

**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 and Gurobi directly to solve the generated model instance. Since 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).

CMPL is a COIN-OR project 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](http://www.coliop.org)).

## 2 CMPL elements

### 2.1 General structure of a CMPL program

The structure of a CMPL program 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.

$$\begin{aligned} c^T \cdot x &\rightarrow \max / \min \\ s.t. \\ A \cdot x &\leq b \\ x &\geq 0 \end{aligned}$$

A CMPL program 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 contribution 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[defset(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, element, 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 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)

### Other syntactic elements

( )	<ul style="list-style-type: none"> <li>- arithmetical bracketing in constant expressions</li> <li>- lists for initialising vectors of constants</li> <li>- parameters for constant functions</li> <li>- increment in an algorithmic set</li> </ul>
[ ]	<ul style="list-style-type: none"> <li>- indexing of vectors</li> <li>- range specification in variable definitions</li> </ul>
{ }	<ul style="list-style-type: none"> <li>- control structures</li> </ul>
..	<ul style="list-style-type: none"> <li>- algorithmic set (e.g. range for indices or loop counters)</li> <li>- range specification in variable definitions</li> </ul>
,	<ul style="list-style-type: none"> <li>- element separation in an initialisation list for constant vectors and enumeration sets</li> <li>- separation of function parameters</li> <li>- separation of indices</li> <li>- separation of loop heads in a loop</li> </ul>
:	<ul style="list-style-type: none"> <li>- mark indicating beginning of sections</li> <li>- definition of variables</li> <li>- definition of parameter type</li> <li>- separation of loop header from loop body</li> <li>- separation of line names</li> </ul>
	<ul style="list-style-type: none"> <li>- separation of alternative blocks in a control structure</li> </ul>

;	- 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.

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 one or more 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 `:=`. The type of a parameter is defined by the assigned data. Possible types are `real`, `integer`, `binary`, `string` and `set`.

Usage:

```

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

```

<i>name</i>	Name of the parameter
<i>index</i>	A position in an array of parameters  The index can be an integer or a string expression. For multidimensional arrays it is necessary to set the index for every dimension separated by commas.
<i>scalarExpression</i>	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.
<i>set</i>	An optional set expression for the definition of the dimension of the array  A set is a collection of distinct objects. Distinction can be made between enumeration sets, algorithmic sets and sets which are based on set operations like unions or intersections.

*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:**

<pre>k := 10;</pre>	parameter <i>k</i> with value 10
<pre>k[1..5] := ( 0.5, 1, 2, 3.3, 5.5); k[] := ( 0.5, 1, 2, 3.3, 5.5);</pre>	vector of parameters with 5 elements
<pre>A[] := (16, 45.4);</pre>	definition of a vector with two integer values <i>a</i> [1]=16 and <i>a</i> [2]=45.
<pre>a[, ] := (( 5.6, 7.7, 10.5 ),           ( 9.8, 4.2, 11.1 ));</pre>	matrix with 2 rows and 3 columns
<pre>b[] := ( 22 ,);</pre>	definition of the vector <i>b</i> with only one element.
<pre>b[] := ( 22 );</pre>	causes an error: array dimensions don't match, since (22) is not interpreted as an array but as an assignment of a scalar expression.
<pre>products := set( "bike1", "bike2"); machineHours[products] := (5.4, 10);</pre>	defines a vector for machine hours based on the set <i>products</i>
<pre>myString := "this is a string";</pre>	string parameter
<pre>q := 3;</pre>	parameter <i>q</i> with value 3
<pre>g[1..q] := ( 1, 2, 3);</pre>	usage of <i>q</i> for the definition of the parameter <i>g</i>
<pre>x := 1(1)2; y := 1(1)2; z := 1(1)2;  cube[x,y,z] := ( ( (1,2), (3,4) ),                 ( (5,6), (7,8) ) );</pre>	definition of a parameter cube that is based on the sets <i>x</i> , <i>y</i> and <i>z</i> .

If a name is used for a defined parameter, different usages of this name with indices can only refer to parameters, but not to model variables (e.g. if *a*[1] is a parameter, then *a*[2], *a* or *a*[1,1] can only be defined as parameter and not as model variables. *a* can also not be used as a local parameter like a loop counter).

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. The main application of local parameters is loop counters 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.

Examples:

<code>x: real;</code>	<code>x</code> is a real model variable with no ranges
<code>x: real[0..100];</code>	<code>x</code> is a real model variable, $0 \leq x \leq 100$
<code>x[1..5]: integer[10..20];</code>	vector with 5 elements, $10 \leq x_n \leq 20; n = 1(1)5$
<code>x[1..5,1..5,1..5]: real[0..];</code>	a three-dimensional array of real model variables with 125 elements identified by indices, $x_{i,j,k} \geq 0; i, j, k = 1(1)5$
<code>parameters:</code> <code>  prod := set( "bike1", "bike2");</code> <code>variables:</code> <code>  x[prod]: real[0.. ];</code>	defines a vector of non-negative real model variables based on the set <code>prod</code>
<code>y: binary;</code>	<code>x</code> is a binary model variable $y \in \{0,1\}$

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 (e.g. if `x[1]` is a model variable, then `x[2]`, `x` or `x[1,1]` can only be defined as model variables).

### 2.3.3 Indices and sets

Sets are used for the definitions of arrays of parameters or model variables and for the iterations in loops. Indices are necessary to identify an element of an array like a vector or matrix of parameters or model variables. A set is a collection of distinct integer and string elements. Sets can be defined by an enumeration of elements or by algorithms within the `parameters` section. It is also possible to build sets using set operations like condition sets or unions or intersections of defined sets. A set can be stored in a scalar parameter or in an element of an array of parameters.

Usage of set definitions:

<code>startNumber(in/decrementor)endNumber</code>	#algorithmic set
<code>[startNumber]..[endNumber]</code>	#algorithmic set
<code>.integer.</code>	#algorithmic set
<code>.string.</code>	#algorithmic set
<code>set(listOfIntAndStrings)</code>	#enumeration set

<code>startNumber(in/decrementor)endNumber</code>	set of integers based on an algorithm The set starts at the <code>startNumber</code> , is changed by an <code>incrementer</code> or <code>decrementer</code> at every iteration and ends at the <code>endNumber</code> .
<code>startNumber..endNumber</code>	set of integers based on an algorithm The set starts at the <code>startNumber</code> , is changed by the number one at every iteration and ends at the <code>endNumber</code> . <code>startNumber</code> and <code>endNumber</code> are optional elements.
<code>startNumber..</code>	infinite set with all integers greater than or equal to <code>startNumber</code>
<code>..endNumber</code>	infinite set with all integers less than or equal to <code>endNumber</code>
<code>..</code>	infinite set with all integers and strings
<code>.integer.</code>	infinite set with all integers
<code>.string.</code>	infinite set with all strings
<code>listOfIntAndStrings</code>	elements of an enumeration set  An enumeration 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 <code>set</code> .  It is possible to define an empty set using an empty array within the statement <code>set()</code> .

### Examples:

<code>s:=..;</code>	<code>s</code> is assigned an infinite set of all integers and strings
<code>s:=..6;</code>	<code>s</code> is assigned $s \in (\dots, 4, 5, 6)$
<code>s:=6..;</code>	<code>s</code> is assigned $s \in (6, 7, 8, \dots)$
<code>s:=0..6;</code> <code>s:=0(1)6;</code>	<code>s</code> is assigned $s \in (0, 1, \dots, 6)$
<code>s:=10(-2)4;</code>	<code>s</code> is assigned $s \in (10, 8, 6, 4)$
<code>prod := set( "bike1", "bike2");</code>	enumeration set of strings
<code>a:= set( 1, "a", 3, "b", 5, "c" );</code>  <code>x[a]:= (10,20,30,40,50,60);</code>  <code>echo x[1];</code> <code>echo x["a"];</code> <code>{i in a: echo x[i];}</code>	enumeration set of strings and integers  vector <code>x</code> identified by the set <code>a</code> is assigned an integer vector  The following user messages are displayed: 10 20 10 20 30 40 50 60

### Usage of set operations and set construction:

<code>set{ setIteration , condition: localParameter };</code>	#condition set
<code>set1 + set2;</code>	#union set
<code>set1 * set2;</code>	#intersection set

### Usage set operations and set construction:

`set1 + set2`

union of `set1` and `set2`

`set1 * set2`

intersection of `set1` and `set2`

`set{ setIteration, condition: param }` The local parameter `param` is to be used for the definition of an iteration over a set (defined by `setIteration`) and is to be evaluated in the condition `condition`. The result is a set of all elements which are in the iterated set and fulfil the condition.

