Biobjective Integer Programming

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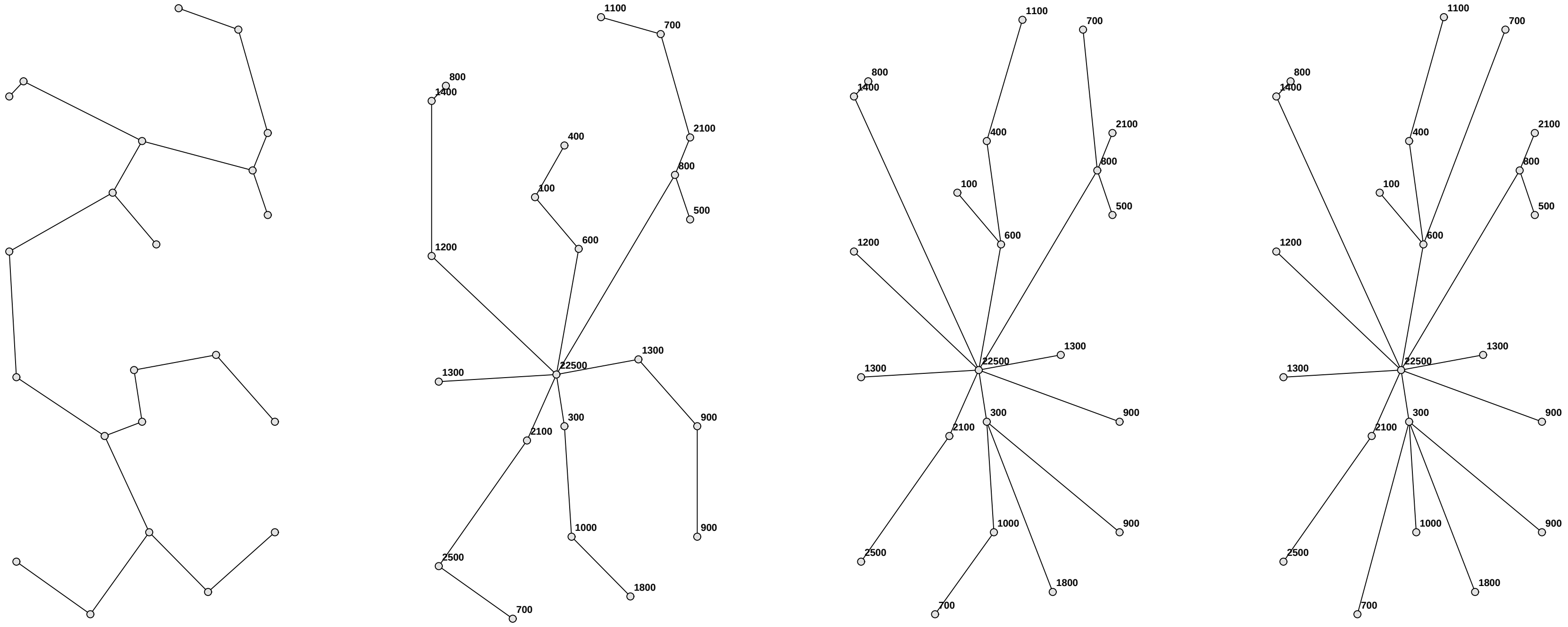

