*]) : x[i,j] } = 1; }
      sos_l { j in locations: sum{ i in (A *> [*,j]) : x[i,j] } <= 1; }
```

The interface for the sets and parameters provided by the pyCmpl script is the CMPL header entry `%data`.

The first step to formulate this problem as a pyCmpl script after importing the pyCmpl package is to create a `Cmpl` object where the argument of the constructor is the name of the CMPL file.

```
#!/usr/bin/python
from pyCmpl import *

m = Cmpl("assignment.cmpl")
```

As in the `%data` entry two 1-tuple sets `machines` and `locations` and one 2-tuple set `A` are necessary for the CMPL model. To create a `CmplSet` a name and for *n*-tuple sets with *n*>1 the rank are needed as arguments for the constructor. The name has to be identical to the corresponding name in the CMPL header entry `%data`. The set data is specified by the `CmplSet` method `setValues`. This is an overloaded method with different arguments for several types of sets.

```
locations = CmplSet("locations")
locations.setValues(1,4)

machines = CmplSet("machines")
machines.setValues(1,3)

combinations = CmplSet("A", 2)
combinations.setValues([ [1,1],[1,2],[1,3],[1,4], [2,1],[2,3],[2,4],\
                         [3,1],[3,2],[3,3],[3,4]])
```

As shown in the listing above the set `locations` is assigned `(1,2,..,4)` and the set `machines` consists of `(1,2,3)` because the first argument of `setValues` for this kind of sets is the starting value and the second argument is the end value while the increment is by default equal to one. The values of the 2-tuple set `combinations` are defined in the form of a list that consists of lists of valid combinations of machines and locations.

For the definition of a CMPL parameter a user has to create a `CmplParameter` object where the first argument of the constructor is the name of the parameter. If the parameter is an array it is also necessary to specify the set or sets through which the parameter array is defined. Therefore it is necessary to commit the `CmplSet combinations` (beside the name `"c"`) to create the CmplParameter array `c` .

```
c = CmplParameter("c",combinations)
c.setValues([13,16,12,11,15,13,20,5,7,10,6])
```

`CmplSet` objects and `CmplParameter` objects can be used in several CMPL models and have to be committed to a `Cmpl` model by the `Cmpl` methods `setSets` and `setParameters`. After this step the problem can be solved by using the `Cmpl` method `solve`.

```
m.setSets(machines,locations,combinations)
m.setParameters(c)

m.solve()
```

After solving the model the status of CMPL and the invoked solver can be analysed through the `Cmpl` attributes `solution.solverStatus` and `solution.cmplStatus`.

```
print "Objective value: " , m.solution.value
print "Objective status: " , m.solution.status
```

If the problem is feasible and a solution is found it is possible to read the names, the types, the activities, the lower and upper bounds and the marginal values of the variables and the constraints into the Python application. The `Cmpl` attributes `solution.variables` and `solution.constraints` contain a list of variable and constraint objects.

```
print "Variables:"
for v in m.solution.variables:
      print v.name, v.type, v.activity,v.lowerBound,v.upperBound

print "Constraints:"
for c in m.solution.constraints:
      print c.name, c.type, c.activity,c.lowerBound,c.upperBound
```

pyCmpl provides its own exception handling through the class `CmplException` that can be used in a `try` and `except` block.

```
try:
      ...
except CmplException, e:
      print e.msg
```

The entire pyCmpl script assignment.py shows as follows:

```
#!/usr/bin/python
from pyCmpl import *

try:
      m = Cmpl("assignment.cmpl")

      locations = CmplSet("locations")
      locations.setValues(1,4)

      machines = CmplSet("machines")
      machines.setValues(1,3)

      combinations = CmplSet("A", 2)
      combinations.setValues([ [1,1],[1,2],[1,3],[1,4],\
                               [2,1],[2,3],[2,4],[3,1],[3,2],[3,3],[3,4]])

      c = CmplParameter("c",combinations)
      c.setValues([13,16,12,11,15,13,20,5,7,10,6])

      m.setSets(machines,locations,combinations)
      m.setParameters(c)

      m.solve()

      print "Objective value: " , m.solution.value
      print "Objective status: " , m.solution.status

      print "Variables:"
      for v in m.solution.variables:
            print v.name, v.type, v.activity,v.lowerBound,v.upperBound

      print "Constraints:"
      for c in m.solution.constraints:
            print c.name, c.type, c.activity,c.lowerBound,c.upperBound

except CmplException, e:
      print e.msg
```

and can be executed by typing the command

```
pyCmpl assignment.py
```

under Linux and Mac in the terminal or under Windows in the CmplShell (c:\program files\Cmpl\cmplShell.bat) and prints the following solution to stdOut.

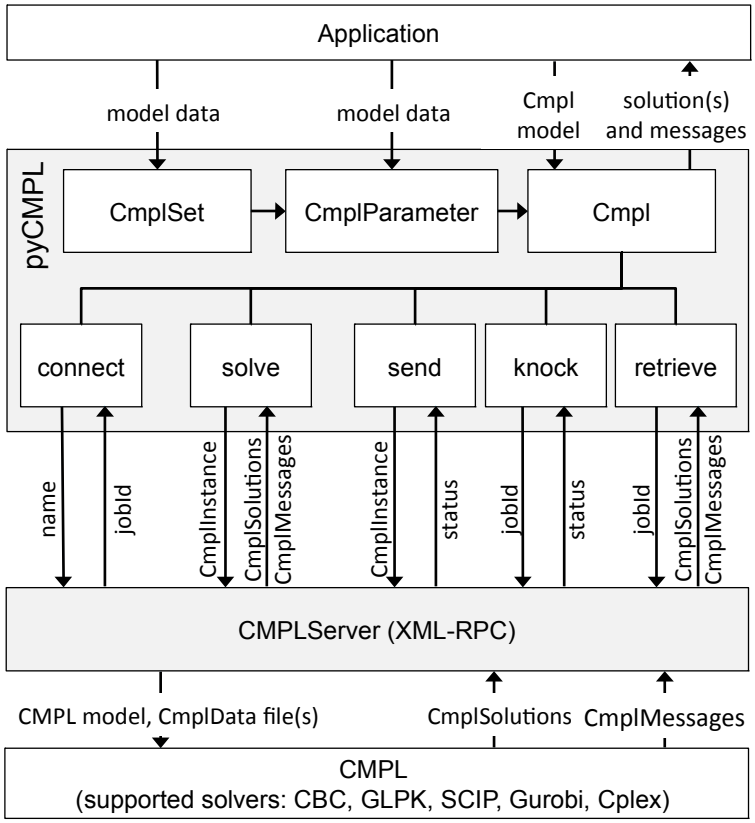
```
Objective value:  29.0
Objective status:  optimal

```

```
Variables:
x[1,1] B 0.0 0.0 1.0
x[1,2] B 0.0 0.0 1.0
x[1,3] B 0.0 0.0 1.0
x[1,4] B 1.0 0.0 1.0
x[2,1] B 0.0 0.0 1.0
x[2,3] B 1.0 0.0 1.0
x[2,4] B 0.0 0.0 1.0
x[3,1] B 1.0 0.0 1.0
x[3,2] B 0.0 0.0 1.0
x[3,3] B 0.0 0.0 1.0
x[3,4] B 0.0 0.0 1.0
Constraints:
sos_m[1] E 1.0 1.0 1.0
sos_m[2] E 1.0 1.0 1.0
sos_m[3] E 1.0 1.0 1.0
sos_l[1] L 1.0 -inf 1.0
sos_l[2] L 0.0 -inf 1.0
sos_l[3] L 1.0 -inf 1.0
sos_l[4] L 1.0 -inf 1.0
```

11.2 Creating pyCMPL scripts using CMPLServer

The class `Cmpl` also provides the functionality to communicate with a CMPLServer that is implemented as a XML-RPC-based web service. XML-RPC provides XML based procedures for Remote Procedure Calls (RPC), which are transmitted between a client and a server via HTTP. (Laurent et al. 2001, p. 1.) Such client-server architecture is reasonable for solving large models remotely on the CMPLServer that is installed on a high performance system. CMPLServer provides several XML-based file formats for the communication between a CMPLServer and its clients. A `CmplInstance` file contains an optimization problem formulated in CMPL, the corresponding sets and parameters in `CmplData` file format and all CMPL and solver options that belong to the CMPL model. If the model is feasible and the solution process is finished a `CmplSolutions` file contains the solution(s) and the status of the invoked solver. If the model is not feasible then only the solver's status and the solver messages are given in the solution file. The `CmplMessages` file is intended to provide the CMPL status and (if existing) the CMPL messages.

As shown in the figure below the first step to communicate with a CMPLServer is the `Cmpl.connect` method that returns (if connected) a `jobId`. After connecting, a problem can be solved synchronously or asynchronously.



The `Cmpl` method `solve` sends a `CmplInstance` to the connected CMPLServer and waits for the returning `CmplSolutions` and `CmplMessages`. After this synchronous process a user can access the solution(s) if the problem is feasible or if not it can be analysed, whether the CMPL formulations or the solver is the cause of the problem. To execute the solving process asynchronously the `Cmpl` methods `send`, `knock` and `retrieve` have to be used. `Cmpl.send` sends a `CmplInstance` to the CMPLServer and starts the solving process remotely. `Cmpl.knock` asks for a CMPL model with a given `jobId` whether the solving process is finished or not. If the problem is finished the `CmplSolutions` and the `CmplMessages` can be read into the user application with `Cmpl.retrieve`.

The first step to create a distributed optimization application is to start the CMPLServer. This can be done by typing the command

```
cmplServer -start
```

under Linux and Mac in the terminal or under Windows in the CmplShell (c:\program files\Cmpl\cmplShell.bat). Optionally a port can be specified as second argument (default 8008).

Assuming that a CMPLServer is running on 194.95.45.70:8008 the assignment problem can be solved remotely only by including

```
m.connect("http://194.95.45.70:8008")
```

in the source code before `Cmpl.solve` is executed.

The pyCmpl script `assignment-remote.py` shows as follows:

