Introduction to BCP – MCF Example

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July 18, 2006

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BCP: Branch-Cut-Price

- Software for branch-and-cut-and-price
- Parallel code
- LP solver : Clp, Cplex, Xpress, . . .
- Most flexible in COIN-OR
- Research code (no stand-alone executable)

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BCP code split into four directories: (see `coin-Bcp/Bcp/src`)

- `include`: all header files
- Tree Manager (`TM`): Maintain the LP associated with each node, manage cuts and variables
- Node level operations (`LP`): cutting, branching, heuristics, fixing, column generation
- Utilities (`Member`): code for interface between TM and LP, initialization

Solver Initialization

Tree Manager	Solver
• read data	

Solver Initialization

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• pack module data	

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Tree Manager		Solver
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• pack module data	$\longrightarrow$	• unpack module data

Solver Initialization

Tree Manager		Solver
• read data		
• pack module data	$\longrightarrow$	• unpack module data
		• setup the LP solver

Processing a node

Tree Manager	**Solver**
• select node	

Processing a node

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- select node
- pack node LP data

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		• solve
		• generate cuts/vars
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		• create LP data for sons

Processing a node

Tree Manager		**Solver**
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• pack node LP data	→	• unpack node LP data
		• solve
		• generate cuts/vars
		• branch
		• create LP data for sons
		• pack node LP data for sons

Processing a node

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• pack node LP data	$\longrightarrow$	• unpack node LP data
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Processing a node

Tree Manager		**Solver**
• select node		
• pack node LP data	→	• unpack node LP data
		• solve
		• generate cuts/vars
		• branch
		• create LP data for sons
• unpack node LP data for sons	←	• pack node LP data for sons
• add sons to tree		

BCP Constraints/Variables

Types of Constraints/Variables:

- Core : present at all nodes
- Algorithmic : separation/generation algorithm
- Indexed : e.g. stored in a vector

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Representation: Constraints are stored as ranged constraints:

$$lb \leq ax \leq ub$$

with $lb = -$`DBL_MAX` or $ub =$ `DBL_MAX` possible

Implementing a Column Generation Application

Member:

- Read input
- Implement variables

TM:

- Set up the LP at the root node
- display of a solution

LP:

- Test feasibility of a solution
- Column generation method
- Computation of a lower bound
- Branching decision

Col. Gen. Example: Multicommodity Flow (MCF-1)

- Directed graph $G = (V, E)$
- N commodities
- (s^i, t^i) : source-sink pair, $i = 0, \ldots, N-1$
- d^i : supply/demand vector for $s^i t^i - \mathit{flow}$, $i = 0, \ldots, N-1$

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- d^i : supply/demand vector for $s^i t^i - flow$, $i = 0, \ldots, N-1$

For each arc $e \in E$:

- 0 : lower bound for total flow on arc
- u_e : finite upper bound for total flow on arc $(0 \leq u_e)$
- w_e : unit cost $(0 \leq w_e)$

MCF: ILP Formulation

Solution:

- f^i: $s^i t^i$-flow with supply/demand vector d^i
- $\sum_i f_e^i \leq u_e$ for all $e \in E$

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ILP Formulation:

$$\min \sum_i w^T f^i$$

$$\sum_i f^i \leq u \qquad (1)$$

$$\sum_{e=(v,w)\in E} f_e^i - \sum_{e=(w,v)\in E} f_e^i = d_v^i \quad \forall v \in V, \forall i \qquad (2)$$

$$0 \leq f^i \leq u \qquad \forall i \qquad (3)$$

$$f^i \text{ integral} \qquad \forall i \qquad (4)$$

MCF: Input data

Class MCF_data (see Member/MCF_data.hpp):

- arcs : vector of struct (tail, head, lb, ub, weight)
- commodities : vector of struct (source, sink, demand)
- numarcs
- numnodes
- numcommodities
- Setup by MCF_data::readDimacsFormat()

MCF: Input data

Class `MCF_data` (see `Member/MCF_data.hpp`):