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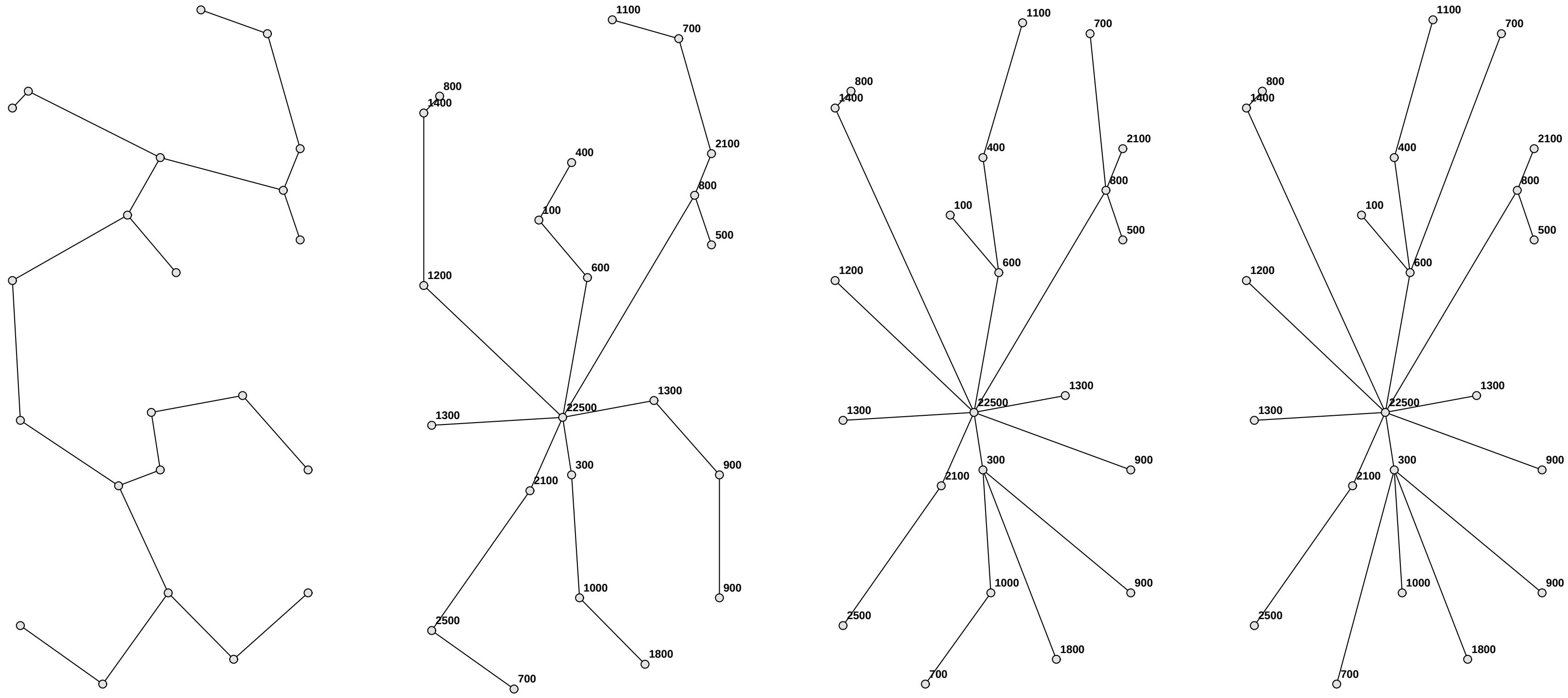
Outline of Talk

- Motivation
- Preliminaries
- The WCN Algorithm
- Implementation
- Example
- Computational Results

Motivation: Cable-Trench Problems

- A single commodity must be supplied to a set of customers from a central supply point.
- We want to design a network, possibly obeying capacity and other side constraints.
- In the Cable-Trench Problem, we consider both
  - the cost of construction (the sum of lengths of all links), and
  - the latency of the resulting network (the sum of length multiplied by demand carried for all links).
- These are competing objectives for which we would like to analyze the tradeoff.
- We can formulate this problem as a biobjective integer program.

Solutions for a Small CTP Instance



(a) (b) (c) (d)

Biobjective Mixed-integer Programs

A *biobjective* or *bicriterion mixed-integer program* (BMIP) is an optimization problem of the form

$$\begin{array}{ll} \text{vmax} & f(x) \\ \text{subject to} & x \in X, \end{array}$$

where

- $f : \mathbb{R}^n \to \mathbb{R}^2$ is the *(bicriterion) objective function*, and
- $X \subset \mathbb{Z}^p \times \mathbb{R}^{n-p}$ is the *feasible region*, usually defined to be

$$\{x \in \mathbb{Z}^p \times \mathbb{R}^{n-p} \mid g_i(x) \leq 0, i = 1, \ldots, m\}$$

for functions $g_i : \mathbb{R}^n \to \mathbb{R}$, $i = 1, \ldots, m$.

The vmax operator indicates that we are interested in generating the *efficient solutions* (defined next).