```
#!/usr/bin/python
from pyCmpl import *

try:
      m = Cmpl("assignment.cmpl")

      locations = CmplSet("locations")
      locations.setValues(1,4)

      machines = CmplSet("machines")
      machines.setValues(1,3)

      combinations = CmplSet("A", 2)
      combinations.setValues([ [1,1],[1,2],[1,3],[1,4],\
                               [2,1],[2,3],[2,4],[3,1],[3,2],[3,3],[3,4]])

      c = CmplParameter("c",combinations)
      c.setValues([13,16,12,11,15,13,20,5,7,10,6])

      m.setSets(machines,locations,combinations)
      m.setParameters(c)

      m.connect("http://194.95.45.70:8008")
      m.solve()

      print "Objective value: " , m.solution.value
      print "Objective status: " , m.solution.status

      print "Variables:"
      for v in m.solution.variables:
            print v.name, v.type, v.activity,v.lowerBound,v.upperBound

      print "Constraints:"
      for c in m.solution.constraints:
            print c.name, c.type, c.activity,c.lowerBound,c.upperBound

except CmplException, e:
      print e.msg
```

The CMPLServer can be stopped by typing the command

```
cmplServer -stop
```

in the terminal or CmplShell. Optionally a port can be specified as second argument, if the port is not 8008.

11.3 pyCMPL reference manual

11.3.1 CmplSets

The class `CmplSet` is intended to define sets that can be used with several `Cmpl` objects.

Methods:

`CmplSet("`*`setName`***`"[,`***`rank`***`])`**

Description: Constructor

Parameter:

`str` ***`setName`***	Name of the set, Has to be equal to the corresponding name in the CMPL model.
`int|long` ***`rank`***	optional - rank *n* for a *n*-tuple set (default 1)

Return: `CmplSet` object

`CmplSet``.`**`setValues(`***`setList`***`)`**

Description: Defines the values of an enumeration set

Parameter:

`list` ***`setList`***	For a set of *n*-tuples with *n*=1 - `list` of single indexing entries `int|long|str` For a set of *n*-tuples with *n*>1 - `list` of `list`(s) that contain `int|long|str` tuples

Return: -

`CmplSet``.`**`setValues(`***`startNumber,endNumber`***`)`**

Description: Defines the values of an algorithmic set
`(startNumber, startNumber+1, ..., endNumber)`

Parameter:

`int|long` ***`startNumber`***	start value of the set
`int|long` ***`endNumber`***	end value of the set

Return: -

`CmplSet``.`**`setValues(`***`startNumber,step,endNumber`***`)`**

Description: Defines the values of an algorithmic set
`(startNumber, startNumber+step, ..., endNumber)`

Parameter:

`int|long` ***`startNumber`***	start value of the set
`int|long` ***`step`***	Positive `int|long` for increment Negative `int|long` for decrement
`int|long` ***`endNumber`***	end value of the set

Return: -

R/o attributes:

CmplSet.**values**

Description: List of the indexing entries of the set

Return: `list` of single indexing entries - for a set of *n*-tuples with *n*=1
of `tuple`(s) - for a set of *n*-tuples with *n*>1

CmplSet.**name**

Description: Name of the set

Return: `str` name of the CMPL set (not the name of the `CmplSet` object)

CmplSet.**rank**

Description: Rank of the set

Return: `int|long` number of *n* of a *n*-tuple set

CmplSet.**len**

Description: Length of the set

Return: `int|long` amount of indexing entries

Examples:

`s = CmplSet("s")`
`s.setValues(0,4)`
 	
`print s.rank`
`print s.len`
`print s.name`
`print s.values`
	`s` is assigned $s \in (0,1,\ldots,4)$
	
	`1`
	`4`
	`s`
	`[0, 1, 2, 3, 4]`

`s = CmplSet("a")`
`s.setValues(10,-2,0)`
 	
`print s.rank`
`print s.len`
`print s.name`
`print s.values`
	`s` is assigned $s \in (10,8,\ldots,0)$
	
	`1`
	`6`
	`s`
	`[10, 8, 6, 4, 2, 0]`

`s = CmplSet("FOOD")`
`s.setValues(["BEEF","CHK","FISH"])`
 	
`print s.rank`
`print s.len`
`print s.name`
`print s.values`
	`s` is assigned $s \in ('BEEF','CHK','FISH')$
	
	`1`
	`3`
	`FOOD`
	`['BEEF', 'CHK', 'FISH']`

`s = CmplSet("c",3)`
`s.setValues([[1,1,1], [1,1,2], \`
`  [1,2,1]])`
	`s` is assigned a 3-tuple set of integers

`print s.rank`
`print s.len`
`print s.name`
`print s.values`
	`3`
	`3`
	`c`
	`[(1, 1, 1), (1, 1, 2), (1, 2, 1)]`

11.3.2 CmplParameters

The class `CmplParameters` is intended to define parameters that can be used with several `Cmpl` objects.

Methods:

`CmplParameter("`*`paramName`***`"[,`***`set1`***`,`***`set2`***`,...])`**

Description: Constructor

Parameter:

`str` *`paramName`*	Name of the parameter Has to be equal to the corresponding name in the CMPL model.
`CmplSet` *`set1,set2,...`*	optional - set or sets through which the parameter array is defined (default `None`)

Return: `CmplParameter` object

*`CmplParameter`***`.setValues(`***`val`***`)`**

Description: Defines the values of a scalar parameter

Parameter:

`int|long|float|` `str` *`val`*	value of the scalar parameter

Return: -

*`CmplParameter`***`.setValues(`***`valList`***`)`**

Description: Defines the values of a parameter array

Parameter:

`list` *`valList`*	`list` of `int|long|float|str|list` - value list of the parameter array

Return: -

R/o attributes:

*`CmplParameter`***`.values`**

Description: List of the values of a parameter

Return: `list` of `int|long|float|str|list` - value list of the parameter array

CmplParameter.**value**

Description: Value of a scalar parameter

Return: `int|long|float|str` - value of the scalar parameter

CmplParameter.**setList**

Description: List of sets through which the parameter array is defined

Return: `list` of `CmplSet` objects through which the parameter array is defined

CmplParameter.**name**

Description: Name of the parameter

Return: `str` - name of the CMPL parameter (not the name of the `CmplParameter` object)

CmplParameter.**rank**

Description: Rank of the parameter

Return: `int|long` - rank of the CMPL parameter

CmplParameter.**len**

Description: Length of the parameter array

Return: `int|long` number of elements in the parameter array

Examples:

`p = CmplParameter("p")`
`p.setValues(2)`
 	
`print p.values`
`print p.value`
`print p.name`
`print p.rank`
`print p.len`
	`p` is assigned `2`
	
	`[2]`
	`2`
	`p`
	`0`
	`1`

`s = CmplSet("s")`
`s.setValues(0,4)`
`p = CmplParameter("p",s)`
`p.setValues([1,2,3,4,5])`
 	
`print p.values`
`print p.name`
`print p.rank`
`print p.len`
	`p` is assigned $(1,2,\ldots,5)$
	
	`[1, 2, 3, 4, 5]`
	`p`
	`1`
	`5`

`products = CmplSet("products")`
`products.setValues(1,3)`
 	
`machines = CmplSet("machines")`	

machines.setValues(1,2) a=CmplParameter("a",machines, products) a.setValues([[8,15,12],[15,10,8]]) print a.values print a.name print a.rank print a.len for e in a.setList: print e.values	 s is assigned a 2X3 matrix of integers [[8, 15, 12], [15, 10, 8]] a 2 6 [1, 2] [1, 2, 3]
s = CmplSet("s",2) s.setValues([[1,1],[2,2]]) p = CmplParameter("p",s) p.setValues([1,1]) print p.values print p.name print p.rank print p.len	 s s assigned the indices of a matrix diagonal s is assigned a 2x2 identity matrix [1, 1] p 2 2

11.3.3 Cmpl

With the `Cmpl` class it is possible to define a CMPL model, to commit sets and parameters to this model, to start and control the solving process and to read the CMPL and solver messages and to have access to the solution(s) via `CmplMessages` and `CmplSolutions` objects.

11.3.3.1 Establishing models

Methods:

`Cmpl("`*`name`***`")`**

Description: Constructor
Parameter: `str` *name* filename of the CMPL model
Return: `Cmpl` object

`Cmpl``.`**`setSets(`***`set1[,set2,...]`***`)`**

Description: Committing `CmplSet` objects to the `Cmpl` model
Parameter: `CmplSet` *set1[,set2,...]* `CmplSet` object(s)
Return: -

Cmpl.**setParameters(***par1[,par2,...]***)**

Description: Committing `CmplParameter` objects to the `Cmpl` model

Parameter: `CmplParameter` *par1[,par2,...]* `CmplParameter` object(s)

Return: -

Examples:

`m = Cmpl("prodmix.cmpl")`
 	
`products = CmplSet("products")`
`products.setValues(1,3)`
 	
`machines = CmplSet("machines")`
`machines.setValues(1,2)`
 	
`c = CmplParameter("c",products)`
`c.setValues([75,80,50])`
 	
`b = CmplParameter("b",machines)`
`b.setValues([1000,1000])`
 	
`a = CmplParameter("a",machines, products)`
`a.setValues([[ 8,15,12],[15,10,8]])`	

`m.setSets(products,machines)`	Commits the sets `products,machines` to the Cmpl object `m`
`m.setParameters(c,a,b)`	Commits the parameter `c,a,b` to the Cmpl object m

11.3.3.2 Manipulating models

Methods:

Cmpl.**setOption(***option***)**

Description: Sets a CMPL, display or solver option

Parameter: `str` *option* option in CmplHeader syntax

Return: `int|long` option id

Cmpl.**delOption(***optId***)**

Description: Deletes an option

Parameter: `int|long` *optId* option id

Return: -

Cmpl.**delOptions()**

Description: Deletes all options

Parameter: -

Return: -

Cmpl.**setOutput(***ok[,leadString]]***)**

Description: Turns the output of CMPL and the invoked solver on or off

Parameter: `bool` *ok* `True|False`

`str` *leadString* optional - Leading string for the output (default - model name)

Return: -

Cmpl.**setRefreshTime(***rTime***)**

Description: Refresh time for getting the output of CMPL and the invoked solver from a CMPLServer if the model is solved synchronously.

Parameter: `float` *rTime* refresh time in seconds (default 0.5)

Return: -

R/o attributes:

Cmpl.**refreshTime**

Description: Returns the refresh time for getting the output of CMPL and the invoked solver from a CMPLServer if the model is solved synchronously.

Return: `float` Refresh time

Examples:

`m = Cmpl("assignment.cmpl")`	

`c1=m.setOption("%display nonZeros")`
`m.setOption("%arg -solver cplex")`
`m.setOption("%display solutionPool")`
	Setting some options

`m.delOption(c1)`	Deletes the first option
`m.delOptions()`	Deletes all options

`m = Cmpl("assignment.cmpl")`
 	
`m.setOutput(True)`
 	
`m.setOutput(True,"my special model")`
	
	The stdOut and stdErr of CMPL and the invoked solver are shown for the `Cmpl` object `m`.
	
	As above but the output starts with the leading string `"my special model>"`.

`m = Cmpl("assignment.cmpl")`
`m.connect("http://194.95.45.70:8008")`
`m.setOutput(True)`
`m.setRefreshTime(1)`
	The stdOut and stdErr of CMPL and the invoked solver located at the specified CMPLServer will be refreshed each second.

11.3.3.3 Solving models

Methods:

Cmpl.**solve()**

Description: Solves a `Cmpl` model either with a local installed CMPL or if the model is connected with a CMPLServer remotely.

Parameter: -

Return: - The status of the model and the solver can be obtained by the attributes `cmplStatus`, `cmplStatusText`,`solverStatus` and `solverStatusText`

Cmpl.**start()**

Description: Solves a `Cmpl` model in a separate thread either with a local installed CMPL or if the model is connected with a CMPLServer remotely.

Parameter: -

Return: - The status of the model and the solver can be obtained by the attributes `cmplStatus`, `cmplStatusText`,`solverStatus` and `solverStatusText`

Cmpl.**join()**

Description: Waits until the solving thread terminates.

Parameter: -

Return: - The status of the model and the solver can be obtained by the attributes `cmplStatus`, `cmplStatusText`,`solverStatus` and `solverStatusText`

Cmpl.**isAlive()**

Description: Return whether the thread is alive

Parameter: -

Return: `bool` `True` or `False` - return whether the thread is alive or not

Cmpl.**connect(***cmplUrl***)**

Description: Connects a CMPLServer under *cmplUrl* – first step of solving a model on a CMPLServer remotely

Parameter: `str` *cmplUrl* URL of the CMPLServer

Return: `str` JobId of the `Cmpl` model on the connected CMPLServer

Cmpl.**disconnect()**

Description: Disconnects the connected CMPLServer

Parameter: –

Return: –

Cmpl.**send()**

Description: Sends the `Cmpl` model instance to the connected CMPLServer - first step of solving a model on a CMPLServer asynchronously (after connect())

Parameter: –

Return: – The status of the model can be obtained by the attributes `cmplStatus` and `cmplStatusText`

Cmpl.**knock()**

Description: Knocks on the door of the connected CMPLServer and asks whether the model is finished - second step of solving a model on a CMPLServer asynchronously

Parameter: –

Return: – The status of the model can be obtained by the attributes `cmplStatus` and `cmplStatusText`

Cmpl.**retrieve()**

Description: Retrieves the `Cmpl` solution(s) if possible from the connected CMPLServer - last step of solving a model on a CMPLServer asynchronously

Parameter: –

Return: – The status of the model and the solver can be obtained by the attributes `cmplStatus`, `cmplStatusText`, `solverStatus` and `solverStatusText`

Cmpl.**cancel()**

Description: Cancels the `Cmpl` solving process on the connected CMPLServer

Parameter: –

Return: – The status of the model can be obtained by the attributes `cmplStatus` and `cmplStatusText`

R/o attributes:

Cmpl.**cmplStatus**

Description: Returns the CMPL related status of the `Cmpl` object

Return: `int`