- `arcs` : vector of struct (`tail`, `head`, `lb`, `ub`, `weight`)
- `commodities` : vector of struct (`source`, `sink`, `demand`)
- `numarcs`
- `numnodes`
- `numcommodities`
- Setup by `MCF_data::readDimacsFormat()`

Parameter `MCF_AddDummySourceSinkArcs` : Add `numcommodities` dummy arcs with large weight to ensure feasibility

MCF: Master Problem

Master Problem:

- Column : $s^i t^i$-flow satisfying d^i for some i
- F^i : matrix of all generated $s^i t^i$-flows ($+$ dummy flow)
- λ^i : multiplier for generated $s^i t^i$-flows

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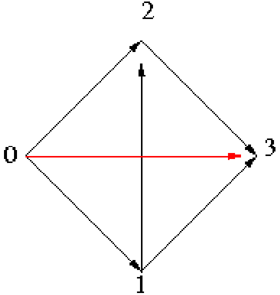
Example: all arcs upper capacity 2, source = 0, sink = 3, $d = 2$.



01	0
02	0
12	0
13	0
23	0
03	2

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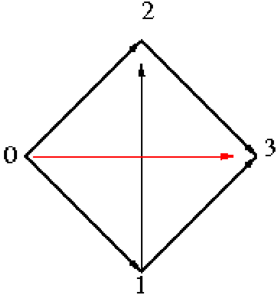

01	0	1
02	0	1
12	0	1
13	0	0
23	0	1
03	2	0

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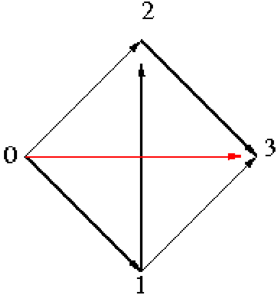

01	0	1	2
02	0	1	0
12	0	1	2
13	0	0	0
23	0	1	2
03	2	0	0

MCF: Master Problem

$$
\begin{aligned}
\min \sum_i w^T F^i \lambda^i & \\
\sum_i F^i \lambda^i \leq u & \qquad (5)\\
e^T \lambda^i = 1 \quad \forall i & \qquad (6)\\
\lambda^i \geq 0 \quad \forall i & \qquad (7)\\
F^i \lambda^i \text{ integer} \quad \forall i & \qquad (8)
\end{aligned}
$$

MCF: Master Problem

$$\min \sum_i w^T F^i \lambda^i$$

$$\sum_i F^i \lambda^i \leq u \tag{5}$$

$$e^T \lambda^i = 1 \quad \forall i \tag{6}$$

$$\lambda^i \geq 0 \quad \forall i \tag{7}$$

$$F^i \lambda^i \text{ integer} \quad \forall i \tag{8}$$

$$\begin{bmatrix} F^0 & F^1 & F^2 \end{bmatrix} \begin{bmatrix} \lambda^0 \\ \lambda^1 \\ \lambda^2 \end{bmatrix} \leq u$$

$$\begin{bmatrix} 1^T & . & . \\ . & 1^T & . \\ . & . & 1^T \end{bmatrix} \begin{bmatrix} \lambda^0 \\ \lambda^1 \\ \lambda^2 \end{bmatrix} = 1$$

MCF: Master Problem

$$\min \sum_i w^T F^i \lambda^i$$

$$\sum_i F^i \lambda^i \leq u \qquad (\pi) \tag{5}$$

$$e^T \lambda^i = 1 \quad \forall i \quad (\nu^i) \tag{6}$$

$$\lambda^i \geq 0 \quad \forall i \tag{7}$$

$$F^i \lambda^i \text{ integer} \quad \forall i \tag{8}$$

Pricing of feasible $s^i t^i$-flow f:

weight of flow : $w^T f$

dual activity: $\pi^T f + \nu^i$

Reduced cost of flow $f = w^T f - \pi^T f - \nu^i = (w^T - \pi^T) f - \nu^i$

Class MCF_vars

MCF_var:

- int commodity : index of commodity
- CoinPackedVector flow : positive flow on arcs
- weight: objective coefficient

See include/MCF_var.hpp, Member/MCF_var.cpp

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MCF_lp::vars_to_cols(): generate columns of the master problem for vars