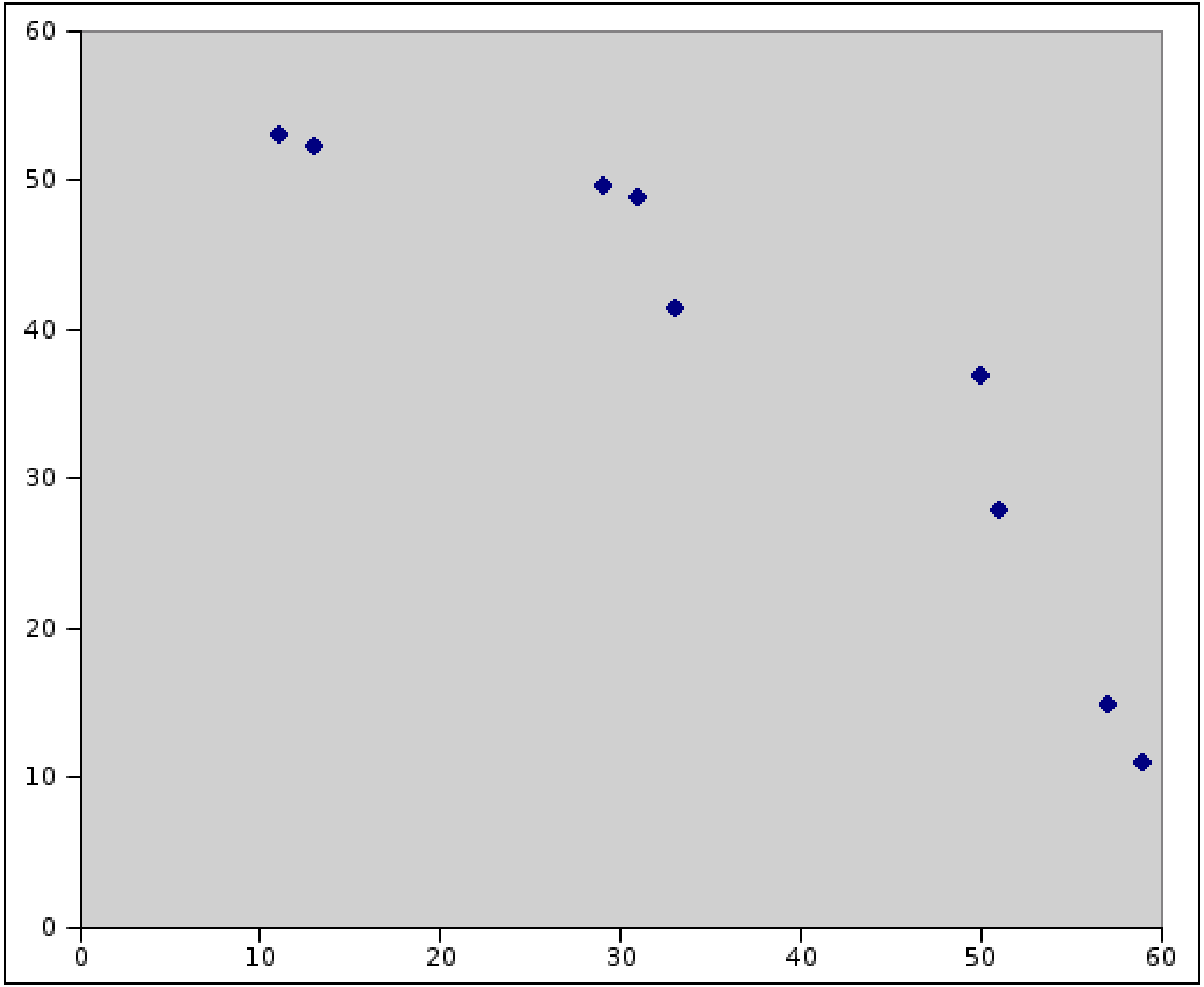
Some Definitions

- $x^1 \in X$ *dominates* $x^2 \in X$ if $f_i(x_1) \geq f_i(x_2)$ for $i = 1, 2$ and at least one inequality is strict.
- If both inequalities are strict the dominance is *strong* (otherwise *weak*).
- Any $x \in X$ not dominated by any other member of X is said to be *efficient*.
- The set of *outcomes* is defined to be $Y = f(X) \subset \mathbb{R}^2$.
- In outcome space, BMIP can be restated as

$$
\begin{array}{ll}
\text{vmax} & y \\
\text{subject to} & y \in f(X),
\end{array}
$$

- If $x \in X$ is efficient, then $y = f(x)$ is *Pareto*.
- For simplicity, we work in outcome space.
- Our goal is to generate the set of all Pareto outcomes.