### Examples:

<code>s1 := set( "a","b","c","d");</code> <code>s2 := set( "a","e","c","f");</code> <code>s3 := s1 + s2;</code> <code>s4 := s1 * s2;</code>	<code>s3</code> is assigned ("a", "b", "c", "d", "e", "f" ) <code>s4</code> is assigned ( "a", "c" )
<code>s5 := set{i in 1..10, i mod 2 = 0: i};</code>	<code>s5</code> is assigned (2, 4, 6, 8, 10)
<code>s6 := set{i in s1, !(i element s2): i};</code>	<code>s6</code> is assigned ( "b", "d" )

### 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:

<pre> 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[] -&gt;max; </pre>	<p><b>generates a line</b> profit</p>
<pre> constraints:     restriction: A[,] * x[] &lt;=b[]; </pre>	<p><b>generates 2 lines</b></p> <p style="text-align: right;">restriction_1 restriction_2</p>

<pre>{ i:=1(1)2:   restriction_\$i\$: A[,]*x[]&lt;=b[]; }</pre>	generates 2 lines	restriction_1 restriction_2
<pre>restriction { i:=1(1)3:   A[,]*x[]&lt;=b[]; }</pre>	generates 2 lines	restriction_1 restriction_2
<pre>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[] -&gt;max; constraints:   capa_\$2\$: A[,] * x[] &lt;=b[];</pre>	generates 3 lines	profit capa_M1 capa_M2

## 2.4 CMPL header

A CMPL header is intended to define CMPL options and solver options for the specific CMPL model. The elements of the CMPL header are not part of the CMPL model. Since a CMPL header is processed before the CMPL model is interpreted, the defined options have an impact on the CMPL model.

Usage CMPL header:

```
%arg optionName [optionValue]           #CMPL options
%opt solverName solverOption [solverOptionValue] #Solver options
```

*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 12 Appendix

Examples:

<code>%arg -solver glpk</code>	GLPK is used as the solver
<code>%arg -solutionAscii</code>	CMPL writes the optimization results in an ASCII file.
<pre>%arg -solver cbc %arg -solverUrl ↓ http://194.95.44.187:8080/ ↓ OSServer/services/OSSolverService</pre>	CBC is to be executed on a OSServer located at 194.95.44.187.

<code>%opt cbc threads 2</code>	If CBC is chosen as solver then 2 threads are executed.
<code>%opt glpk nopresol</code>	If GLPK is used then the presolver is switched off.

## 3 Expressions

### 3.1 Overview

Expressions are rules for computing a value during the run-time of a CMPL program. Therefore an 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. 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 or a set. Therefore only real, integer, binary, string or set expressions are possible in CMPL. An 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:

<code>a[] := (1,2,5);</code>	
<code>echo max( a[] );</code>	returns user message 5
<code>echo min( a[] );</code>	returns user message 1
<code>echo count( a[] );</code>	returns user message 3
<code>echo count( a[1] );</code>	returns user message 1
<code>echo count( a[5] );</code>	returns user message 0
<code>echo count( a[] );</code>	returns user message 3

<pre>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]);</pre>	<b>user messages:</b> 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
---	---

### 3.3 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:

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

`p, q` integer expression  
`x` real or integer expression

Examples:

<pre>c[1] := sqrt( 36 ); c[2] := exp(10); c[3] := ln(10);</pre>	<b>value is:</b> 6.000000 22026.465795 2.302585
---	--

<code>c[4] := lg(10000);</code>	4.000000	
<code>c[5] := ld(8);</code>	3.000000	
<code>c[6] := rand(10);</code>	7.000000	(random number)
<code>c[7] := sin(2.5);</code>	0.598472	
<code>c[8] := cos(7.7);</code>	0.153374	
<code>c[9] := tan(10.1);</code>	0.800789	
<code>c[10] := acos(0.1);</code>	1.470629	
<code>c[11] := asin(0.4);</code>	0.411517	
<code>c[12] := atan(1.1);</code>	0.832981	
<code>c[13] := sinh(10);</code>	11013.232875	
<code>c[14] := cosh(3);</code>	10.067662	
<code>c[15] := tanh(15);</code>	1.000000	
<code>c[16] := abs(-12.55);</code>	12.550000	
<code>c[17] := ceil(12.55);</code>	13.000000	
<code>c[18] := floor(-12.55);</code>	-13.000000	
<code>c[19] := round(12.4);</code>	12.000000	
<code>c[20] := 35 div 4;</code>	8	
<code>c[21] := 35 mod 4;</code>	3	

### 3.4 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:

<code>a := 6.666;</code> <code>echo integer(a);</code> <code>echo binary(a);</code> <code>a:=0;</code> <code>echo binary(a);</code>	returns the user messages: 7 1 0
<code>a := 6.6666;</code> <code>echo string(a);</code>	6.666600
<code>b := 100;</code> <code>echo real(b);</code>	100.000000

<pre>echo binary(b); b := 0; echo binary(b); b:= 100; echo string(b);</pre>	<pre>1 0 100</pre>
<pre>c :=1; echo real(c); echo integer(c); echo string(c);</pre>	<pre>1.000000 1 1</pre>
<pre>e := "1.888"; echo real(e); echo integer(e); echo binary(e); e := ""; echo binary(e);</pre>	<pre>1.888000 1 1 0</pre>

### 3.5 String operations

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

Usage:

<code>expression + expression</code>	#concat strings if one expression #has the type string
<code>format( formatString, expression )</code>	#converts a number into a #string using a format string
<code>len( stringExpression )</code>	#length of a string
<code>type( expression )</code>	#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:

<code>%&lt;flags&gt;&lt;width&gt;&lt;.precision&gt;specifier</code>
---

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 <i>width</i> is not specified in the <i>format</i> 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 <i>precision</i> is not specified in the <i>format</i> string, but as an additional integer value argument preceding the argument that has to be formatted.

#### Examples:

<pre>a:=66.77777; echo type(a)+ " " + a + " to string " + format("%10.2f", a);</pre>	<pre>returns the user message real 66.777770 to string 66.78</pre>
--	--

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:

<pre>s:= set( 7, "qwe", 6, "fe", 5, 8 ); echo "set is " + string(s);</pre>	<pre>returns the user message set is set( 7, "qwe", 6, "fe", 5, 8 )</pre>
--	---

### 3.6 Set functions

With the following functions a user can identify the specific characteristics of a set.

Usage:

```

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

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

```

*array* array of parameters or model variables with at least one free index.

*set* set expression

*element* an integer or string that is to be checked

Examples:

<pre> a:= set( 1, "a", 3, "b", 5, "c" ); echo "length of the set: "+ len(a); </pre>	<pre> returns the user message length of the set: 6 </pre>
<pre> A[,] := ( ( 1,2,3,4,5),           (1,2,3,4,5,6,7));  row := defset(A[,]); col := defset(A[1,]); </pre>	<pre> row is assigned the set 1..2 col is assigned the set 1..5 </pre>
<pre> a:= set( 1, "a", 3, "b", 5, "c" ); echo "a" element a; echo 5 element a; echo "bb" element a; </pre>	<pre> returns the user message 1 returns the user message 1 returns the user message 0 </pre>

## 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:

<pre>{a&lt;0: error "negative value"; }</pre>	If a is negative an error message is displayed and the CMPL program will be terminated.
<pre>echo "constant definitions finished";</pre>	A user message is displayed.
<pre>{ i:=1(1)3: echo "value:" + i;}</pre>	The following user messages are displayed: value: 1 value: 2 value: 3

## 4.2 Readcsv and readstdin

CMPL has two 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:

<pre>a := readstdin("give me a number");</pre>	reads a value from <code>stdin</code> to be used as value for <code>a</code> . 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
<pre>parameters:     c[] := readcsv("c.csv");     b[] := readcsv("b.csv");     A[,] := readcsv("a.csv"); variables:     x[defset(c[])]: real[0..]; objectives:     c[]T * x[]-&gt;max; constraints:     A[,] * x[] &lt;= b[];</pre>	<p>Using <code>readcsv</code> CMPL generates the following model:</p> $1 \cdot x_1 + 2 \cdot x_2 + 3 \cdot x_3 \rightarrow \max !$ <p>s.t.</p> $5.6 \cdot x_1 + 7.7 \cdot x_2 + 10.5 \cdot x_3 \leq 15$ $9.8 \cdot x_1 + 4.2 \cdot x_2 + 11.1 \cdot x_3 \leq 20$ $x_j \geq 0; j=1(1)3$

### 4.3 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 semi-colon.

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:

<pre>c[] := ( 1, 2, 3 ); b[] := ( 15, 20 ); A[,] := ( ( 5.6, 7.7, 10.5 ),           ( 9.8, 4.2, 11.1 ) );</pre>	const-def.gen
<pre>parameters:     include "const-def.cmpl" variables:     x[defset(c[])]: real[0..];</pre>	<p>Using the <code>include</code> statement CMPL generates the following model:</p>

<pre> objectives:     c[]T * x[] -&gt; max; constraints:     A[,] * x[] &lt;= b[]; </pre>	<pre> 1·x<sub>1</sub>+2·x<sub>2</sub>+3·x<sub>3</sub>→max! s.t. 5.6·x<sub>1</sub>+7.7·x<sub>2</sub>+10.5·x<sub>3</sub>≤15 9.8·x<sub>1</sub>+4.2·x<sub>2</sub>+11.1·x<sub>3</sub>≤20 x<sub>j</sub>≥0; j=1(1)3 </pre> <p>Using the keyword <code>include</code> - it is possible to include the CMPL expressions in file "const-def.cmpl" in another CMPL file.</p>
---	---