MCF: Setting the Master at the Root

Variables:

- Dummy flow variables are algorithmic variables ($\lambda_0^i \; \forall \; i$)
- All generated variables are algorithmic

See in `TM/MCF_tm.cpp`:

`MCF_tm::initialize_core`

`MCF_tm::create_root`

MCF: Setting the Master at the Root

Variables:

- Dummy flow variables are algorithmic variables ($\lambda_0^i \ \forall \ i$)
- All generated variables are algorithmic

Constraints:

- All constraints are core constraints
- Upper bound constraints: $0 \leq u_e \ \forall \ e \in E$
- Dummy upper bound constraints: $dem(i)\lambda_0^i \leq dem(i) \ \forall i$
- Convexity constraints: $\lambda_0^i = 1 \ \forall \ i$

See in `TM/MCF_tm.cpp`:

`MCF_tm::initialize_core`

`MCF_tm::create_root`

Class MCF_tm*: Derived from* BCP_tm_user

Data:

- MCF_data data

Methods:

- pack_module_data() : pack data needed at the node level. Called once for each processor used as a solver.
- initialize_core() : Transmit core constraints/variables to BCP.
- create_root : set up the problem at the root node
- pack_var_algo() : pack algorithmic vars
- unpack_var_algo() : unpack algorithmic vars
- display_feasible_solution() : display solution

Node operations

1. **Initialize new node**
2. Solve node LP
3. **Test feasibility of node LP solution**
4. **Compute lower bound for node LP**
5. Fathom node (if possible)
6. **Perform fixing on vars**
7. Update row effectiveness records
8. **Generate cuts, Generate vars**
9. **Generate heuristic solution**
10. Fathom node (if possible)
11. **Decide to branch, fathom, or repeat loop**
12. Add to node LP the cuts/vars generated, if loop is repeated
13. Purge cut pool, var pool

Class MCF_LP*: Derived from* BCP_lp_user

Data:

- OsiSolverInterface* cg_lp: pointer on Osi LP solver used for column generation
- MCF_data data: problem data
- vector<MCF_branch_decision>* branch_history: branch_history[i]: vector of branching decision involving commodity *i* (arc, lb, ub)
- map<int,double>* flows: flows[i]: map between index of arc and positive flow for commodity *i* in LP solution
- BCP_vec<BCP_var*> gen_vars: vector holding generated vars
- bool generated_vars: indicator for success in column generation

See LP/MCF_lp.cpp, include/MCF_lp.hpp

Class MCF_LP*: Derived from* BCP_lp_user *(cont)*

Methods:

- `unpack_module_data()`
- `pack_var_algo()`, `unpack_var_algo()`
- `initialize_new_search_tree_node()` : Natural place for initializing user defined variables of `MCF_lp`.
- `test_feasibility()`: Test feasibility of current LP solution.
- `compute_lower_bound()`: Lower bound on optimal value of subproblem
- `generate_vars_in_lp()`: Pass new variables to BCP
- `vars_to_cols()` : Function generating a column from the var representation
- `select_branching_candidates()` : Generate rules for creating potential sons

MCF: Computing a Lower Bound

Initially, lower bound of a node is set to the lower bound of its father

- Try to generate a variable with negative reduced cost
- If successful, lower bound is currently known lower bound
- If unsuccessful, lower bound is the current LP value

See `MCF_lp::compute_lower_bound()` in `LP/MCF_lp.cpp`

MCF: Column Generation

- π, ν^i : optimal dual solution of the Master

(see `MCF_lp::compute_lower_bound` in `LP/MCF_lp.cpp`)

MCF: Column Generation

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Column generation:

$$\min(w^T - \pi^T)f^i - \nu^i$$

$$\sum_{e=(w,v)\in E} f_e^i - \sum_{e=(w,v)\in E} f_e^i = d_v^i \quad \forall v \in V \tag{9}$$

$$\ell^i \leq f^i \leq u^i \tag{10}$$

$$f^i \text{ integral} \tag{11}$$

If solution is negative , then f^i is the new column

(see `MCF_lp::compute_lower_bound` in `LP/MCF_lp.cpp`)