Illustrating Pareto Outcomes



Probing Algorithms

- A wide array of algorithms for generating Pareto outcomes have been proposed.
- We will focus on *probing algorithms* that *scalarize* the objective, i.e., replace it with a single criterion.
- Such algorithms reduce solution of a BMIP to a series of MIPs.
- The main factor in the running time is the number of probes.
- The most obvious scalarization is the *weighted sum objective*.
- We replace the original objective with

$$\max_{y \in f(X)} \beta y_1 + (1 - \beta) y_2$$

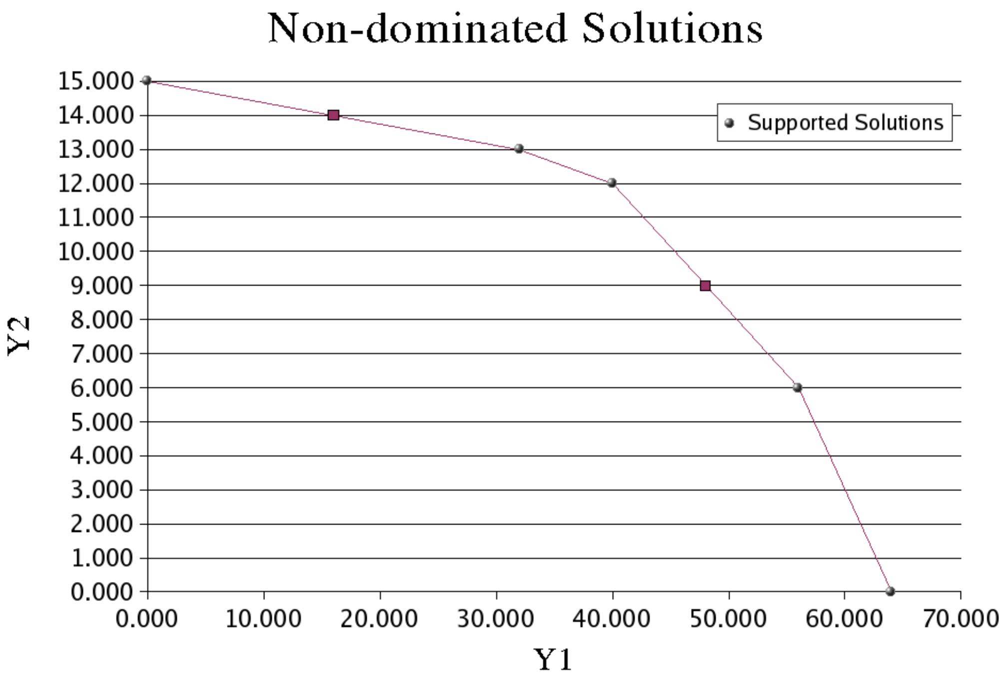
to obtain a parameterized family of MIPs.

Supported Outcomes

- Optimal solutions to weighted sum MIPs are extreme points of $conv(Y_E)$.
- Such outcomes are called *supported outcomes*.
- The set of all supported outcomes can easily be generated by solving a sequence of MIPs.
- Every supported outcome is Pareto, but the converse is not true.
- This makes it difficult as a tool to generate all Pareto outcomes.
- Chalmet (1986) suggested restricting the subproblems so that each Pareto outcome is supported on some subregion.
- Using this technique, it is possible to generate all Pareto outcomes.

Quick Example

$$
\begin{aligned}
\text{vmax} \quad & [8x_1, x_2] \\
\text{s.t.} \quad & 7x_1 + x_2 \le 56 \\
& 28x_1 + 9x_2 \le 252 \\
& 3x_1 + 7x_2 \le 105 \\
& x_1, x_2 \ge 0
\end{aligned}
$$