## 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:

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

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

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

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 expres-

sions 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;
```

<i>lineName</i>	optional element description of objective
<i>linearTerm</i>	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];
```

<i>lineName</i>	optional element description of objective
<i>linearTerm</i>	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 be 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:

<pre>s1 := set( "a", "b", "c", "d"); {k in s1: ... }</pre>	k is iterated over all elements of the set $s_1$
<pre>s2 := 1(1)10; {k in s2: ... }</pre>	k is iterated in the sequence $k \in \{1, 2, \dots, 10\}$
<pre>s3 := 2..6; {k := s3: ... }</pre>	k is iterated in the sequence $k \in \{2, 3, \dots, 6\}$

## 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:

<pre>=, == &lt;&gt;, != &lt; &gt; &lt;= &gt;=</pre>	<p>equality</p> <p>inequality</p> <p>less than</p> <p>greater than</p> <p>equal to or less than</p> <p>equal to or greater than</p>
---	---

Comparison operators for sets:

<pre>= == &lt;&gt; != &lt; &gt; &lt;= &gt;=</pre>	<p>equality</p> <p>tests whether the iteration order of two sets is equal</p> <p>inequality</p> <p>tests whether the iteration order of two sets is not equal</p> <p>subset or not equal</p> <p>greater than</p> <p>subset or equal</p> <p>equal to or greater than</p>
---	---

Logical operators:

<pre>&amp;&amp;    !</pre>	<p>AND</p> <p>OR</p> <p>NOT</p>
----------------------------	---------------------------------

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:

<pre>i:=1; j:=2; {i&gt;j : ... } {!(i&gt;j) : ... } {!i    j=2 : ... } {!i &amp;&amp; j=2 : ... }</pre>	<p>condition is false</p> <p>condition is true</p> <p>condition is true</p> <p>condition is false (!i is false, because i is not 0)</p>
---	---

### 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:

<pre>constraints:   { k:=1 : ... }</pre>	<p>k is assigned 1 and used as local parameter within the control structure.</p>
--	--

### 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 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];
```

<i>reference</i>	a reference to a control header specified by a name or a local parameter
<b>break</b> [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.
<b>continue</b> [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 <code>continue</code> is equivalent to <code>break</code> .
<b>repeat</b> [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*            defined iteration headers

*iterationHeader1*

*controlBody*            CMPL statements that are executed in every iteration

## Examples:

<pre>{ i := 1(1)3 : ... }</pre>	loop counter <i>i</i> with a start value of 1, an increment of 1 and an end condition of 3
<pre>{ i in 1..3 : ... }</pre>	alternative definition of a loop counter; loop counter <i>i</i> with a start value of 1 and an end condition of 3. (The increment is automatically defined as 1)
<pre>products:= set( "p1", "p2", "p3"); hours[products]:= (20,55,10); { i in products:   echo "hours of product " +     i + " : "+ hours[i]; }</pre>	for loop using the set <i>products</i> returns user messages hours of product: p1 : 20 hours of product: p2 : 55 hours of product: p3 : 10
<pre>{ i := 1(1)2:   { j := 2(2)4: A[i,j] := i + j; } }</pre>	defines $A[1,2] = 3$ , $A[1,4] = 5$ , $A[2,2] = 4$ and $A[2,4] = 6$

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

<pre>{ i := 1(1)2, j := 2(2)4:   A[i,j] := i + j; }</pre>	defines $A[1,2] = 3$ , $A[1,4] = 5$ , $A[2,2] = 4$ and $A[2,4] = 6$
<pre>{ i := 1(1)5, j := 1(1)i:   A[i,j] := i + j; }</pre>	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 ] }
```

<i>condition</i>	If the evaluated condition is true, the code within the body is executed.
<i>thenBody</i>	This body is executed if the <i>condition</i> is true.
<i>elseBody</i>	This body is executed if the <i>condition</i> is false.

#### Examples:

<pre>{i := 1(1)5, j := 1(1)5:   {i = j: A[i,j] := 1; }   {i != j: A[i,j] := 0; } }</pre>	definition of the identity matrix with combined loops and two if-then clauses
<pre>{i := 1(1)5, j := 1(1)5:   {i = j: A[i,j] := 1;     default: A[i,j] := 0; } }</pre>	same example, but with one if-then-else clause
<pre>i:=10; { i&lt;10: echo "i less than 10";     default: echo "i greater than 9"; }</pre>	example of an if-then-else clause returns user message <code>i greater than 9</code>
<pre>sum{ i = j : 1   default: 2 }</pre>	conditional expression, evaluates to 1 if <code>i = j</code> , 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:

<pre>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"; }</pre>	example of a switch clause returns user message <code>i equals 2</code>
---	--

## 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; }
```

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

Examples:

<pre>i:=2; {i&lt;=4:   A[i] := i;   i := i+1;   repeat; }</pre>	<p>while loop with a global parameter</p> <p>Can only be used in the <code>parameters</code> section, because the assignment to a global parameter is not permitted in other sections.</p> <p>defines <code>A[2] = 2</code>, <code>A[3] = 3</code> and <code>A[4] = 4</code></p>
<pre>{a := 1, a &lt; 5:   echo a;   a := a + 1;   repeat; }</pre>	<p>while loop using a local parameter</p> <p>Can be used in all sections.</p> <p>returns user messages</p> <pre>1 2 3 4</pre>
<pre>{a:=1:   xx {:     echo a;     a := a + 1;     {a&gt;=4: break xx;}     repeat;   } }</pre>	<p>Alternative formulation:</p> <p>The outer control structure defines the local parameter <code>a</code>. 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 <code>break</code> statement in the inner control structure. (Without this reference the <code>break</code> statement would refer to the condition <code>a&gt;=4</code>)</p>

## 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.

## Examples:

<pre>x[1..3] := (2, 4, 6); a := sum{i := 1(1)3 : x[i] };</pre>	a is assigned 12
<pre>products:= set( "p1", "p2", "p3"); hours[products]:=(20,55,10); totalHours:= sum{i in products: hours[i] };</pre>	totalHours is assigned 85
<pre>x[1..3,1..2]:=((1,2), (3,4), (5,6)); b:= sum{i := 1(1)3, j := 1(1)2: x[i,j] };</pre>	using <code>sum</code> with more than one control header b is assigned 21.
<pre>s:=set(); d:= sum{i in s: i  default: -1 };</pre>	sums up all elements in the set <i>s</i> . Since <i>s</i> is an empty set, <i>d</i> is assigned to the alternative default value -1.
<pre>e:= set{i:= 1..10: i^2 };</pre>	e is assigned the set (1, 4, 9, 16, 25, 36, 49, 64, 81, 100)
<pre>f:= set{i:= 1..100, round(sqrt(i))^2 = i: i };</pre>	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);
```

<pre> variables:     x[1..3]: real[0..]; objectives:     sum{j:=1..3: c[j] *x[j]}-&gt;max; constraints:     { i:=1..2:         sum{j:=1..3: a[i,j] * x[j]}&lt;= b[i];     } </pre>	<p>objective definition using a sum  <math>20 \cdot x_1 + 10 \cdot x_2 + 10 \cdot x_3 \rightarrow \max !</math></p> <p>constraints definition using a sum  <math>1 \cdot x_1 + 2 \cdot x_2 + 3 \cdot x_3 \leq 100</math>  <math>4 \cdot x_1 + 5 \cdot x_2 + 6 \cdot x_3 \leq 100</math></p>
--	---

## 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 always 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.

Usage:

<code>vector[[set]]</code>	#column vector
<code>vector[[set]]<b>T</b></code>	#transpose of column vector - row vector
<code>matrix[index, [set]]</code>	#column vector
<code>matrix[[set], index]</code>	#also column vector
<code>matrix[index, [set]]<b>T</b></code>	#transpose of column vector - row vector
<code>matrix[[set], index]<b>T</b></code>	#transpose of column vector - row vector
<code>matrix[[set1], [set2]]</code>	#matrix

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

Examples:

<code>x[]</code>	vector with free index across the entire defined area
<code>x[2..5]</code>	vector with free index in the range 2 – 5