```
CMPL_UNKNOWN = 0
CMPL_OK = 1
CMPL_WARNINGS = 2
CMPL_FAILED = 3

CMPLSERVER_OK = 6
CMPLSERVER_ERROR = 7
CMPLSERVER_CLEANED = 8

PROBLEM_RUNNING = 9
PROBLEM_FINISHED = 10
PROBLEM_CANCELED = 11
PROBLEM_NOTRUNNING = 12
```

Cmpl.**cmplStatusText**

Description: Returns the CMPL related status text of the `Cmpl` object

Return: `str`

```
CMPL_UNKNOWN
CMPL_OK
CMPL_WARNINGS
CMPL_FAILED

SOLVER_OK
SOLVER_FAILED

CMPLSERVER_OK
CMPLSERVER_ERROR
CMPLSERVER_CLEANED

PROBLEM_RUNNING
PROBLEM_FINISHED
PROBLEM_CANCELED
PROBLEM_NOTRUNNING
```

Cmpl.**solverStatus**

Description: Returns the solver related status of the `Cmpl` object

Return: `int` `SOLVER_OK = 4`
`SOLVER_FAILED = 5`

Cmpl.**solverStatusText**

Description: Returns the solver related status text of the `Cmpl` object

Return: `str` `SOLVER_OK`
`SOLVER_FAILED`

Cmpl.**jobId**

Description: Returns the jobId of the `Cmpl` problem at the connected CMPLServer

Return: `str` String of the jobId

Cmpl.**output**

Description: Returns the output of CMPL and the invoked solver.
Intended to use if an application needs to parse the output.

Return: `str` String of output of CMPL and the invoked solver

Examples:

`m = Cmpl("assignment.cmpl")` `m.solve()`	Solves the `Cmpl` object `m` locally

`m = Cmpl("assignment.cmpl")`
`m.connect("http://194.95.45.70:8008")`
`m.solve()`
	Solves the `Cmpl` object `m` remotely and synchronously on the specified CMPLServer

`m = Cmpl("assignment.cmpl")`
`m.connect("http://194.95.45.70:8008")`
`m.send()`
`m.knock()`
`m.retrieve()`
	Solves the `Cmpl` object `m` remotely and asynchronously on the specified CMPLServer

`models= []`
`models.append(Cmpl("m1.cmpl"))`
`models.append(Cmpl("m2.cmpl"))`
`models.append(Cmpl("m3.cmpl"))`
 	
`for m in models:`
`  m.start()`
 	
`for m in models:`
`  m.join()`
	Starts all models in separate threads.
	
	Waits until the all solving threads are terminated.

`m = Cmpl("assignment.cmpl")` `m.solve()`	

`if m.solverstatus!=SOLVER_OK:` `  m.solutionReport()`	Displays the optimal solution if the solver didm't fail.

11.3.3.4 Reading solutions

Methods:

Cmpl.**solutionReport()**

Description: Writes a standard solution report to stdOut
Parameter: -
Return: -

Cmpl.**saveSolution(***[solFileName]***)**

Description: Saves the solution(s) as `CmplSolutions` file
Parameter: `str` *solFileName* optional file name (default `<modelname>.csol`)
Return: -

Cmpl.**saveSolutionAscii(***[solFileName]***)**

Description: Saves the solution(s) as ASCII file
Parameter: `str` *solFileName* optional file name (default `<modelname>.sol`)
Return: -

Cmpl.**saveSolutionCsv(***[solFileName]***)**

Description: Saves the solution(s) as CSV file
Parameter: `str` *solFileName* optional file name (default `<modelname>.csv`)
Return: -

Cmpl.**varByName(***[solIdx]***)**

Description: Enables a direct access to variables by their name
Parameter: `int|long` *solIdx* optional solution index (default `0`)
Return: -

Cmpl.**conByName(***[solIdx]***)**

Description: Enables a direct access to constraints by their name
Parameter: `int|long` *solIdx* optional solution index (default `0`)
Return: -

R/o attributes:

Cmpl.**nrOfVariables**

Description: Returns the number of variables of the generated and solved CMPL model

Return: `int|long` Number of variables

Cmpl.**nrOfConstraints**

Description: Returns the number of constraints of the generated and solved CMPL model

Return: `int|long` Number of constraints

Cmpl.**objectiveName**

Description: Returns the name of the objective function of the generated and solved CMPL model

Return: `str` objective name

Cmpl.**objectiveSense**

Description: Returns the objective sense of the generated and solved CMPL model

Return: `str` objective sense

Cmpl.**nrOfSolutions**

Description: Returns the number of solutions of the generated and solved CMPL model

Return: `int|long` Number of solutions

Cmpl.**solver**

Description: Returns the name of the invoked solver of the generated and solved CMPL model

Return: `str` Invoked solver

Cmpl.**solverMessage**

Description: Returns the message of the invoked solver of the generated and solved CMPL model

Return: `str` Message of the invoked solver

Cmpl.**varDisplayOptions**

Description: Returns the a string with the display options for the variables of the generated and solved CMPL model

Return: `str` Display options for the variables

Cmpl.**conDisplayOptions**

Description: Returns the a string with the display options for the constraints of the generated and solved CMPL model

Return: `str` Display options for the constraints

Cmpl.**solution**

Description: Returns the first (optimal) `CmplSolutions` object

Return: `CmplSolutions` first (optimal) solution

Cmpl.**solutionPool**

Description: Returns a list of `CmplSolutions` objects

Return: `list` of `CmplSolutions` objects — List of `CmplSolution` object for solutions found

CmplSolutions.**status**

Description: Returns the a string with the status of the current solution provided by the invoked solver

Return: `str` solution status

CmplSolutions.**value**

Description: Returns the value of the objective function of the current solution

Return: `float` objective function value

CmplSolutions.**idx**

Description: Returns the index of the current solution

Return: `int|long` index of the current solution

CmplSolutions.**variables**

Description: Returns a list of `CmplSolLine` objects for the variables of the current solution

Return: `list` of *`CmplSolLine`* objects — List of variables

CmplSolutions.**constraints**

Description: Returns a list of `CmplSolLine` objects for the constraints of the current solution

Return: `list` of *`CmplSolLine`* objects — List of constraints

CmplSolLine.**idx**

Description: Index of the variable or constraint

Return: `int|long` Index of the variable or constraint

CmplSolLine.**name**

Description: Name of the variable or constraint

Return: `str` Name of the variable or constraint

CmplSolLine.**type**

Description: Type of the variable or constraint

Return: *str* Type of the variable or constraint
`C|I|B` for variables
`L|E|G` for constraints

CmplSolLine.**activity**

Description: Activity of the variable or constraint

Return: *int|float* Activity of the variable or constraint

CmplSolLine.**lowerBound**

Description: Lower bound of the variable or constraint

Return: `float` Lower bound of the variable or constraint

CmplSolLine.**upperBound**

Description: Upper bound of the variable or constraint

Return: `float` Upper bound of the variable or constraint

CmplSolLine.**marginal**

Description: Marginal value (shadow prices or reduced costs) bound of the variable or constraint

Return: `float` Marginal value of the variable or constraint

Examples:

```
m = Cmpl("assignment.cmpl")
...

m.solve()

print m.solver
print m.solverMessage
print m.nrOfVariables
print m.nrOfConstraints
print m.varDisplayOptions
print m.conDisplayOptions
print m.objectiveName
print m.objectiveSense
print m.solution.value
print m.solution.status
print m.nrOfSolutions
print m.solution.idx
```

Solves the example from subchapter 11.1 and displays some information about the generated and solved model

```
COIN-OR cbc

11
7
(all)
(all)
costs
min
29.0
optimal
1
0
```

```
for v in m.solution.variables:
      print v.idx,v.name, v.type, \
            v.activity,v.lowerBound,\
            v.upperBound

for c in m.solution.constraints:
      print c.idx, c.name, c.type, \
            c.activity,c.lowerBound, \
            c.upperBound
```

Displays all information about variables and constraints of the optimal solution

```
Variables:
0 x[1,1] B 0.0 0.0 1.0
1 x[1,2] B 0.0 0.0 1.0
2 x[1,3] B 0.0 0.0 1.0
3 x[1,4] B 1.0 0.0 1.0
4 x[2,1] B 0.0 0.0 1.0
5 x[2,3] B 1.0 0.0 1.0
6 x[2,4] B 0.0 0.0 1.0
7 x[3,1] B 1.0 0.0 1.0
8 x[3,2] B 0.0 0.0 1.0
9 x[3,3] B 0.0 0.0 1.0
10 x[3,4] B 0.0 0.0 1.0
Constraints:
0 sos_m[1] E 1.0 1.0 1.0
1 sos_m[2] E 1.0 1.0 1.0
2 sos_m[3] E 1.0 1.0 1.0
3 sos_l[1] L 1.0 -inf 1.0
4 sos_l[2] L 0.0 -inf 1.0
5 sos_l[3] L 1.0 -inf 1.0
6 sos_l[4] L 1.0 -inf 1.0
```

```
m = Cmpl("assignment.cmpl")
...
m.setOption("%display nonZeros")
m.setOption("%arg -solver cplex")
m.setOption("%display solutionPool")
m.solve()

for s in m.solutionPool:
      print "Solution number: ",s.idx+1
      print "Objective value: ",s.value
      print "Objective status: ",s.status

      print "Variables:"
      for v in s.variables:
            print v.idx,v.name, v.type, \
                  v.activity,v.lowerBound,\
                  v.upperBound

      print "Constraints:"
      for c in s.constraints:
            print c.idx,c.name,c.type, \
                  c.activity,c.lowerBound, \
                  c.upperBound
```

Solves the example from subchapter 11.1 and displays all information about variables and constraints of all solution found

```
Solution number:  1
Objective value:  29.0
Objective status: integer optimal
solution
Variables:
3 x[1,4] B 1.0 0.0 1.0
5 x[2,3] B 1.0 0.0 1.0
7 x[3,1] B 1.0 0.0 1.0

Constraints:
0 sos_m[1] E 1.0 1.0 1.0
1 sos_m[2] E 1.0 1.0 1.0
2 sos_m[3] E 1.0 1.0 1.0
3 sos_l[1] L 1.0 -inf 1.0
```

	5 sos_l[3] L 1.0 -inf 1.0 6 sos_l[4] L 1.0 -inf 1.0 Solution number: 2 Objective value: 29.0 Objective status:integer feasible solution ...

for s in m.solutionPool:
 	
  m.varByName(s.idx)
  m.conByName(s.idx)
 	
  print "Variables:"
  for c in combinations.values:
  print m.x[c].name,m.x[c].type, \
  m.x[c].activity,\
  m.x[c].lowerBound,\
  m.x[c].upperBound
 	
  print "Constraints:"
  for i in m.sos_m:
  print m.sos_m[i].name,\
  m.sos_m[i].type, \
  m.sos_m[i].activity,\
  m.sos_m[i].lowerBound,\
  m.sos_m[i].upperBound
 	
  for j in m.sos_l:
  print m.sos_l[j].name,\
  m.sos_l[j].type,\
  m.sos_l[j].activity,\
  m.sos_l[j].lowerBound,\
  m.sos_l[j].upperBound
	As above but with direct access to the variable and constraint names
	
	Enables the direct access to the variable and constraint names of the current solution
	
	Iterates the variables x[i,j] over the value list of the CmplSet object combinations
	
	Iterates over the internal list of the indexing entries of the constraints with the name sos_m
	
	Iterates over the internal list of the indexing entries of the constraints with the name sos_l

11.3.3.5 Reading CMPL messages

R/o attributes:

Cmpl.**cmplMessages**

Description: Returns a list of CmplMsg objects that contain the CMPL messages

Return: list of *CmplMsg* objects — List of CMPL messages

CmplMsg.**type**

Description: Returns the type of the messages

Return: `str` message type `warning|error`

CmplMsg.**file**

Description: Returns the name of the CMPL file in that the error or warning occurs

Return: `str` CMPL file name

CmplMsg.**line**

Description: Returns the line in the CMPL file in that the error or warning occurs

Return: `str` line number

CmplMsg.**describtion**

Description: Returns the a description of the error or warning message

Return: `str` description of the error or warning

Examples:

```
model = Cmpl("diet.cmpl")
...
model.solve()

if model.cmplStatus==CMPL_WARNINGS:
      for m in model.cmplMessages:
            print m.type, \
                  m.file,\
                  m.line, \
                  m.describtion
```

If some warnings for the CMPL model `diet.cmpl` appear the messages will be shown.

11.3.4 CmplExceptions

pyCMPL provides its own exception handling. If an error occurs either by using pyCmpl classes or in the CMPL model a `CmplException` is raised by pyCmpl automatically. This exception can be handled through using a try-except block.

```
try:
      # do something
except CmplException, e:
      print e.msg
```

11.4 Examples

11.4.1 The diet problem

In this subchapter the pyCMPL formulation of the diet problem already discussed in subchapter 10.1.1 is dealt with.

The first step is to formulate the CMPL model `diet.cmpl` where the sets and parameters that are created in the pyCmpl script have to be specified in the CMPL header entry `%data`:

```
%data : NUTR set, FOOD set, costs[FOOD], vitamin[NUTR,FOOD], vitMin[NUTR]

variables:
      x[FOOD]: integer[2..10];

objectives:
      cost: costs[]T * x[]->min;

constraints:
      $2$: vitamin[,] * x[] >= vitMin[];
```

The corresponding pyCMPL script `diet.py` is formulated as follows:

```
#!/usr/bin/python

from pyCmpl import *

try:
      model = Cmpl("diet.cmpl")

      nutr = CmplSet("NUTR")
      nutr.setValues(["A", "B1", "B2", "C"])

      food = CmplSet("FOOD")
      food.setValues(["BEEF","CHK","FISH","HAM","MCH","MTL","SPG","TUR"])

      costs = CmplParameter("costs",food)
      costs.setValues([3.19, 2.59, 2.29, 2.89, 1.89, 1.99, 1.99, 2.49])

      vitmin = CmplParameter("vitMin",nutr)
      vitmin.setValues([ 700, 700, 700, 700])

      vitamin = CmplParameter("vitamin",nutr, food)
      vitamin.setValues([ [60,8,8,40,15,70,25,60],[20,0,10,40,35,30,50,20] , \
                          [10,20,15,35,15,15,25,15],[15,20,10,10,15,15,15,10]])

      model.setSets(nutr,food)
      model.setParameters(costs,vitmin,vitamin)
```

```
      model.solve()
      model.solutionReport()

except CmplException, e:
      print e.msg
```

Executing this pyCMPL model by using the command:

```
pyCmpl diet.py
```

leads to the following output created by pyCMPL's standard solution report:

```
------------------------------------------------------------------------------------------------------------
Problem               diet.cmpl
Nr. of variables      8
Nr. of constraints    4
Objective name        cost
Solver name           COIN-OR cbc
Display variables     (all)
Display constraints   (all)
------------------------------------------------------------------------------------------------------------

Objective status      optimal
Objective value       101.14              (min!)

Variables
Name                 Type            Activity          LowerBound          UpperBound            Marginal
------------------------------------------------------------------------------------------------------------
x[BEEF]                 I                   2                2.00               10.00                 nan
x[CHK]                  I                   8                2.00               10.00                 nan
x[FISH]                 I                   2                2.00               10.00                 nan
x[HAM]                  I                   2                2.00               10.00                 nan
x[MCH]                  I                  10                2.00               10.00                 nan
x[MTL]                  I                  10                2.00               10.00                 nan
x[SPG]                  I                  10                2.00               10.00                 nan
x[TUR]                  I                   2                2.00               10.00                 nan
------------------------------------------------------------------------------------------------------------

Constraints
Name                 Type            Activity          LowerBound          UpperBound            Marginal
------------------------------------------------------------------------------------------------------------
line[A]                 G             1500.00              700.00                 inf                 nan
line[B1]                G             1330.00              700.00                 inf                 nan
line[B2]                G              860.00              700.00                 inf                 nan
line[C]                 G              700.00              700.00                 inf                 nan
------------------------------------------------------------------------------------------------------------
```

11.4.2 Transportation problem

This subchapter discusses the pyCMPL formulation of the transportation problem from subchapter 10.1.6.

The CMPL model `transportation.cmpl` can be formulated as follows:

```
%data : plants set,centers set,routes set[2],c[routes], s[plants], d[centers]

variables:
      x[routes]: real[0..];
```

```
objectives:
      costs: sum{ [i,j] in routes : c[i,j]*x[i,j] } ->min;
constraints:
      supplies {i in plants : sum{j in routes *> [i,*] : x[i,j]} = s[i];}
      demands  {j in centers: sum{i in routes *> [*,j] : x[i,j]} <= d[j];}
```

The corresponding pyCMPL script `transportation.py` is formulated as follows:

```
#!/usr/bin/python

from pyCmpl import *

try:
      model = Cmpl("transportation.cmpl")

      routes = CmplSet("routes",2)
      routes.setValues([[1,1],[1,2],[1,4],[2,2],[2,3],[2,4],[3,1],[3,3]])

      plants = CmplSet("plants")
      plants.setValues(1,3)

      centers = CmplSet("centers")
      centers.setValues(1,4)

      costs = CmplParameter("c",routes)
      costs.setValues([3,2,6,5,2,3,2,4])

      s = CmplParameter("s",plants)
      s.setValues([5000,6000,2500])

      d = CmplParameter("d",centers)
      d.setValues([6000,4000,2000,2500])

      model.setSets(routes, plants, centers)
      model.setParameters(costs,s,d)

      model.setOutput(True)
      model.setOption("%display nonZeros")
      model.solve()

      if model.solverStatus == SOLVER_OK:
            model.solutionReport()
      else:
            print "Solver failed " + model.solver + " " + model.solverMessage

except CmplException, e:
      print e.msg
```

Executing this pyCMPL model by using the command:

```
pyCmpl transportation.py
```

leads to the following output of CMPL and CBC and the standard solution report:

```
transportation> CMPL model generation - running
transportation>
transportation> CMPL version: 1.8.0
transportation> Authors: Thomas Schleiff, Mike Steglich
transportation> Distributed under the GPLv3
transportation>
transportation> create model instance ...
transportation> write model instance ...
transportation> CMPL model generation - finished
transportation>
transportation> Solver - running
transportation>
transportation>
transportation>
transportation> Optimization Services Solver
transportation> Main Authors: Horand Gassmann, Jun Ma, and Kipp Martin
transportation> Distributed under the Eclipse Public License
transportation> OS Version: 2.6.0
transportation> Build Date: May 25 2013
transportation> SVN Version: 4605
transportation>
transportation> Input String =  -config transportation_704532.cFconf
transportation> call ossslex
transportation> done with call to ossslex
transportation> configFileName = transportation_704532.cFconf
transportation> Call Text Extra
transportation> Done with call Text Extra
transportation> call ossslex
transportation> HERE ARE THE OPTION VALUES:
transportation> Config file = transportation_704532.cFconf
transportation> OSiL file = transportation_704532.osil
transportation> OSrL file = transportation_704532.osrl
transportation> Service Method = solve
transportation>
transportation> Solution written to cmplSolution file
transportation>
transportation> Solver - finished
-----------------------------------------------------------------------------------------------------
Problem               transportation.cmpl
Nr. of variables      8
Nr. of constraints    7
Objective name        costs
Solver name           COIN-OR clp
Display variables     nonZeroVariables(all)
Display constraints   nonZeroConstraints(all)
-----------------------------------------------------------------------------------------------------

Objective status      optimal
Objective value       36500.00            (min!)

Variables
Name                 Type            Activity         LowerBound         UpperBound            Marginal
-----------------------------------------------------------------------------------------------------
x[1,1]                  C             2500.00               0.00                inf                0.00
x[1,2]                  C             2500.00               0.00                inf                0.00
x[2,2]                  C             1500.00               0.00                inf                0.00
x[2,3]                  C             2000.00               0.00                inf                0.00
x[2,4]                  C             2500.00               0.00                inf                0.00
x[3,1]                  C             2500.00               0.00                inf                0.00
-----------------------------------------------------------------------------------------------------
```

```
Constraints
Name                 Type            Activity         LowerBound         UpperBound            Marginal
------------------------------------------------------------------------------------------------------
supplies[1]             E             5000.00            5000.00            5000.00                3.00
supplies[2]             E             6000.00            6000.00            6000.00                6.00
supplies[3]             E             2500.00            2500.00            2500.00                2.00
demands[1]              L             5000.00               -inf            6000.00                 nan
demands[2]              L             4000.00               -inf            4000.00               -1.00
demands[3]              L             2000.00               -inf            2000.00               -4.00
demands[4]              L             2500.00               -inf            2500.00               -3.00
------------------------------------------------------------------------------------------------------
```

11.4.3 The shortest path problem

Consider an undirected network $G=(V,A)$ where V is a set of nodes and A is a set of arcs joining pairs of nodes. The decision is to find the shortest path from a starting node s to a target node t. This problem can be formulated as an LP as follows (Hillier and Liebermann 2010, p. 383f.):

$$\sum_{(i,j)\in A} c_{ij} \cdot x_{ij} \rightarrow min!$$

$$s.t.$$

$$\sum_{(i,j)\in A} x_{ij} - \sum_{(j,i)\in A} x_{ji} = \begin{cases} 1 & , if\ i=s \\ -1 & , if\ i=t \\ 0 & , otherwise \end{cases} ; \forall i \in V$$

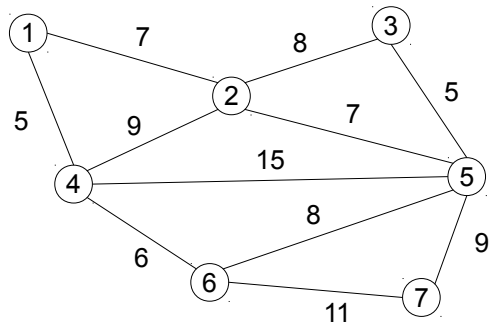
$$x_{ij} \geq 0; \forall (i,j) \in A$$

The decision variables are $x_{ij}; \forall \in A$ with $x_{ij}=1$ if the arc $i \rightarrow j$ is used. The parameters $c_{ij}; \forall \in A$ define the distance between the nodes i and j, but can also are interpreted as the time a vehicle takes to drive from node i to node j.

This mathematical model can be formulated as follows whilst the sets A an V and the parameters c_{ij}, t and s are defined in a pyCMPL script.

```
%data : A set[2], c[A], V set , s, t

parameters:
      { i in V: { i=s : rHs[i]:=1; |
                  i=t : rHs[i]:=-1; |
                  default: rHs[i]:=0;}  }

variables:
      x[A] :real[0..];

objectives:
      sum{ [i,j] in A: c[i,j]*x[i,j] } -> min;

constraints:
      node { i in V:  sum{ j in (A *> [i,*]) : x[i,j]  } -
                      sum{ j in (A *> [*,i]) : x[j,i]  }  = rHs[i];}
```

To describe the formulation of the shortest path problem in pyCMPL the simple example shown in the following figure is used where the weights on the arcs are interpreted as the time a vehicle needs to travel from a node *i* to a node *j*.



Assuming that the staring node is node 1 and the target node is node 7 the corresponding pyCMPL script `shortest-path.py` is formulated as follows:

```
#!/usr/bin/python

from pyCmpl import *

try:
      model = Cmpl("shortest-path.cmpl")

      routes = CmplSet("A",2)
      routes.setValues([ [1,2],[1,4],[2,1],[2,3],[2,4],[2,5],\
                         [3,2],[3,5],[4,1],[4,2],[4,5],[4,6],\
                         [5,2],[5,3],[5,4],[5,6],[5,7],\
                         [6,4],[6,5],[6,7],[7,5],[7,6] ])

      nodes = CmplSet("V")
      nodes.setValues(1,7)

      c = CmplParameter("c", routes)
      c.setValues([7,5,7,8,9,7,8,5,5,9,15,6,7,5,15,8,9,6,8,11,9,11])

      sNode = CmplParameter("s")
      sNode.setValues(1)

      tNode = CmplParameter("t")
      tNode.setValues(7)

      model.setSets(routes, nodes)
      model.setParameters(c,sNode,tNode)

      model.solve()
      print "Objective Value: ", model.solution.value
```

```
      for v in model.solution.variables:
            if v.activity>0:
                  print v.name , " " , v.activity

except CmplException, e:
      print e.msg
```

Executing this pyCMPL model through using the command:

```
pyCmpl shortes-path.py
```

leads to the following output of the pyCMPL script:

```
Objective Value:  22.0
x[1,4]   1.0
x[4,6]   1.0
x[6,7]   1.0
```

The optimal route is 1→4→6→7 with a travelling time of 22 (minutes or hours).

11.4.4 Solving randomized shortest path problems in parallel

For the last example it was shown that the optimal route travelling from node 1 to node 7 is 1→4→6→7. This solution is based on the assumption that the travelling times between nodes are certain. This example describes how a randomized shortest path problem can be solved where subproblems describing random situations are solved in own threads in parallel.

Assuming that the staring node is node 1 and the target node is node 7 the corresponding pyCMPL script `shortest-path.py` is formulated as follows:

```
1   #!/usr/bin/python
2   from __future__ import division
3
4   from pyCmpl import *
5   import random
6
7   try:
8         routes = CmplSet("A",2)
9         routes.setValues([ [1,2],[1,4],[2,1],[2,3],[2,4],[2,5],\
10                           [3,2],[3,5],[4,1],[4,2],[4,5],[4,6],\
11                           [5,2],[5,3],[5,4],[5,6],[5,7],\
12                           [6,4],[6,5],[6,7],[7,5],[7,6] ])
13
14        nodes = CmplSet("V")
15        nodes.setValues(1,7)
16
17        c = CmplParameter("c", routes)
18        c.setValues([7,5,7,8,9,7,8,5,5,9,15,6,7,5,15,8,9,6,8,11,9,11])
```

```
19
20        sNode = CmplParameter("s")
21        sNode.setValues(1)
22
23        tNode = CmplParameter("t")
24        tNode.setValues(7)
25
26        models= []
27        randC = []
28        for i in range(5):
29              models.append(Cmpl("shortest-path.cmpl"))
30              models[i].setSets(routes, nodes)
31
32              tmpC =[]
33              for m in c.values:
34                    tmpC.append( m + random.randint(-40,40)/10)
35
36              randC.append(CmplParameter("c", routes))
37              randC[i].setValues(tmpC)
38
39              models[i].setParameters(randC[i],sNode,tNode)
40
41        for m in models:
42              m.start()
43
44        for m in models:
45              m.join()
46
47        i = 0
48        for m in models:
49              print "problem : " , i , " needed time " , m.solution.value
50              for v in m.solution.variables:
51                    if v.activity>0:
52                          print v.name , " " , v.activity
53              i = i + 1
54
56  except CmplException, e:
57        print e.msg
```

This script uses the same sets and parameters as before but for each of the 5 instantiated models in line 29 a new parameter array c is created whilst the original array c is changed by random numbers in line 34. In line 42 all of the models are starting and in line 45 the pyCmpl script is waiting for the termination of all of the models.

Executing this pyCMPL model through using the command:

```
pyCmpl shortes-path.py
```

can lead to the following output of the pyCMPL script, but every new run will show different results because of the random numbers.