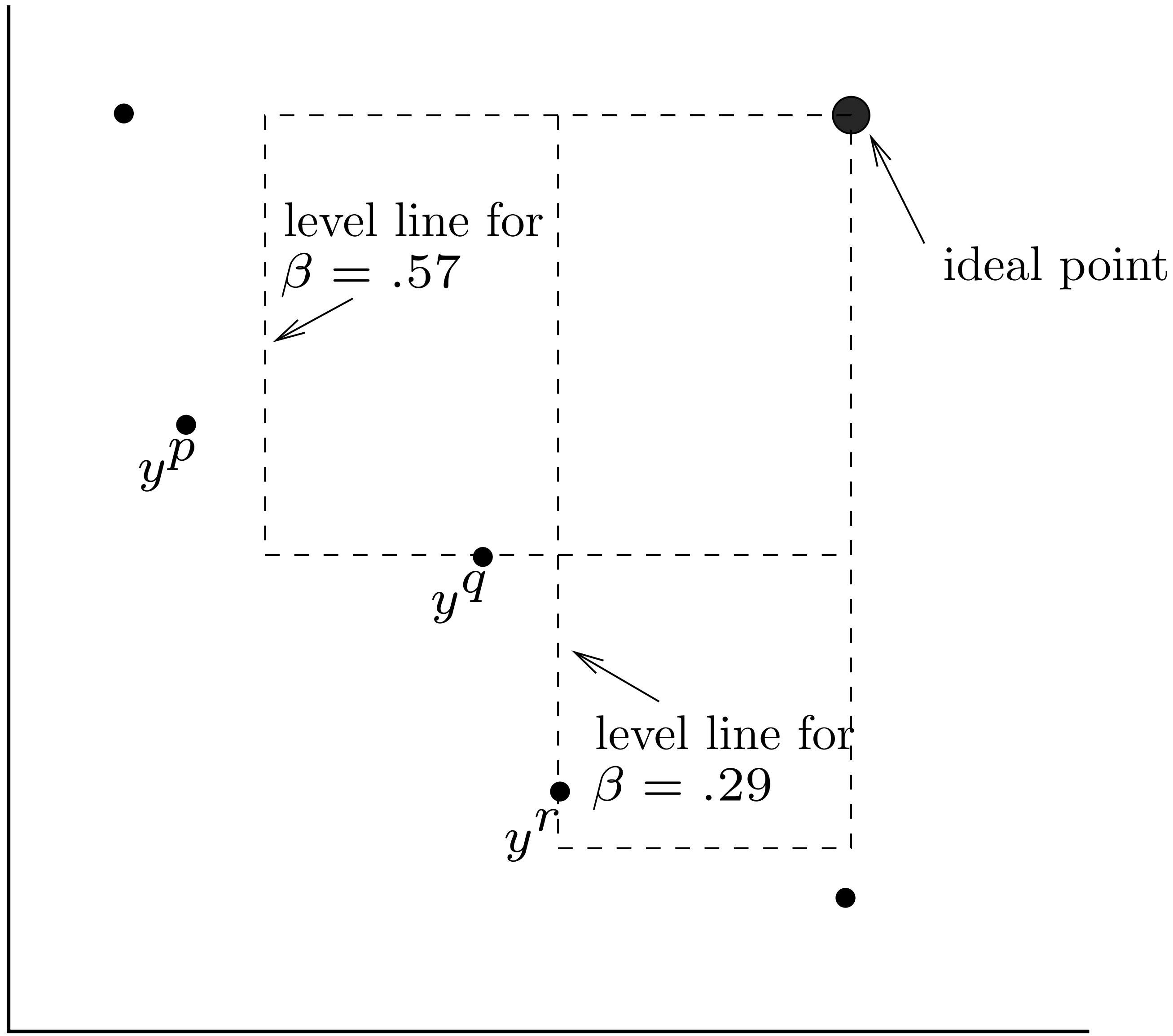
The Weighted Chebyshev Norm

- To generate unsupported outcomes, we replace the weighted sum objective with a *weighted Chebyshev norm* (WCN) objective.
- The *Chebyshev norm* (l_∞ norm) in $\mathbb{R}^2$ is defined by $\|y\|_\infty = \max\{|y_1|, |y_2|\}$.
- The *weighted Chebyshev norm* with weight $0 \leq \beta \leq 1$ is defined by $\|y\|_\infty = \max\{\beta|y_1|, (1-\beta)|y_2|\}$.
- The *ideal point* y^* is (y_1^*, y_2^*) where $y_i^* = \max_{x \in X}(f(x))_i$.
- Methods based on the WCN select outcomes with minimum WCN distance from the ideal point by solving

$$\min_{y \in f(X)} \{\|y^* - y\|_\infty^\beta\}. \tag{1}$$

- Bowman (1976) showed that every Pareto outcome is a solution to (1) for some $0 \leq \beta \leq 1$.
- The converse only holds if the instance is uniformly dominant.