<code>A[, ]</code>	matrix with two free indices
<code>A[1, ]</code>	matrix with one fixed and one free index; this is a column vector.
<code>A[, 1]</code>	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

```

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

Examples:

<pre> 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[] -&gt;max; constraints:   a[, ] * x[] &lt;=b[]; </pre>	<p>objective definition using implicit loops  <math>20 \cdot x_1 + 10 \cdot x_2 + 10 \cdot x_3 \rightarrow \max !</math></p> <p>constraint definition using implicit loops  <math>1 \cdot x_1 + 2 \cdot x_2 + 3 \cdot x_3 \leq 100</math>  <math>4 \cdot x_1 + 5 \cdot x_2 + 6 \cdot x_3 \leq 100</math></p>
--	--

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:

<pre> 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[] -&gt;max; constraints:   a[, ] * x[] + d[] &lt;=b[]; </pre>	<p>constraints definition using implicit loops</p> $1 \cdot x_1 + 2 \cdot x_2 + 3 \cdot x_3 \leq 90$ $4 \cdot x_1 + 5 \cdot x_2 + 6 \cdot x_3 \leq 90$ <p>equivalent to</p> $a[, ] * x[] \leq b[] - d[];$
<pre>0 &lt;= x[1..3]+y[1..3]+z[2]&lt;= b[1..3];</pre>	<p>implicit loops for a column vector</p>
<pre>0 &lt;= x[1] + y[1] + z[2] &lt;= b[1]; 0 &lt;= x[2] + y[2] + z[2] &lt;= b[2]; 0 &lt;= x[3] + y[3] + z[2] &lt;= b[3];</pre>	<p>equivalent formulation</p>
<pre> 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..]; </pre>	
<pre>objectives:   c[]T * x[] -&gt;max;</pre>	
<pre>constraints:   a[, ] * x[] + z[] &lt;=b[];</pre>	<p>constraints definition using implicit loops</p> $1 \cdot x_1 + 2 \cdot x_2 + 3 \cdot x_3 + z_1 \leq 90$ $4 \cdot x_1 + 5 \cdot x_2 + 6 \cdot x_3 + z_2 \leq 90$

## 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.

### 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/Steglich (2007), p. 25ff.] :

$w := u \cdot v$ ,  $u \leq u \leq \bar{u}$  ( $u$  real or integer),  $v \in [0,1]$   
 is equivalent to

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

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.] :

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

$u$  real or integer and  
 $v = \underline{v} + \sum_{j=0}^d 2^j \cdot y_j$ ,  $v \leq \bar{v}$ , with  $d = \lceil \lg(\bar{v} - \underline{v} + 1) \rceil - 1$   
 $w = u \cdot \underline{v} + \sum_{j=0}^d 2^j \cdot w_j$   
 $\underline{u} \cdot y_j \leq w_j \leq \bar{u} \cdot y_j$   
 $\underline{u} \cdot (1 - y_j) \leq u - w_j \leq \bar{u} \cdot (1 - y_j)$   
 $y_j \in [0,1], j = 0(1)d$

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>] <input file>
```

Usage: **cmpl** [options] [<input file>]

#### Model mode:

-i <cmplFile> : input file  
-m [<File>] : export model in MPS format in a file or stdout

-x [<File>] : export model in OSiL XML format in a file or stdout  
-noOutput : no generating of a MPS or OSiL file

### Solver mode:

-solver <solver> : name of the solver you want to use  
-solverUrl <url> : URL of the solver service  
w/o a defined remote solver service, a local solver is used  
-solutionCsv : optimization results in CSV format  
A file <cmplFileName>.csv will be created.  
-solutionAscii : optimization results in ASCII format  
A file <cmplFileName>.sol will be created.  
-silent : optimization results are not displayed  
-obj <objName> : name of the objective function  
-objSense <max/min> : objective sense  
-maxDecimals <x> : maximal number of decimals in the solution report (max 12)  
-dontRemoveTmpFiles : Don't remove temporary files (mps,osil,osrl,gsol)

### General options:

-e [<File>] : output for error messages and warnings  
-e simple output to stderr (default)  
-e<File> output in MprL XML format to file  
-silent : suppresses CMPL and solver messages (assuming -e <problemName>.mprl)  
-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  
-gn : no matrix reductions  
-gf : Generated constraints for products of variables are included at the original position of the product.  
-cd : no warning at multiple parameter definition  
-ca : no warning for deprecated '=' assignment expression  
-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
- ff : format option: generate free MPS
- f% <format> : format option for MPS or OSiL files (C++ style - default %f)
- h : get this help
- v : version

**Examples - solver mode:**

<code>cmpl test.cmpl</code>	solves the problem <code>test.cmpl</code> locally with the default solver and displays a standard solution report
<code>cmpl -solver glpk test.cmpl</code>	solves the problem <code>test.cmpl</code> locally using GLPK and displays a standard solution report
<code>cmpl -solverUrl ↵ http://194.95.44.187:8080/ ↵ OSServer/services/OSSolverService ↵ test.cmpl</code>	solves the problem <code>test.cmpl</code> remotely with the defined web service and displays a standard solution report
<code>cmpl -solutionCsv test.cmpl</code>	solves the problem <code>test.cmpl</code> locally with the default solver writes the solution in the CSV-file <code>test.csv</code> and displays a standard solution report

**Examples - model mode:**

<code>cmpl -i test.cmpl -m test.mps</code>	reads the file <code>test.cmpl</code> and generates the MPS-file <code>test.mps</code> .
<code>cmpl -ff -i test.cmpl -m test.mps</code>	reads the file <code>test.cmpl</code> and generates the Free-MPS-file <code>test.mps</code> .
<code>cmpl -i test.cmpl -x test.osil</code>	reads the file <code>test.cmpl</code> and generates the OSiL-file <code>test.osil</code> .

## 9.2 Input and output file formats

### 9.2.1 Overview

CMPL uses several ASCII files for the communication with the user and other programs such as solvers.

CMPL	input file 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 IN-frastructure 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 or Gurobi is chosen as solver.
MPrL	output file for the status of the results or errors of a CMPL model XML file in accordance with the MPrL schema

## 9.2.2 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

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

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

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

constraints:
  machine$2$: A[,] * x[] <= b[];

```

### 9.2.3 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\\_\(format\)](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.mps
* OBJNAME profit
* OBJSENSE max
ROWS
N  profit
L  machine1
L  machine2
COLUMNS
  x1      profit          1  machine1      5.600000
  x1      machine2       9.800000
  x2      profit          2  machine1      7.700000
  x2      machine2       4.200000
  x3      profit          3  machine1     10.500000
  x3      machine2     11.100000
RHS
  RHS      machine1      15  machine2      20
RANGES
BOUNDS
ENDATA
```

### 9.2.4 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.mps
* OBJNAME profit
* OBJSENSE max
ROWS
N  profit
L  machine1
L  machine2
```

```

COLUMNS
x1 profit 1 machine1 5.600000
x1 machine2 9.800000
x2 profit 2 machine1 7.700000
x2 machine2 4.200000
x3 profit 3 machine1 10.500000
x3 machine2 11.100000
RHS
RHS machine1 15 machine2 20
RANGES
BOUNDS
ENDATA

```

## 9.2.5 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.gen</name>
    <description>generated by CMPL</description>
  </instanceHeader>
  <instanceData>
    <variables numberOfVariables="3">
      <var name="x1" type="C" lb="0"/>
      <var name="x2" type="C" lb="0"/>
      <var name="x3" 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="machine1" ub="15"/>

```

```

        <con name="machine2" 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>

```

## 9.2.6 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." [cf. Gassmann, Ma, Martin, Sheng, 2011, p. 41ff.]

The following OSoL-file describes a couple of parameters for the CBC solver.

```

<?xml version="1.0" encoding="UTF-8"?>
<osol 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/OSoL.xsd">
  <general>
    <solverToInvoke>cbc</solverToInvoke>
  </general>
  <job>
  </job>
  <optimization>
    <solverOptions numberOfSolverOptions="4">

```

```

        <solverOption name="reslim" solver="cbc" type="numeric" value="1"/>
        <solverOption name="maxN" solver="cbc" value="5" />
        <solverOption name="cuts" solver="cbc" value="off" />
    </solverOptions>
</optimization>
</osol>

```

## 9.2.7 MPrL

MPrL 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. MPrL is intended for communication with other software that uses CMPL for modelling linear optimization problems.

An MPrL 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"?>
<mplrl xmlns="www.coliop.org" xmlns:xsi="http://www.w3.org/2001/XMLSchema-
instance" xsi:schemaLocation="www.coliop.org
http://www.coliop.org/schemas/Mprl.xsd">
  <general>
    <generalStatus>normal</generalStatus>
    <mplName>CMPL</mplName>
    <instanceName>test.cmpl</instanceName>
    <message>cmpl finished normal</message>
  </general>
</mplrl>

```

If a semicolon is not set in line 26, CMPL will finish with errors that are represented in the following MPrL file.