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If solution is $< \nu^i$, then f^i is the new column

(see `MCF_lp::compute_lower_bound` in `LP/MCF_lp.cpp`)

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Minimum cost flow problem $\Rightarrow$ Solve as an LP
(see `MCF_lp::compute_lower_bound` in `LP/MCF_lp.cpp`)

Branching

`MCF_lp::select_branching_candidates()`: Called at the end of each iteration. Possible return values are:

- `BCP_DoNotBranch_Fathomed` : fathomed without branching
- `BCP_DoNotBranch` : continue to work on this node
- `BCP_DoBranch` : Branching must be done. Must create the candidates

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$\Rightarrow$ Must branch

Branching rule:

- Select an arc e (not dummy) and i with $F^i\lambda^i = z$ fractional
- First child: Use only columns where flow of i on e is $> z$
- Second child: Use only columns where flow of i on e is $< z$

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- Second child: Use only columns where flow of i on e is $< z$
- Need to know ℓ_e^i and u_e^i for all i and e for col. gen.
  $\Rightarrow$ use `branch_history[i]`

Class MCF_branching_var

MCF_branching_var:

- artificial variable used to keep branching history around
- weight 0
- coefficients 0
- upper: 1, lower 0: identify child

See include/MCF_var.hpp, Member/MCF_var.cpp

Class MCF_branching_var

MCF_branching_var:

- artificial variable used to keep branching history around
- weight 0
- coefficients 0
- upper: 1, lower 0: identify child

Data:

- commodity: commodity i used in branching
- arc_index: arc e used in branching
- lb_child0, ub_child0, lb_child1, ub_child1: bounds for commodity i on e in the children

See include/MCF_var.hpp, Member/MCF_var.cpp

Branching object

Create the candidates using:
`BCP_lp_branching_object::BCP_lp_branching_object()`
Its relevant parameters are:

- `int children` : # children
- `BCP_vec<BCP_var*> *new_vars` : vector for new vars
- `BCP_vec<BCP_cut*> *new_cuts` : vector for new cuts
- `BCP_vec<int> *fvp` : vector for indices of variables whose bounds are changed
  Negative indices : vars from `new_vars`,
  index $-i-1$ corresponding to entry i
- `BCP_vec<int> *fcp` : vector for indices of cuts whose bounds are changed.
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Branching object (cont)

- `BCP_vec<double> *fvb` : vector for lower/upper bounds for each vars in `fvp`, for each child

- `BCP_vec<double> *fcb` : vector for lower/upper bounds for each constraint in `fcp`, for each child
- 4 additional parameters (implied parts)

Pass `NULL` for irrelevant parameters

Branching object (cont)MCF

- `BCP_vec<double> *fvb` : vector for lower/upper bounds for each vars in `fvp`, for each child
  [0, 0, 0, 1, 0, 0, 1, 1, 0, 0, 0, 1]
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Branching object: Forced vs. Implied

Forced changes:

- Used during strong branching
- Sent to the tree manager if branching object is selected
- Used in the children if branching object is selected

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Implied changes:

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- **NOT** Sent to the tree manager if branching object is selected
- **NOT** Used in the children if branching object is selected

Many implied changes $\Rightarrow$ storing them is costly.
If implied changes are used, implement them also in
`MCF_lp::_initialize_new_search_tree_node()`

MCF: Parameter File

Predefined parameters:
Class `MCF_par` (see `include/MCF_par.hpp`)
Class `BCP_lp_par`   Class `BCP_tm_par`

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Class `MCF_par` (see `include/MCF_par.hpp`)
Class `BCP_lp_par` Class `BCP_tm_par`

Some parameters with their default values:

- `MCF_AddDummySourceSinkArcs`: 1
- `MCF_InputFilename`: `small`
- `BCP_VerbosityShutUp`: 0
- `BCP_MaxRunTime` : 3600
- `BCP_Granularity` : 1e-8
- `BCP_IntegerTolerance` : 1e-5
- `BCP_TreeSearchStrategy` : 1
  // 0: Best Bound 1: BFS 2: DFS