Illustrating the WCN



Uniform Dominance

- Members of X that are *not* strongly dominated by some efficient solution are called *weakly dominated*.
- Weakly dominated solutions are optimal to (1) for some β.
- If X does not contain any weakly dominated solutions, then the instance is said to be *uniformly dominant*.
- The assumption of uniform dominance simplifies computation substantially, but is not satisfied in most practical settings.
- The deal with this, we need to modify the algorithm.

Ordering the Pareto Outcomes

- Eswaran (1989) suggested ordering the Pareto outcomes so that
  - $Y_E = \{y_p \mid 1 \leq p \leq N\}$, and
  - if $p < q$, then $y_1^p < y_1^q$ (and hence $y_2^p > y_2^q$).
- For any Pareto outcome y_p, if we define

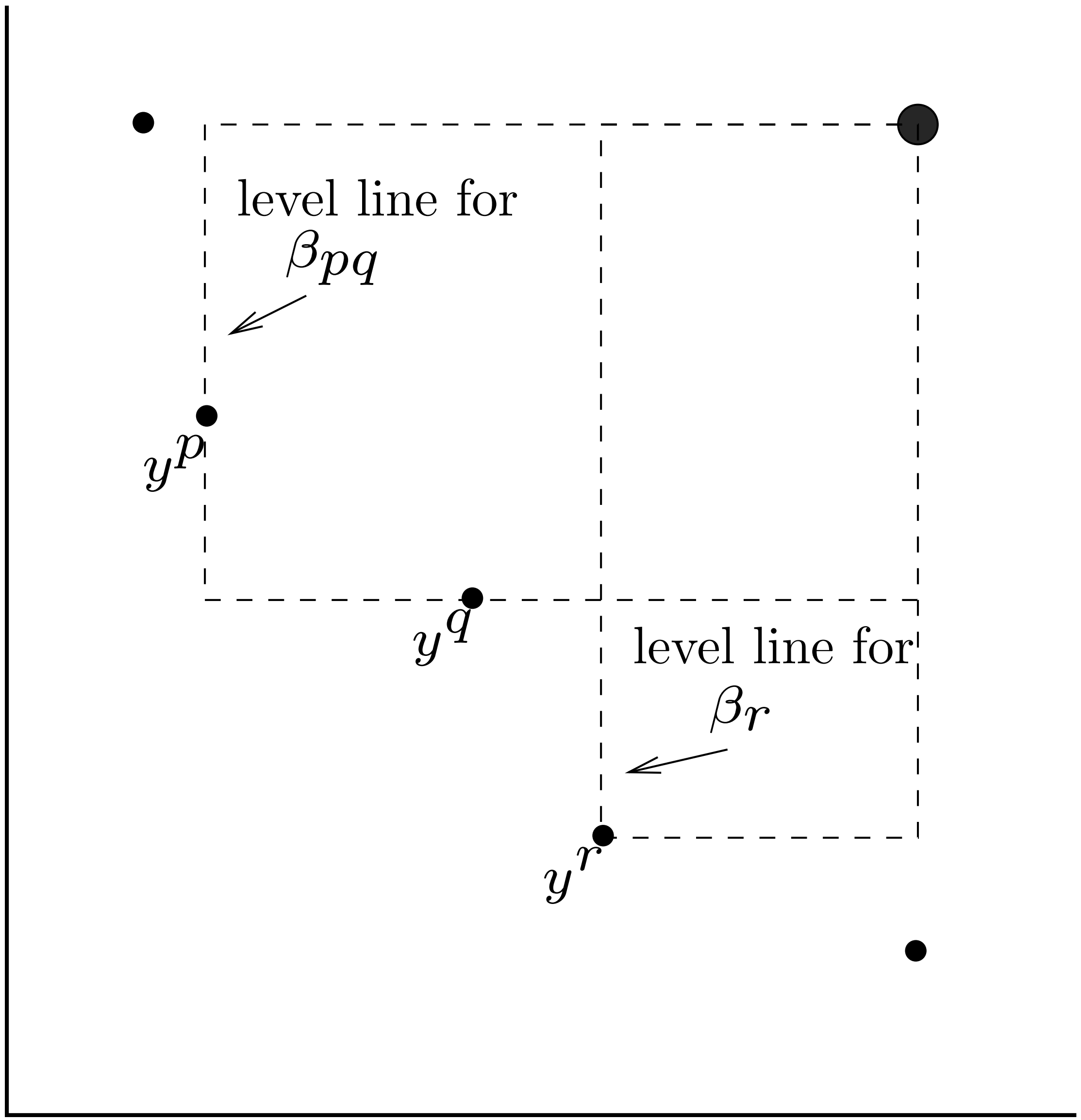
$$\beta_p = (y_2^* - y_2^p)/(y_1^* - y_1^p + y_2^* - y_2^p),$$