```

<?xml version="1.0" encoding="UTF-8"?>
<mplrl xmlns="www.coliop.org" xmlns:xsi="http://www.w3.org/2001/XMLSchema-
instance" xsi:schemaLocation="www.coliop.org
http://www.coliop.org/schemas/Mprl.xsd">
  <general>
    <generalStatus>error</generalStatus>
    <mplName>CMPL</mplName>
    <instanceName>test.cmpl</instanceName>
    <message>cmpl finished with errors</message>
  </general>
  <mplResult numberOfMessages="1">
    <mplmessage type="error" file="test.cmpl" line="26" description="syntax
error"/>
  </mplResult>
</mplrl>

```

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="mprl">
    <xsd:complexType>
      <xsd:sequence>
        <xsd:element ref="general" minOccurs="1" maxOccurs="1"/>
        <xsd:element ref="mplResult" 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="mplName" 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="mplResult">
    <xsd:complexType>
      <xsd:sequence>
        <xsd:element ref="mplMessage" minOccurs="0" maxOccurs="unbounded"/>
      </xsd:sequence>
      <xsd:attribute name="numberOfMessages" type="xsd:nonNegativeInteger"
        use="required"/>
    </xsd:complexType>
  </xsd:element>
  <xsd:element name="mplMessage">
    <xsd:complexType>
      <xsd:attribute name="type" use="required">
        <xsd:simpleType>
          <xsd:restriction base="xsd:string">
            <xsd:enumeration value="error"/>
          </xsd:restriction>
        </xsd:simpleType>
      </xsd:attribute>
    </xsd:complexType>
  </xsd:element>
</xsd:schema>
```

```

        <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>

```

## 9.2.8 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." [cf. 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.optimizationser
    vices.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: 2.4.2
        Build Date: Jan 1 2012
        SVN Version: 4413
    </serviceName>
    <instanceName>test.cmpl</instanceName>
    <solverInvoked>COIN-OR clp</solverInvoked>
</general>
<job>
    <timingInformation numberOfTimes="1">
        <time type="elapsedTime" unit="second" category="total">
            4.41e-4</time>
        </timingInformation>
</job>
<optimization numberOfSolutions="1" numberOfVariables="3" numberOfCon
    straints="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">-.200000000000000012</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>

```

### 9.2.9 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 since 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 Using CMPL with several solvers

There are two ways to interact with several solver.

It is recommended to use one of the solver, which are directly supported and executed by CMPL. The CMPL installation routine installs also the (customized) COIN-OR OSSolverService (including the COIN-OR solvers CLP, CBC and Symphony) and GLPK. If you have installed Gurobi then you can also use this solver directly.

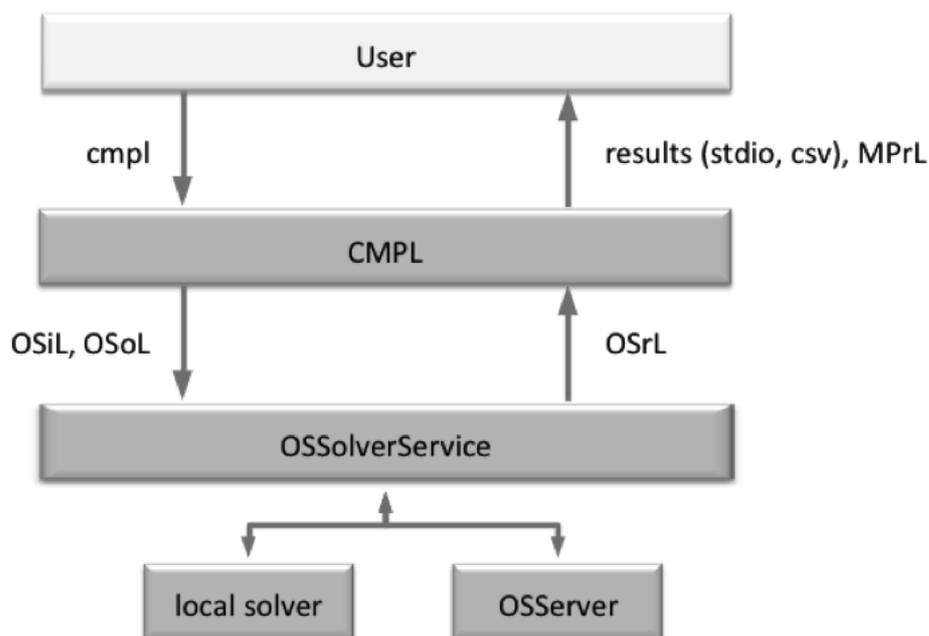
Since CMPL transforms a CMPL model into an MPS, a Free-MPS or an OSiL file, the model can be solved using most free or commercial solvers.

#### 9.3.1 COIN-OR OSSolverService

Like CMPL the OSSolverService is also a COIN-OR project.

"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." [cf. Gassmann, Ma, Martin, Sheng, 2011, p. 4.] For more information please visit <https://projects.coin-or.org/OS>.

CMPL interacts with the OSSolverService directly as shown in the picture below.



The user has to formulate the CMPL model. CMPL transforms the CMPL model into an OSiL file. If in the CMPL header some solver parameters are defined, 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. This behaviour depends on CMPL command line arguments.

`cmpl <problem>.cmpl` lead to solve the problem using a local solver. If the command `cmpl <problem-name>.cmpl -solverUrl http://<domain>:8080/OSServer/services/OSSolverService` is used then OSSolverService executes a solver on a OSServer located at `domain`. It is possible but not necessary to specify which solver is to be used. The default solver for linear programs is CLP and for linear integer programs CBC. For more information about the OSServer please visit the COIN-OS website: <https://projects.coin-or.org/OS>.

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.

### 9.3.2 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 or from the shell 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. GLPK can be used by typing `cmpl <problemName>.cmpl -solver glpk` or by using the CMPL header flag `%arg -solver glpk`. Most of the GLPK solver options can be used by defining solver options `%opt glpk solverOption [solverOptionValue]` in the CMPL header. Please see Appendix 12.2.

### 9.3.3 Gurobi

If Gurobi is installed on the same computer as CMPL then Gurobi can be executed directly only by using the command `cmpl <problemName>.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 by defining solver options `%opt gurobi solverOption [solverOptionValue]`.

Please see: <http://www.gurobi.com/doc/46/refman/node591.html>

### 9.3.4 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 -ff -m <problemname>.mps <problemname>.cmpl       #Free-MPS export

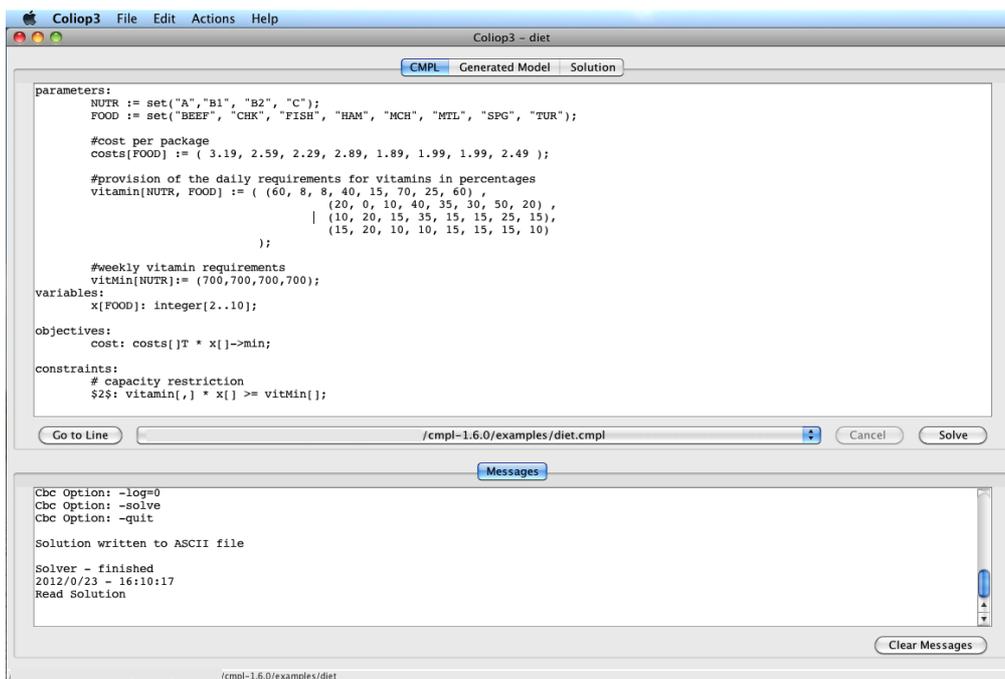
cmpl -x <problemname>.osil <problemname>.cmpl          #OSiL export
```