```
problem :  0  needed time  23.7
x[1,4]   1.0
x[4,6]   1.0
x[6,7]   1.0
problem :  1  needed time  20.2
x[1,2]   1.0
x[2,5]   1.0
x[5,7]   1.0
problem :  2  needed time  13.3
x[1,4]   1.0
x[4,6]   1.0
x[6,7]   1.0
problem :  3  needed time  17.6
x[1,2]   1.0
x[2,5]   1.0
x[5,7]   1.0
problem :  4  needed time  20.7
x[1,4]   1.0
x[4,6]   1.0
x[6,7]   1.0
```

Depending on the uncertain traffic situations two different routes between the nodes $1 \rightarrow 7$ can be optimal: 1→4→6→7 and 1→2→5→7 .

11.4.5 Column generation for a cutting stock problem

The following pyCMPL script including the example is based on the the AMPL formulation of a column generator for a cutting stock problem and is taken from (Fourer, Gay & Kernigham 2003, p. 304ff).

In this cutting stock problem long raw rolls of paper have to be cut up into combinations of smaller widths that have to meet given orders and the objective is to minimize the waste.

In the example, the raw width is 110" and the demands for particular widths are given in the following table:

orders (demand)	withs
48	20"
35	45"
24	50"
10	55"
8	75"

Fourer, Gay & Kernigham use the so-called Gilmore-Gomory procedure to define cutting patterns by involving two linear programs.

The first model is a cutting optimization model that finds the minimum number of raw rolls with a given set of possible cutting patterns subject to fulfilling the orders for the particular widths. This problem can be formulated as in the CMPL file `cut.cmpl` as follows:

```
%data :rollWidth, widths set, patterns set, orders[widths],nbr[widths,patterns]

variables:
      cut[patterns]: integer[0..];

objectives:
      number: sum{ j in patterns: cut[j] }->min;

constraints:
      fill {i in widths: sum{ j in patterns : nbr[i,j]*cut[j] } >= orders[i]; }
```

The parameter `rollWidth` defines the width of the raw rolls, the set `widths` defines the widths to be cut, the set `patterns` the set of the patterns, the parameter `orders` the number of orders per width and the parameters `nbr[i,j]` the number of rolls of width `i` in pattern `j`. The variables are the `cut[j]` and they define how many cuts of a pattern `j` are to be produced.

The second model is the pattern generation model that is indented to identify a new pattern that can be used in the cutting optimization.

```
%data :  widths set, price[widths], rollWidth

variables:
      use[widths]: integer[0..];
      reducedCosts : real;

objectives:
      sum{ i in widths: price[i] * use[i]} -> max;

constraints:
      sum{ i in widths : i * use[i] } <= rollWidth;
```

This model in the CMPL file `cut-pattern.cmpl` requires as specified in the `%data` entry the set `widths`, the parameter `rollWidth` and a parameter vector `price`, that contains the marginals of the constraints `fill` of a solved `cut.cmpl` problem with a relaxation of the integer variables `cut[j]`.

It is a knapsack problem that "fills" a knapsack (here a raw roll with a given width `rollWidth`) with the most valuable things (here the desired widths via the variables `use[i]`) where the value of a width `i` is specified by the `price[i]`.

The relationship between these two CMPL models and the entire cutting optimization procedure is controlled by the following pyCMPL script `cut.py`

```
1   #!/usr/bin/python
2
3   from pyCmpl import *
4   import math
```

```
5
6  try:
7        cuttingOpt = Cmpl("cut.cmpl")
8        patternGen = Cmpl("cut-pattern.cmpl")
9
10       cuttingOpt.setOption("%arg -solver cplex")
11       patternGen.setOption("%arg -solver cplex")
12
13       r = CmplParameter("rollWidth")
14       r.setValues(110)
15
16       w = CmplSet("widths")
17       w.setValues([ 20, 45, 50, 55, 75])
18
19       o = CmplParameter("orders",w)
20       o.setValues([ 48, 35, 24, 10, 8 ])
21
22       nPat=w.len
23       p = CmplSet("patterns")
24       p.setValues(1,nPat)
25
26       nbr = []
27       for i in range(nPat):
28             nbr.append( [ 0 for j in range(nPat) ] )
29
30       for i in w.values:
31             pos = w.values.index(i)
32             nbr[pos][pos] = int(math.floor( r.value / i ))
33
34       n = CmplParameter("nbr", w, p)
35       n.setValues(nbr)
36
37       price = []
38       for i in range(w.len):
39             price.append(0)
40
41       pr = CmplParameter("price", w)
42       pr.setValues(price)
43
44       cuttingOpt.setSets(w,p)
45       cuttingOpt.setParameters(r, o, n)
46
47       patternGen.setSets(w)
48       patternGen.setParameters(r,pr)
49
50       ri = cuttingOpt.setOption("%arg -integerRelaxation")
```

```
51
52       while True:
53             cuttingOpt.solve()
54             cuttingOpt.conByName()
56
57             for i in w.values:
58                   pos = w.values.index(i)
59                   price[pos] = cuttingOpt.fill[i].marginal
60
61             pr.setValues(price)
62
63             patternGen.solve()
64             patternGen.varByName()
65
66             if (1-patternGen.solution.value) < -0.00001:
67                   nPat = nPat + 1
68                   p.setValues(1,nPat)
69                   for i in w.values:
70                         pos = w.values.index(i)
71                         nbr[pos].append(patternGen.use[i].activity)
72                   n.setValues(nbr)
73             else:
74                   break
75
76       cuttingOpt.delOption(ri)
77
78       cuttingOpt.solve()
79       cuttingOpt.varByName()
80
81       print "Objective value: " , cuttingOpt.solution.value
82       for j in p.values:
83             if cuttingOpt.cut[j].activity>0:
84                   print cuttingOpt.cut[j].activity, " pieces of pattern: "
85                   for i in range(len(w.values)):
86                         print "\twidth ", w.values[i] , " - " , nbr[i][j-1]
87
88 except CmplException, e:
89       print e.msg
```

Cplex is chosen as solver for both in the lines 7 and 8 instantiated models (lines 10,11). In the next lines 13-18 the parameters `rollWidth` and `orders` and the set `widths` are created and the corresponding data are assigned. The lines 26-35 are intended to create an initial set of patterns whilst the matrix `nbr` contains only of one pattern per width, where the diagonal elements are equal to the maximal possible number of rolls of the particular width. After creating the vector `price` with null values in the lines 37-42 all relevant sets and parameters are committed to both `Cmpl` objects (lines 44-48).

In the next lines the Gilmore-Gomory procedure is performed.

1. Solve the cutting optimization problem `cut.cmpl` with an integer relaxation (line 50 and 53).
2. Assign the shadow prices `cuttingOpt.fill[i].marginal` to the corresponding elements `price[i]` for each pattern (lines 57-59).
3. Solve the pattern generation model `cut-pattern.cmpl` (line 63).
4. If (1 – optimal objective value) is approximately < 0 (line 66)

   then add a new pattern using the activities `patternGen.use[i].activity` for all elements in `widths (lines 69-72)` and jump to step 1.

   else

   Solve the final cutting optimization problem `cut.cmpl` as integer program (line 76 and 78)

After finding the final solution the next lines (lines 79-86) are intended to provide some information about the final integer solution.

Executing this pyCMPL model through using the command:

```
pyCmpl cut.py
```

leads to the following output of the pyCMPL script:

```
Objective value:  47.0
8  pieces of pattern:
      width  20  -  0
      width  45  -  0
      width  50  -  2
      width  55  -  0
      width  75  -  0
5  pieces of pattern:
      width  20  -  0
      width  45  -  0
      width  50  -  0
      width  55  -  2
      width  75  -  0
8  pieces of pattern:
      width  20  -  1
      width  45  -  0
      width  50  -  0
      width  55  -  0
      width  75  -  1
18  pieces of pattern:
      width  20  -  1
      width  45  -  2
      width  50  -  0
      width  55  -  0
      width  75  -  0
```

```
8  pieces of pattern:
      width  20  -  3
      width  45  -  0
      width  50  -  1
      width  55  -  0
      width  75  -  0
```

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- Support via mailing list

  Please use our CMPL mailing list hosted at COIN-OR http://list.coin-or.org/mailman/listinfo/Cmpl to get a direct support, to post bugs or to communicate wishes.

13 Appendix

13.1 Selected CBC parameters

The CBC parameters are taken (mostly unchanged) from the CBC command line help. Only the CBC parameters that are useful in a CMPL context are described afterwards.

Usage CBC parameters:

```
%opt cbc solverOption [solverOptionValue]
```

Double parameters:

dualB(ound) *doubleValue*

Initially algorithm acts as if no gap between bounds exceeds this value

Range of values is 1e-20 to 1e+12, default 1e+10

dualT(olerance) *doubleValue*

For an optimal solution no dual infeasibility may exceed this value
Range of values is 1e-20 to 1e+12, default 1e-07

objective(Scale) *doubleValue*

Scale factor to apply to objective

Range of values is -1e+20 to 1e+20, default 1

primalT(olerance) *doubleValue*

For an optimal solution no primal infeasibility may exceed this value

Range of values is 1e-20 to 1e+12, default 1e-07

primalW(eight) *doubleValue*

Initially algorithm acts as if it costs this much to be infeasible

Range of values is 1e-20 to 1e+20, default 1e+10

rhs(Scale) *doubleValue*

Scale factor to apply to rhs and bounds

Range of values is -1e+20 to 1e+20, default 1

Branch and Cut double parameters:

allow(ableGap) *doubleValue*

Stop when gap between best possible and best less than this

Range of values is 0 to 1e+20, default 0

artif(icialCost) *doubleValue*

Costs >= these are treated as artificials in feasibility pump 0.0 off - otherwise variables with costs >= these are treated as artificials and fixed to lower bound in feasibility pump

Range of values is 0 to 1.79769e+308, default 0

cuto(ff) *doubleValue*

All solutions must be better than this value (in a minimization sense).

This is also set by code whenever it obtains a solution and is set to value of objective for solution minus cutoff increment.

Range of values is -1e+60 to 1e+60, default 1e+50

fix(OnDj) *doubleValue*

Try heuristic based on fixing variables with reduced costs greater than this

If this is set integer variables with reduced costs greater than this will be fixed before branch and bound - use with extreme caution!

Range of values is -1e+20 to 1e+20, default -1

fraction(forBAB) *doubleValue*

Fraction in feasibility pump

After a pass in feasibility pump, variables which have not moved about are fixed and if the pre-processed model is small enough a few nodes of branch and bound are done on reduced problem. Small problem has to be less than this fraction of original.

Range of values is 1e-05 to 1.1, default 0.5

inc(rement) *doubleValue*

A valid solution must be at least this much better than last integer solution

Whenever a solution is found the bound on solutions is set to solution (in a minimization sense) plus this. If it is not set then the code will try and work one out.

Range of values is -1e+20 to 1e+20, default 1e-05

inf(easibilityWeight) *doubleValue*

Each integer infeasibility is expected to cost this much

Range of values is 0 to 1e+20, default 0

integerT(olerance) *doubleValue*

For an optimal solution no integer variable may be this away from an integer value

Range of values is 1e-20 to 0.5, default 1e-06

preT(olerance) *doubleValue*

Tolerance to use in presolve

Range of values is 1e-20 to 1e+12, default 1e-08

pumpC(utoff) *doubleValue*

Fake cutoff for use in feasibility pump

0.0 off - otherwise add a constraint forcing objective below this value in feasibility pump

Range of values is -1.79769e+308 to 1.79769e+308, default 0

pumpI(ncrement) *doubleValue*

Fake increment for use in feasibility pump

0.0 off - otherwise use as absolute increment to cut off when solution found in feasibility pump

Range of values is -1.79769e+308 to 1.79769e+308, default 0

ratio(Gap) *doubleValue*

If the gap between best solution and best possible solution is less than this fraction of the objective value at the root node then the search will terminate.

Range of values is 0 to 1e+20, default 0

reallyO(bjectiveScale) *doubleValue*

Scale factor to apply to objective in place

Range of values is -1e+20 to 1e+20, default 1

sec(onds) *doubleValue*

maximum seconds

After this many seconds coin solver will act as if maximum nodes had been reached.

Range of values is -1 to 1e+12, default 1e+08

tighten(Factor) *doubleValue*

Tighten bounds using this times largest activity at continuous solution

Range of values is 0.001 to 1e+20, default -1

Integer parameters:

idiot(Crash) *integerValue*

This is a type of 'crash' which works well on some homogeneous problems. It works best on problems with unit elements and rhs but will do something to any model. It should only be used before primal. It can be set to -1 when the code decides for itself whether to use it, 0 to switch off or n > 0 to do n passes.

Range of values is -1 to 99999999, default -1

maxF(actor) *integerValue*

Maximum number of iterations between refactorizations

Range of values is 1 to 999999, default 200

maxIt(erations) *integerValue*

Maximum number of iterations before stopping

Range of values is 0 to 2147483647, default 2147483647

passP(resolve) *integerValue*

How many passes in presolve

Range of values is -200 to 100, default 5

pO(ptions) *integerValue*

If this is > 0 then presolve will give more information and branch and cut will give statistics

Range of values is 0 to 2147483647, default 0

slp(Value) *integerValue*

Number of slp passes before primal

If you are solving a quadratic problem using primal then it may be helpful to do some sequential Lps to get a good approximate solution.

Range of values is -1 to 50000, default -1

slog(Level) *integerValue*

Level of detail in (LP) Solver output

Range of values is -1 to 63, default 1

subs(titution) *integerValue*

How long a column to substitute for in presolve

Normally Presolve gets rid of 'free' variables when there are no more than 3 variables in column. If you increase this the number of rows may decrease but number of elements may increase.

Range of values is 0 to 10000, default 3

Branch and Cut integer parameters:

cutD(epth) *integerValue*

Depth in tree at which to do cuts

Cut generators may be - off, on only at root, on if they look possible and on. If they are done every node then that is that, but it may be worth doing them every so often. The original method was every so many nodes but it is more logical to do it whenever depth in tree is a multiple of K. This option does that and defaults to -1 (off -> code decides).

Range of values is -1 to 999999, default -1

cutL(ength) *integerValue*

Length of a cut

At present this only applies to Gomory cuts. -1 (default) leaves as is. Any value >0 says that all cuts <= this length can be generated both at root node and in tree. 0 says to use some dynamic lengths. If value >=10,000,000 then the length in tree is value%10000000 - so 10000100 means unlimited length at root and 100 in tree.

Range of values is -1 to 2147483647, default -1

dense(Threshold) *integerValue*

Whether to use dense factorization

Range of values is -1 to 10000, default -1

depth(MiniBab) *integerValue*

Depth at which to try mini BAB

Rather a complicated parameter but can be useful. -1 means off for large problems but on as if -12 for problems where rows+columns<500, -2 means use Cplex if it is linked in. Otherwise if negative then go into depth first complete search fast branch and bound when depth>= -value-2 (so -3 will use this at depth>=1). This mode is only switched on after 500 nodes. If you really want to switch it off for small problems then set this to -999. If >=0 the value doesn't matter very much. The code will do approximately 100 nodes of fast branch and bound every now and then at depth>=5. The actual logic is too twisted to describe here.

Range of values is -2147483647 to 2147483647, default -1

diveO(pt) *integerValue*

Diving options

If >2 && <8 then modify diving options

–3 only at root and if no solution,

–4 only at root and if this heuristic has not got solution,

–5 only at depth <4,

–6 decay, 7 run up to 2 times

if solution found 4 otherwise.

Range of values is -1 to 200000, default 3

hOp(tions) *integerValue*

Heuristic options

1 says stop heuristic immediately allowable gap reached. Others are for feasibility pump - 2 says do exact number of passes given, 4 only applies if initial cutoff given and says relax after 50 passes, while 8 will adapt cutoff rhs after first solution if it looks as if code is stalling.

Range of values is -9999999 to 9999999, default 0

hot(StartMaxIts) *integerValue*

Maximum iterations on hot start

Range of values is 0 to 2147483647, default 100

log(Level) *integerValue*

Level of detail in Coin branch and Cut output

If 0 then there should be no output in normal circumstances. 1 is probably the best value for most uses, while 2 and 3 give more information.

Range of values is -63 to 63, default 1

maxN(odes) *integerValue*

Maximum number of nodes to do

Range of values is -1 to 2147483647, default 2147483647

maxS(olutions) *integerValue*

Maximum number of solutions to get

You may want to stop after (say) two solutions or an hour. This is checked every node in tree, so it is possible to get more solutions from heuristics.

Range of values is 1 to 2147483647, default -1

passC(uts) *integerValue*

Number of cut passes at root node

The default is 100 passes if less than 500 columns, 100 passes (but stop if drop small if less than 5000 columns, 20 otherwise

Range of values is -9999999 to 9999999, default -1

passF(easibilityPump) *integerValue*

How many passes in feasibility pump

This fine tunes Feasibility Pump by doing more or fewer passes.

Range of values is 0 to 10000, default 30

passT(reeCuts) *integerValue*

Number of cut passes in tree

Range of values is -9999999 to 9999999, default 1

small(Factorization) *integerValue*

Whether to use small factorization

If processed problem <= this use small factorization

Range of values is -1 to 10000, default -1

strong(Branching) *integerValue*

Number of variables to look at in strong branching

Range of values is 0 to 999999, default 5

thread(s) *integerValue*

Number of threads to try and use

To use multiple threads, set threads to number wanted. It may be better to use one or two more than number of cpus available. If 100+n then n threads and search is repeatable (maybe be somewhat slower), if 200+n use threads for root cuts, 400+n threads used in sub-trees.

Range of values is -100 to 100000, default 0

trust(PseudoCosts) *integerValue*

Number of branches before we trust pseudocosts

Range of values is -3 to 2000000, default 5

Keyword parameters:

bscale *option*

Whether to scale in barrier (and ordering speed)

Possible options: off on off1 on1 off2 on2, default off

chol(esky) *option*

Which cholesky algorithm

Possible options: native dense fudge(Long_dummy) wssmp_dummy

crash *option*

Whether to create basis for problem

If crash is set on and there is an all slack basis then Clp will flip or put structural variables into basis with the aim of getting dual feasible. On the whole dual seems to be better without it and there are alternative types of 'crash' for primal e.g. 'idiot' or 'sprint'.

Possible options: off on so(low_halim) ha(lim_solow(JJF mods)), dfeault off

cross(over) *option*

Whether to get a basic solution after barrier

Interior point algorithms do not obtain a basic solution (and the feasibility criterion is a bit suspect (JJF)). This option will crossover to a basic solution suitable for ranging or branch and cut. With the current state of quadratic it may be a good idea to switch off crossover for quadratic (and maybe presolve as well) - the option maybe does this.

Possible options: on off maybe presolve, default on

dualP(ivot) *option*

Dual pivot choice algorithm

Possible options: auto(matic) dant(zig) partial steep(est), default auto(matic)

fact(orization) *option*

Which factorization to use

Possible options: normal dense simple osl, default normal

gamma((Delta)) *option*

Whether to regularize barrier

Possible options: off on gamma delta onstrong gammastrong deltastrong, default off

KKT *option*

Whether to use KKT factorization

Possible options: off on, default off

perturb(ation) *option*

Whether to perturb problem

Possible options: on off, default on

presolve *option*

Presolve analyzes the model to find such things as redundant equations, equations which fix some variables, equations which can be transformed into bounds etc etc. For the initial solve of any problem this is worth doing unless you know that it will have no effect. on will normally do 5 passes while using 'more' will do 10. If the problem is very large you may need to write the original to file using 'file'.

Possible options for presolve are: on off more file, default on

primalP(ivot) *option*

Primal pivot choice algorithm

Possible options: auto(matic) exa(ct) dant(zig) part(ial) steep(est) change sprint, default auto(matic)

scal(ing) *option*

Whether to scale problem

Possible options: off equi(librium) geo(metric) auto(matic) dynamic rows(only), default auto(matic)

spars(eFactor) *option*

Whether factorization treated as sparse

Possible options: on off, default on

timeM(ode) *option*

Whether to use CPU or elapsed time

cpu uses CPU time for stopping, while elapsed uses elapsed time. (On Windows, elapsed time is always used).

Possible options: cpu elapsed, default cpu

vector *option*

If this parameter is set to on ClpPackedMatrix uses extra column copy in odd format.

Possible options: off on, default off

Branch and Cut keyword parameters:

clique(Cuts) *option*

Whether to use Clique cuts

Possible options: off on root ifmove forceOn onglobal, default ifmove

combine(Solutions) *option*

Whether to use combine solution heuristic

This switches on a heuristic which does branch and cut on the problem given by just using variables which have appeared in one or more solutions. It obviously only tries after two or more solutions. See Rounding for meaning of on,both,before

Possible options: off on both before, default on

combine2(Solutions) *option*

Whether to use crossover solution heuristic

This switches on a heuristic which does branch and cut on the problem given by fixing variables which have same value in two or more solutions. It obviously only tries after two or more solutions. See Rounding for meaning of on,both,before

Possible options: off on both before, default off

cost(Strategy) *option*

How to use costs as priorities

This orders the variables in order of their absolute costs - with largest cost ones being branched on first. This primitive strategy can be surprsingly effective. The column order option is obviously not on costs but easy to code here.

Possible options: off pri(orities) column(Order?) 01f(irst?) 01l(ast?) length(?), default off

cuts(OnOff) *option*

Switches all cuts on or off

This can be used to switch on or off all cuts (apart from Reduce and Split). Then you can do individual ones off or on See branchAndCut for information on options.

Possible options: off on root ifmove forceOn, default on

Dins *option*

This switches on Distance induced neighborhood Search. See Rounding for meaning of on,both,before

Possible options: off on both before often, default off

DivingS(ome) *option*

This switches on a random diving heuristic at various times. C - Coefficient, F - Fractional, G - Guided, L - LineSearch, P - PseudoCost, V - VectorLength. You may prefer to use individual on/off See Rounding for meaning of on,both,before

Possible options: off on both before, default off

DivingC(oefficient) *option*

Whether to try DiveCoefficient

Possible options: off on both before, default on

DivingF(ractional) *option*

Whether to try DiveFractional

Possible options: off on both before, default off

DivingG(uided) *option*

Whether to try DiveGuided

Possible options: off on both before, default off

DivingL(ineSearch) *option*

Whether to try DiveLineSearch

Possible options: off on both before, default off

DivingP(seudoCost) *option*

Whether to try DivePseudoCost

Possible options: off on both before, default off

DivingV(ectorLength) *option*

Whether to try DiveVectorLength

Possible options: off on both before, default off

feas(ibilityPump) *option*

This switches on feasibility pump heuristic at root. This is due to Fischetti, Lodi and Glover and uses a sequence of Lps to try and get an integer feasible solution. Some fine tuning is available by passFeasibilityPump and also pumpTune. See Rounding for meaning of on,both,before

Possible options: off on both before, default on

flow(CoverCuts) *option*

This switches on flow cover cuts (either at root or in entire tree)

See branchAndCut for information on options.

Possible options: off on root ifmove forceOn onglobal, default ifmove

gomory(Cuts) *option*

Whether to use Gomory cuts

The original cuts - beware of imitations! Having gone out of favor, they are now more fashionable as LP solvers are more robust and they interact well with other cuts. They will almost always give cuts (although in this executable they are limited as to number of variables in cut). However the cuts may be dense so it is worth experimenting (Long allows any length). See branchAndCut for information on options.

Possible options: off on root ifmove forceOn onglobal forceandglobal forceLongOn long, default ifmove

greedy(Heuristic) *option*

Whether to use a greedy heuristic

Switches on a greedy heuristic which will try and obtain a solution. It may just fix a percentage of variables and then try a small branch and cut run. See Rounding for meaning of on,both,before

Possible options: off on both before, default on

heur(isticsOnOff) *option*

Switches most heuristics on or off

Possible options: off on, default on

knapsack(Cuts) *option*

This switches on knapsack cuts (either at root or in entire tree)

Possible options: off on root ifmove forceOn onglobal forceandglobal, default ifmove

lift(AndProjectCuts) *option*

Whether to use Lift and Project cuts

Possible options: off on root ifmove forceOn, default off

local(TreeSearch) *option*

This switches on a local search algorithm when a solution is found. This is from Fischetti and Lodi and is not really a heuristic although it can be used as one. When used from Coin solve it has limited functionality. It is not switched on when heuristics are switched on.

Possible options: off on, default off

mixed(IntegerRoundingCuts) *option*

This switches on mixed integer rounding cuts (either at root or in entire tree) See branchAndCut for information on options.

Possible options: off on root ifmove forceOn onglobal, default ifmove

naive(Heuristics) *option*

Really silly stuff e.g. fix all integers with costs to zero!. Do option does heuristic before preprocessing

Possible options: off on both before, default off

node(Strategy) *option*

What strategy to use to select nodes

Normally before a solution the code will choose node with fewest infeasibilities. You can choose depth as the criterion. You can also say if up or down branch must be done first (the up down choice will carry on after solution). Default has now been changed to hybrid which is breadth first on small depth nodes then fewest.

Possible options: hybrid fewest depth upfewest downfewest updepth downdepth, default fewest

pivotAndC(omplement) *option*

Whether to try Pivot and Complement heuristic

Possible options: off on both before, default off

pivotAndF(ix) *option*

Whether to try Pivot and Fix heuristic

Possible options: off on both before, default off

preprocess *option*

This tries to reduce size of model in a similar way to presolve and it also tries to strengthen the model - this can be very useful and is worth trying. Save option saves on file presolved.mps. equal will turn <= cliques into ==. sos will create sos sets if all 0-1 in sets (well one extra is allowed) and no overlaps. trysos is same but allows any number extra. equalall will turn all valid inequalities into equalities with integer slacks.

Possible options: off on save equal sos trysos equalall strategy aggregate forcesos, default sos

probing(Cuts) *option*

This switches on probing cuts (either at root or in entire tree) See branchAndCut for information on options. but strong options do more probing

Possible options: off on root ifmove forceOn onglobal forceonglobal forceOnBut forceOnStrong forceOnButStrong strongRoot, default forceOnStrong

rand(omizedRounding) *option*

Whether to try randomized rounding heuristic

Possible options: off on both before, default off

reduce(AndSplitCuts) *option*

This switches on reduce and split cuts (either at root or in entire tree) See branchAndCut for information on options.

Possible options: off on root ifmove forceOn, default off

residual(CapacityCuts) *option*

Residual capacity cuts. See branchAndCut for information on options.

Possible options: off on root ifmove forceOn, default off

Rens *option*

This switches on Relaxation enforced neighborhood Search. on just does 50 nodes 200 or 1000 does that many nodes. Doh option does heuristic before preprocessing

Possible options: off on both before 200 1000 10000 dj djbefore, default off

Rins *option*

This switches on Relaxed induced neighborhood Search. Doh option does heuristic before preprocessing

Possible options: off on both before often, default on

round(ingHeuristic) *option*

This switches on a simple (but effective) rounding heuristic at each node of tree. On means do in solve i.e. after preprocessing, Before means do if doHeuristics used, off otherwise, and both means do if doHeuristics and in solve.

Possible options: off on both before, default on

two(MirCuts) *option*

This switches on two phase mixed integer rounding cuts (either at root or in entire tree) See branchAndCut for information on options.

Possible options: off on root ifmove forceOn onglobal forceandglobal forceLongOn, default root

Vnd(VariableNeighborhoodSearch) *option*

Whether to try Variable Neighborhood Search

Possible options: off on both before intree, default off

Actions:

barr(ier)	Solve using primal dual predictor corrector algorithm
dualS(implex)	Do dual simplex algorithm
either(Simplex)	Do dual or primal simplex algorithm
initialS	Solve to continuous
	This just solves the problem to continuous - without adding any cuts
outDup	takes duplicate rows etc out of integer model
primalS	Do primal simplex algorithm
reallyS	Scales model in place
stat	Print some statistics
tightLP	Poor person's preSolve for now

Branch and Cut actions:

branch	Do Branch and Cut

13.2 Selected GLPK parameters

The following parameters are taken from the GLPK command line help.

Only the GLPK parameters that are useful in a CMPL context are described afterwards.

Usage GLPK parameters:

```
%opt glpk solverOption [solverOptionValue]
```

General options:

simplex	use simplex method (default)
interior	use interior point method (LP only)
scale	scale problem (default)
noscale	do not scale problem
ranges *filename*	write sensitivity analysis report to filename in
	printable format (simplex only)

tmlim *nnn*	limit solution time to nnn seconds
memlim *nnn*	limit available memory to nnn megabytes
wlp *filename*	write problem to filename in CPLEX LP format
wglp *filename*	write problem to filename in GLPK format
wcnf *filename*	write problem to filename in DIMACS CNF-SAT format
log *filename*	write copy of terminal output to filename

LP basis factorization options:

luf	LU + Forrest-Tomlin update (faster, less stable; default)
cbg	LU + Schur complement + Bartels-Golub update (slower, more stable)
cgr	LU + Schur complement + Givens rotation update (slower, more stable)

Options specific to simplex solver:

primal	use primal simplex (default)
dual	use dual simplex
std	use standard initial basis of all slacks
adv	use advanced initial basis (default)
bib	use Bixby's initial basis
steep	use steepest edge technique (default)
nosteep	use standard "textbook" pricing
relax	use Harris' two-pass ratio test (default)
norelax	use standard "textbook" ratio test
presol	use presolver (default; assumes scale and adv)
nopresol	do not use presolver
exact	use simplex method based on exact arithmetic
xcheck	check final basis using exact arithmetic

Options specific to interior-point solver:

nord	use natural (original) ordering
qmd	use quotient minimum degree ordering

amd	use approximate minimum degree ordering (default)
symamd	use approximate minimum degree ordering

Options specific to MIP solver:

nomip	consider all integer variables as continuous (allows solving MIP as pure LP)
first	branch on first integer variable
last	branch on last integer variable
mostf	branch on most fractional variable
drtom	branch using heuristic by Driebeck and Tomlin (default)
pcost	branch using hybrid pseudocost heuristic (may be useful for hard instances)
dfs	backtrack using depth first search
bfs	backtrack using breadth first search
bestp	backtrack using the best projection heuristic
bestb	backtrack using node with best local bound (default)
intopt	use MIP presolver (default)
nointopt	do not use MIP presolver
binarize	replace general integer variables by binary ones (assumes intopt)
fpump	apply feasibility pump heuristic
gomory	generate Gomory's mixed integer cuts
mir	generate MIR (mixed integer rounding) cuts
cover	generate mixed cover cuts
clique	generate clique cuts
cuts	generate all cuts above
mipgap *tol*	set relative mip gap tolerance to tol
minisat	translate integer feasibility problem to CNF-SAT and solve it with MiniSat solver
objbnd *bound*	add inequality obj <= bound (minimization) or obj >= bound (maximization) to integer feasibility problem (assumes minisat)

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