  then y^p is the unique optimal outcome for (1) with $\beta = \beta_p$.
- For any pair of Pareto outcomes y^p and y^q with $p < q$, if we define

$$\beta_{pq} = (y_2^* - y_2^q)/(y_1^* - y_1^p + y_2^* - y_2^q), \tag{2}$$

  then y^p and y^q are both optimal outcomes for (1) with $\beta = \beta_{pq}$.
- This provides us with a notion of *adjacency* and *breakpoints*.

Breakpoints Between Pareto Outcomes with the WCN



Algorithms Based on the WCN

- Eswaran (1989) proposed an algorithm based on binary search over the values of β, but the number of probes can be prohibitive.
- Solanki (1991) proposed an algorithm to generate an approximation to the Pareto set using the WCN.
- The Solanki algorithm probes between pairs of known outcomes using a procedure similar to that of Chalmet.
- We propose an algorithm that extends Solanki's ideas.
- The WCN Algorithm
  - is based on standard MILP solution techniques,
  - can produce all Pareto outcomes with $2N - 1$ probes, and
  - can produce the breakpoints between solutions.

The WCN Algorithm

Let $P(\beta)$ be the parameterized subproblem defined by (1) for a given weight β. The WCN algorithm is then:

Initialization Solve $P(1)$ and $P(0)$ to identify optimal outcomes y^1 and y^N, respectively, and the ideal point $y^* = (y_1^1, y_2^N)$. Set $I = \{(y^1, y^N)\}$.

Iteration While $I \neq \emptyset$ do:

1. Remove any (y^p, y^q) from I.
2. Compute β_{pq} as in (2) and solve $P(\beta_{pq})$. If the outcome is y^p or y^q, then y^p and y^q are adjacent in the list $(y^1, y^2, \ldots, y^N)$.
3. Otherwise, a new outcome y^r is generated. Add (y^p, y^r) and (y^r, y^q) to I.

This reduces solution of the original BMIP to solution of a sequence of $2N-1$ subproblems, but still requires the assumption of uniform dominance.

Solving $P(\beta)$

- Problem (1) is equivalent to

$$\begin{array}{lrcl} \text{minimize} & z & & \\ \text{subject to} & z & \geq & \beta(y_1^* - y_1), \\ & z & \geq & (1-\beta)(y_2^* - y_2), \text{ and} \\ & y & \in & f(X). \end{array} \qquad (3)$$

- This is a MIP, which can be solved by standard methods.
- This reformulation can still produce weakly dominated outcomes.