## 9.4 Using CMPL with Coliop

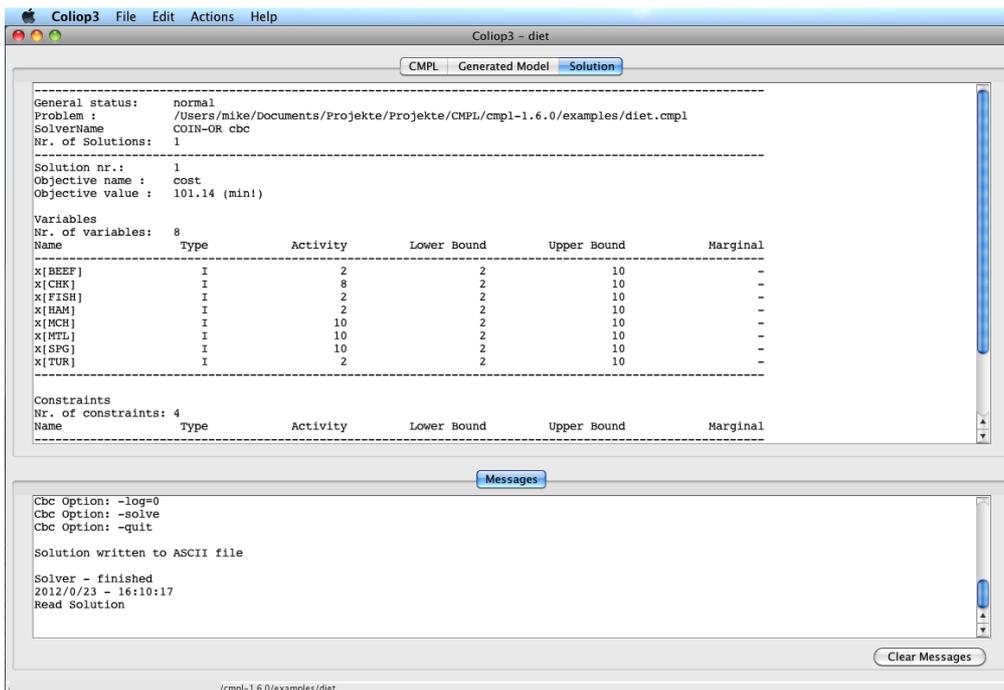
Coliop is an (simple) IDE (Integrated Development Environment) for CMPL intended to solve linear programming (LP) problems and mixed integer programming (MIP) problems. Coliop is a project of the Technical University of Applied Sciences Wildau and the Institute for Operations Research and Business Management 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).

Since 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>.

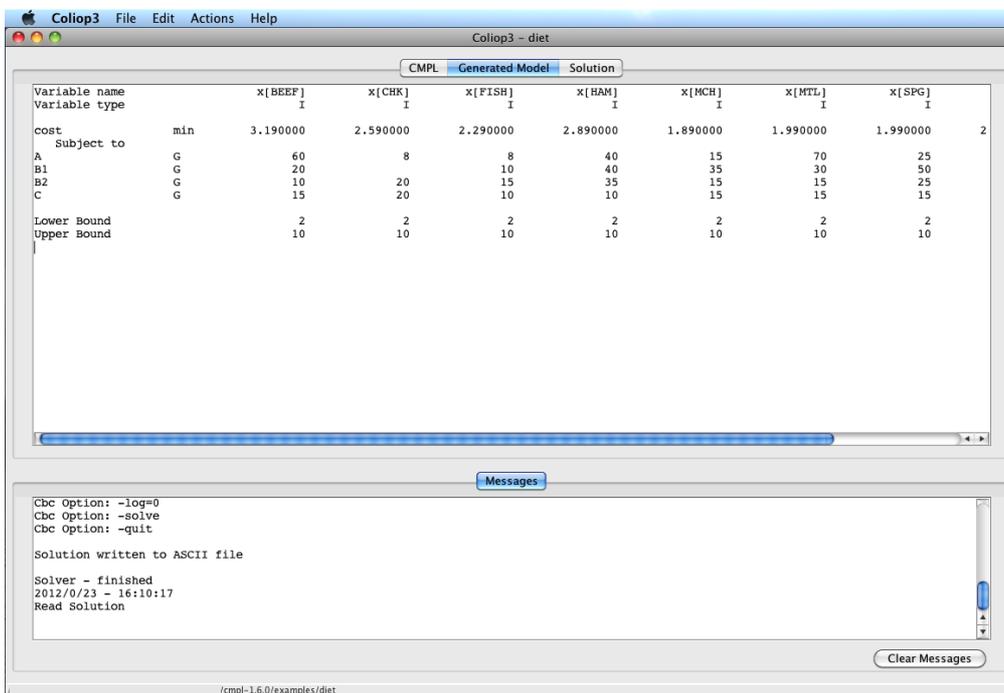
The first working step is to create or to open a CMPL model. By pushing the button <Solve> the model can be solved.



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.

$$60 \cdot x_{BEEF} + 8 \cdot x_{CHK} + 8 \cdot x_{FISH} + 40 \cdot x_{HAM} + 15 \cdot x_{MCH} + 70 \cdot x_{MTL} + 25 x_{SPG} + 60 \cdot x_{TUR} \leq 700$$

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

$$10 \cdot x_{BEEF} + 20 \cdot x_{CHK} + 15 \cdot x_{FISH} + 35 \cdot x_{HAM} + 15 \cdot x_{MCH} + 15 \cdot x_{MTL} + 25 x_{SPG} + 15 \cdot x_{TUR} \leq 700$$

$$15 \cdot x_{BEEF} + 20 \cdot x_{CHK} + 10 \cdot x_{FISH} + 10 \cdot x_{HAM} + 15 \cdot x_{MCH} + 15 \cdot x_{MTL} + 15 x_{SPG} + 10 \cdot x_{TUR} \leq 700$$

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

The CMPL model `diet.cmpl` is 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[ ];

```

**CMPL command:**

```

cmpl diet.cmpl

```

**Solution:**

```

-----
General status:      normal
Problem :           diet.cmpl
SolverName          COIN-OR cbc
Nr. of Solutions:   1
-----
Solution nr.:       1
Objective name :    cost
Objective value :   101.14 (min!)
-----
Variables
Nr. of variables:   8
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
Nr. of constraints: 4
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.*

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

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

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

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

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

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

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

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

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

    #profit contribution per unit
    {j:=defset(price[]): c[j] := price[j]-costs[j]; }

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

variables:
    x[defset(price[])]: integer;
```

```

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

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

```

CMPL command:

```

cmpl production-mix.cmpl -solver glpk

```

Solution:

```

-----
General status:      normal
Problem :           production-mix.cmpl
SolverName          GLPK
Nr. of Solutions:   1
-----

Solution nr.:       1
Objective name :    profit
Objective value :   6395 (max!)

Variables
Nr. of variables:   3
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
Nr. of constraints: 2
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	

		P1	P2	P3	upper bounds [h]
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.

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

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

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

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

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

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

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

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

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

The CML model `production-mix-fixed-costs.cml` is formulated as follows:

```
%arg -solver gurobi

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

    #machine hours required per unit
    a[,] := ((8, 15, 12), (15, 10, 8));
    #upper bounds of the machines
    b[] := (1000, 1000);

    #profit contribution per unit
    {j:=defset(price[]): c[j] := price[j]-costs[j]; }

    #upper bound of a product
    xMax[] := (250, 240, 250 );
    xMin[] := (45, 45, 45 );
```

```

#fixed setup costs
FC[] := ( 500, 400, 500);
variables:
  {j:=1(1)dim(c[]): x[j]: integer[0..xMax[j]]; }
  y[defset(price[])] : binary;

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

constraints:
  res: a[,] * x[] <= b[];
  {j in defset(price[]): xMin[j] * y[j] <= x[j] <= xMax[j] * y[j]; }

```

#### CMPL command:

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

#### Solution:

```

-----
General status:      normal
Problem :           production-mix-fixed-costs.cmpl
SolverName          Gurobi
Nr. of Solutions:   1
-----

Solution nr.:       1
Objective name :    profit
Objective value :   4880 (max!)

Variables
Nr. of variables:   6
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
Nr. of constraints: 8
Name                Type          Activity    Lower Bound    Upper Bound    Marginal
-----
res_1                L             990        -Infinity      1000           -
res_2                L             660        -Infinity      1000           -
line_4               L              0          -Infinity      0              -
line_5               L              0          -Infinity      0              -
line_6               L            -21         -Infinity      0              -
line_7               L            -174        -Infinity      0              -
line_8               L              0          -Infinity      0              -
line_9               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 CML file knapsack-data.cml:

```
parameters:
  boxes := 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:

```
include "knapsack-data.cmpl"
variables:
    x[boxes] : binary;
objectives:
    sales: p[]T * x[] ->max;
constraints:
    weight: w[]T * x[] <= maxWeight;
```

CMPL command:

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

Solution:

```
-----
General status:    normal
Problem :         knapsack-max-basic.cmpl
SolverName        COIN-OR cbc
Nr. of Solutions: 1
-----
Solution nr.:     1
Objective name :   sales
Objective value :  700 (max!)

Variables
Nr. of variables: 10
Name              Type          Activity    Lower Bound    Upper Bound    Marginal
-----
x[1]              B              1           0              1             -
x[2]              B              1           0              1             -
x[3]              B              0           0              1             -
x[4]              B              1           0              1             -
x[5]              B              0           0              1             -
x[6]              B              1           0              1             -
x[7]              B              0           0              1             -
x[8]              B              1           0              1             -
x[9]              B              1           0              1             -
x[10]             B              1           0              1             -
-----

Constraints
Nr. of constraints: 1
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:

```
include "knapsack-data.cmpl"
variables:
    x[boxes] : binary;
objectives:
    weight: w[]T * x[] ->min;
constraints:
    sales: p[]T * x[] >= minSales;
```

CMPL command:

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

Solution:

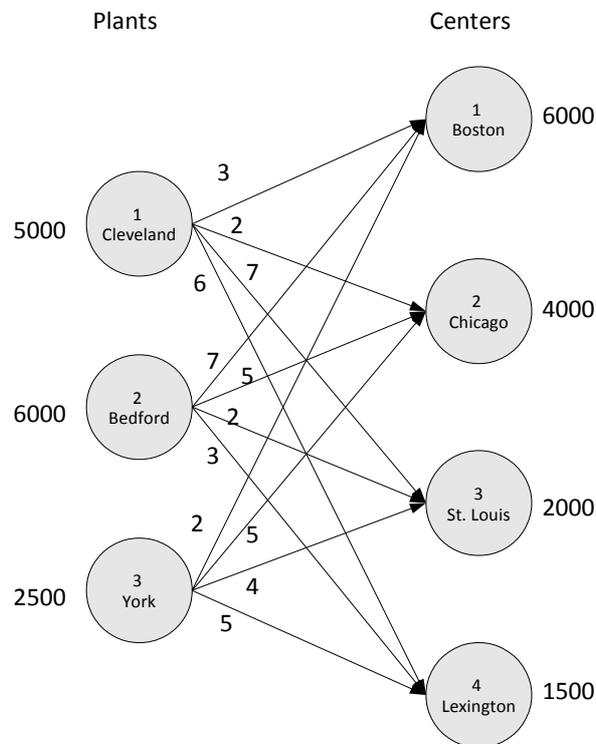
```
-----
General status:      normal
Problem :            knapsack-min-basic.cmpl
SolverName           COIN-OR cbc
Nr. of Solutions:   1
-----
Solution nr.:       1
Objective name :    weight
Objective value :   47 (min!)
-----
Variables
Nr. of variables:   10
Name                Type          Activity    Lower Bound  Upper Bound  Marginal
-----
x[1]                B              1           0            1            -
x[2]                B              1           0            1            -
x[3]                B              0           0            1            -
x[4]                B              1           0            1            -
x[5]                B              0           0            1            -
x[6]                B              0           0            1            -
x[7]                B              0           0            1            -
x[8]                B              0           0            1            -
x[9]                B              1           0            1            -
x[10]               B              1           0            1            -
-----
Constraints
Nr. of constraints: 1
Name                Type          Activity    Lower Bound  Upper Bound  Marginal
-----
sales               G              630        600          Infinity     -
-----
```

### 10.1.5 Transportation problem

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: *An Introduction to Management Science - Quantitative Approaches to Decision Making*, 13th ed., South-Western, Cengage Learning 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 firm 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:

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

s.t.

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

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

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

$x_{ij}$  – 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 destination  $j$

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

```
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];}

```

**CMPL command:**

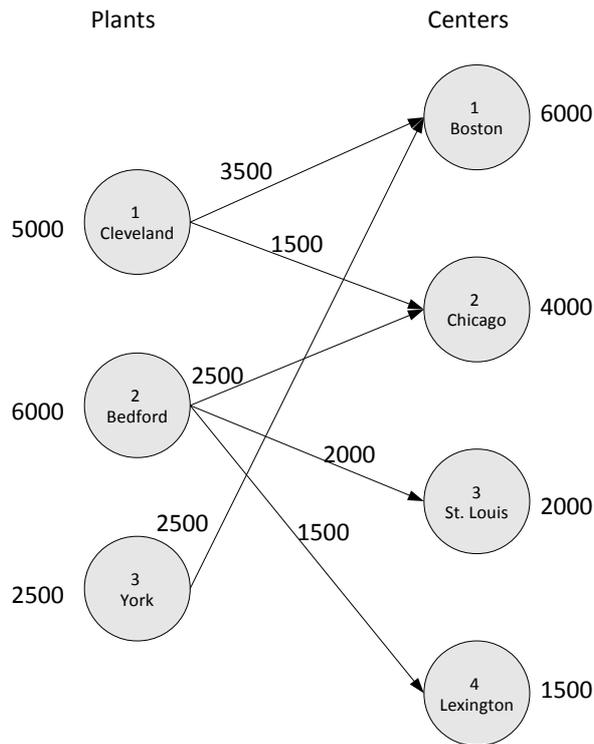
```
cmpl transportation.cmpl
```

**Solution:**

```

-----
General status:    normal
Problem :         transportation.cmpl
SolverName        COIN-OR clp
Nr. of Solutions: 1
-----
Solution nr.:     1
Objective name :   costs
Objective value :  39500 (min!)
-----
Variables
Nr. of variables: 12
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[1,3]            C               0           0             Infinity     8
x[1,4]            C               0           0             Infinity     6
x[2,1]            C               0           0             Infinity     1
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
x[3,2]            C               0           0             Infinity     4
x[3,3]            C               0           0             Infinity     6
x[3,4]            C               0           0             Infinity     6
-----
Constraints
Nr. of constraints: 7
Name              Type          Activity    Lower Bound  Upper Bound  Marginal
-----
supplies_1        L              5000       -Infinity     5000         -3
supplies_2        L              6000       -Infinity     6000          -
supplies_3        L              2500       -Infinity     2500         -4
demands_1         E              6000        6000         6000          6
demands_2         E              4000        4000         4000          5
demands_3         E              2000        2000         2000          2
demands_4         E              1500        1500         1500          3
-----

```



### 10.1.6 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:

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

$i \neq h$        $i \neq j$

s. t.

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

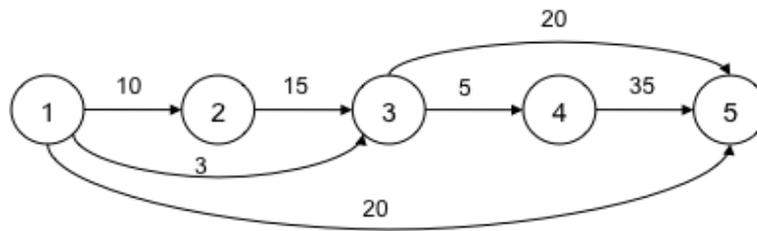
$$\sum_{h=1}^n x_{hj} = 1 \quad ; j=1(1)n$$

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

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 CML model `quadratic-assignment.cml` can be formulated as follows:

```

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 -solver glpk

```

Solution:

```

OSSolverServices      - running
-----
General status:      normal
Problem :            quadratic-assignment.cmpl
SolverName           COIN-OR glpk
Nr. of Solutions:    1
-----
Solution nr.:        1
Objective name :      costs
Objective value :     155 (min!)
-----
Variables
Nr. of variables:    375
Name                 Type           Activity     Lower Bound   Upper Bound   Marginal
-----
x[1,1]               B              0            0             1             -
x[1,2]               B              0            0             1             -
x[1,3]               B              0            0             1             -
x[1,4]               B              1            0             1             -
x[1,5]               B              0            0             1             -
x[2,1]               B              1            0             1             -
x[2,2]               B              0            0             1             -
x[2,3]               B              0            0             1             -
x[2,4]               B              0            0             1             -
x[2,5]               B              0            0             1             -
x[3,1]               B              0            0             1             -
x[3,2]               B              1            0             1             -
x[3,3]               B              0            0             1             -
x[3,4]               B              0            0             1             -
x[3,5]               B              0            0             1             -
x[4,1]               B              0            0             1             -
x[4,2]               B              0            0             1             -
x[4,3]               B              0            0             1             -
x[4,4]               B              0            0             1             -
x[4,5]               B              1            0             1             -
x[5,1]               B              0            0             1             -
x[5,2]               B              0            0             1             -
x[5,3]               B              1            0             1             -
x[5,4]               B              0            0             1             -
x[5,5]               B              0            0             1             -
...
-----
Constraints
Nr. of constraints:  710
Name                 Type           Activity     Lower Bound   Upper Bound   Marginal
-----
...
sos1_1               E              1            1             1             -
sos1_2               E              1            1             1             -
sos1_3               E              1            1             1             -
sos1_4               E              1            1             1             -
sos1_5               E              1            1             1             -

```

sos2_1	E	1	1	1	-
sos2_2	E	1	1	1	-
sos2_3	E	1	1	1	-
sos2_4	E	1	1	1	-
sos2_5	E	1	1	1	-
...					
-----					

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

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

### 10.1.7 Generic travelling salesman problem

The travelling salesman problem is well known and often described. In the following CML 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 CML model `tsp.cml` can be formulated as follows:

```
%arg -solver cbc
%arg -cd
%opt cbc threats 2

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:

```

-----
General status:    normal
Problem :         tsp.cmpl
SolverName        COIN-OR cbc
Nr. of Solutions: 1
-----
Solution nr.:     1
Objective name :   distance
Objective value :  321.319 (min!)
-----
Variables
Nr. of variables: 109
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 section 10.1.4 a 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[]:=(0,0,0,0,0,0,0,0,0,0,0);

{ 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 58 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
    x1:= 0;
    xo:= 2;
    xn:= (x1+xo)/2;

    { (xo-x1) > e :

```

```

fd:= 12 - 12 * xn^3 - 12 * xn^5;
{ fd >= 0 : x1:=xn; |
  fd <= 0 : xo:=xn ;}
xn:= (x1+xo)/2;

fx := 12 * xn -3 * xn^4 - 2 * xn^6;
echo "f'(xn): " + format("%10.4f",fd) + " x1: " +
      format("%6.4f",x1) +
      " 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 x1: 0.0000 xo: 1.0000 xn: 0.5000 f(xn): 5.7812
f'(xn):    10.1250 x1: 0.5000 xo: 1.0000 xn: 0.7500 f(xn): 7.6948
f'(xn):     4.0898 x1: 0.7500 xo: 1.0000 xn: 0.8750 f(xn): 7.8439
f'(xn):    -2.1940 x1: 0.7500 xo: 0.8750 xn: 0.8125 f(xn): 7.8672
f'(xn):     1.3144 x1: 0.8125 xo: 0.8750 xn: 0.8438 f(xn): 7.8829
f'(xn):    -0.3397 x1: 0.8125 xo: 0.8438 xn: 0.8281 f(xn): 7.8815
f'(xn):     0.5113 x1: 0.8281 xo: 0.8438 xn: 0.8359 f(xn): 7.8839
Optimal solution found
x: 0.836
function value: 7.883868

```

## 10.3 Several selected CMPL applications

### 10.3.1 Calculating the Fibonacci sequence

By definition, the first Fibonacci sequence starts with the numbers 0 and 1, and each remaining number is the sum of the previous two.

$$a_{n+1} = a_n + a_{n-1} \quad ; \quad a_1 = 0, a_2 = 1, n \in \mathbb{N}$$

CMPL code to calculate the Fibonacci sequence (`fibonacci.cmpl`):

```

%arg -noOutput

parameters:

```

```

# initialing the first elements
F[1..2] := (0, 1);
# Calculating the Fibonacci sequence until the 10th element
{i:=3(1)10: F[i] := F[i-2] + F[i-1]; }
echo "The Fibonacci sequence for the first 10 elements";
{i:=1(1)10: echo "element " + i + ": " + F[i]; }

```

CMPL command:

```

cmpl fibonacci.cmpl

```

Calculated sequence:

```

The Fibonacci sequence for the first 10 elements
element 1: 0
element 2: 1
element 3: 1
element 4: 2
element 5: 3
element 6: 5
element 7: 8
element 8: 13
element 9: 21
element 10: 34

```

### 10.3.2 Calculating primes

A prime is defined as a natural number that has exactly two distinct natural number divisors: 1 and itself.

CMPL code to calculate the sequence of primes (`primes.cmpl`):

```

%arg -noOutput
parameters:
    # Initialing the first element
    P[1] := 2;
    # Calculating a prime sequence in the range 3 until 10
    {i := 3(1)10:
        #Test whether number is prime
        t := 1;
        {j := defset(P[]), t != 0:
            t := i mod P[j];
        }
        # If number is prime, save then as prime number
        {t != 0:
            P[count(P[]) + 1] := i;
        }
    }
}

```

```
echo "The prime sequence in the range 3 until 10";  
{i:=defset(P[]): echo "element " + i + ": " + P[i]; }
```

CMPL command:

```
cmpl primes.cmpl
```

Calculated sequence:

```
The prime sequence in the range 3 until 10  
element 1: 2  
element 2: 3  
element 3: 5  
element 4: 7
```

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## 12 Appendix

### 12.1 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 CMLP 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

**artificialCost** *doubleValue*

Costs  $\geq$  these are treated as artificials in feasibility pump 0.0 off - otherwise variables with costs  $\geq$  these are treated as artificials and fixed to lower bound in feasibility pump

Range of values is 0 to 1.79769e+308, default 0

**cutoff** *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

**increment** *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

**integerTolerance** *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

**preTolerance** *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  $\geq 10,000,000$  then the length in tree is  $\text{value} \% 10000000$  - 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  $\text{rows} + \text{columns} < 500$ , -2 means use Cplex if it is linked in. Otherwise if negative then go into depth first complete search fast branch and bound when  $\text{depth} \geq -\text{value} - 2$  (so -3 will use this at  $\text{depth} \geq 1$ ). 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  $\geq 0$  the value doesn't matter very much. The code will do approximately 100 nodes of fast branch and bound every now and then at  $\text{depth} \geq 5$ . 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  $\leq$  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 surprisingly effective. The column order option is obviously not on costs but easy to code here.

Possible options: off pri(ortities) 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!. Doh option does heuristic before pre-processing

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  $\leq$  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:**

<b>barr(ier)</b>	Solve using primal dual predictor corrector algorithm
<b>dualS(implex)</b>	Do dual simplex algorithm
<b>either(Simplex)</b>	Do dual or primal simplex algorithm
<b>initialS</b>	Solve to continuous
	This just solves the problem to continuous - without adding any cuts
<b>outDup</b>	takes duplicate rows etc out of integer model
<b>primalS</b>	Do primal simplex algorithm
<b>reallyS</b>	Scales model in place
<b>stat</b>	Print some statistics
<b>tightLP</b>	Poor person's preSolve for now

**Branch and Cut actions:**

<b>branch</b>	Do Branch and Cut
---------------	-------------------

## 12.2 Selected GLPK parameters

The following parameters are taken from the the GLPK command line help.

Only the CBC parameters that are useful in a CMPL context are described afterwards.

Usage GLPK parameters:

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

### General options:

<b>simplex</b>	use simplex method (default)
<b>interior</b>	use interior point method (LP only)
<b>scale</b>	scale problem (default)
<b>noscale</b>	do not scale problem
<b>ranges filename</b>	write sensitivity analysis report to filename in printable format (simplex only)
<b>tmlim nnn</b>	limit solution time to nnn seconds
<b>memlim nnn</b>	limit available memory to nnn megabytes
<b>wlp filename</b>	write problem to filename in CPLEX LP format
<b>wglp filename</b>	write problem to filename in GLPK format
<b>wcnf filename</b>	write problem to filename in DIMACS CNF-SAT format
<b>log filename</b>	write copy of terminal output to filename

### LP basis factorization options:

<b>luf</b>	LU + Forrest-Tomlin update (faster, less stable; default)
<b>cbg</b>	LU + Schur complement + Bartels-Golub update (slower, more stable)
<b>cgr</b>	LU + Schur complement + Givens rotation update (slower, more stable)

### Options specific to simplex solver:

<b>primal</b>	use primal simplex (default)
<b>dual</b>	use dual simplex
<b>std</b>	use standard initial basis of all slacks
<b>adv</b>	use advanced initial basis (default)
<b>bib</b>	use Bixby's initial basis

<b>steep</b>	use steepest edge technique (default)
<b>nosteep</b>	use standard "textbook" pricing
<b>relax</b>	use Harris' two-pass ratio test (default)
<b>norelax</b>	use standard "textbook" ratio test
<b>presol</b>	use presolver (default; assumes scale and adv)
<b>nopresol</b>	do not use presolver
<b>exact</b>	use simplex method based on exact arithmetic
<b>xcheck</b>	check final basis using exact arithmetic

#### Options specific to interior-point solver:

<b>nord</b>	use natural (original) ordering
<b>qmd</b>	use quotient minimum degree ordering
<b>amd</b>	use approximate minimum degree ordering (default)
<b>symamd</b>	use approximate minimum degree ordering

#### Options specific to MIP solver:

<b>nomip</b>	consider all integer variables as continuous (allows solving MIP as pure LP)
<b>first</b>	branch on first integer variable
<b>last</b>	branch on last integer variable
<b>mostf</b>	branch on most fractional variable
<b>drtom</b>	branch using heuristic by Driebeck and Tomlin (default)
<b>pcost</b>	branch using hybrid pseudocost heuristic (may be useful for hard instances)
<b>dfs</b>	backtrack using depth first search
<b>bfs</b>	backtrack using breadth first search
<b>bestp</b>	backtrack using the best projection heuristic
<b>bestb</b>	backtrack using node with best local bound (default)
<b>intopt</b>	use MIP presolver (default)
<b>nointopt</b>	do not use MIP presolver
<b>binarize</b>	replace general integer variables by binary ones (assumes intopt)
<b>fpump</b>	apply feasibility pump heuristic
<b>gomory</b>	generate Gomory's mixed integer cuts
<b>mir</b>	generate MIR (mixed integer rounding) cuts
<b>cover</b>	generate mixed cover cuts
<b>clique</b>	generate clique cuts
<b>cuts</b>	generate all cuts above
<b>mipgap</b> <i>tol</i>	set relative mip gap tolerance to <i>tol</i>

<b>minisat</b>	translate integer feasibility problem to CNF-SAT and solve it with MiniSat solver
<b>objbnd</b> <i>bound</i>	add inequality $obj \leq bound$ (minimization) or $obj \geq bound$ (maximization) to integer feasibility problem (assumes minisat)

### 12.3 Selected Gurobi parameters

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

Please see: <http://www.gurobi.com/doc/46/refman/node591.html>

Usage Gurobi parameters:

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

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