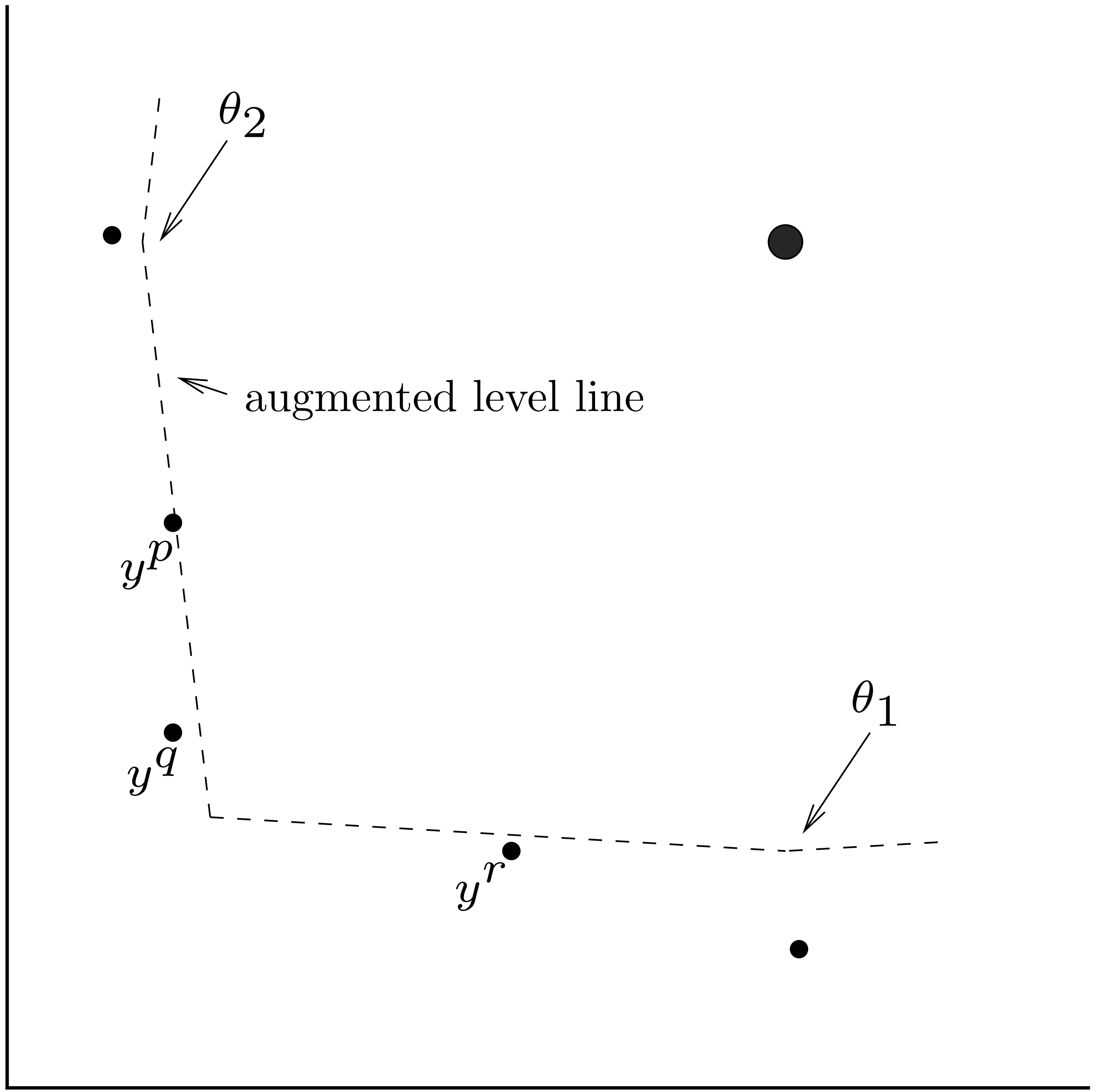
Relaxing the Uniform Dominance Requirement

- Dealing with weakly dominated outcomes is the most challenging aspect of these methods.
- We need a method of preventing $P(\beta)$ from producing weakly dominated outcomes.
- Weakly dominated outcomes are the same WCN distance from the ideal point as the outcomes they are dominated by.
- However, they are farther from the ideal point as measured by the l_p norm for $p < \infty$.
- One solution is to replace the WCN with the *augmented Chebyshev norm* (ACN), defined by

$$\|(y_1, y_2)\|_{\infty}^{\beta,\rho} = \max\{\beta|y_1|, (1-\beta)|y_2|\} + \rho(|y_1| + |y_2|),$$

where ρ is a small positive number.

Illustrating the ACN



Solving $P(\beta)$ with the ACN

- The problem of determining the outcome closest to the ideal point under this metric is

$$\begin{array}{lrcl} \min & z & + & \rho(|y_1^* - y_1| + |y_2^* - y_2|) \\ \text{subject to} & z & \geq & \beta(y_1^* - y_1) \\ & z & \geq & (1-\beta)(y_2^* - y_2) \\ & y & \in & f(X). \end{array} \tag{4}$$

- Because $y_k^* - y_k \geq 0$ for all $y \in f(X)$, the objective function can be rewritten as

$$\min z - \rho(y_1 + y_2).$$

- For fixed $\rho > 0$ small enough:
  - all optimal outcomes for problem (4) are Pareto (in particular, they are not weakly dominated), and
  - for a given Pareto outcome y for problem (4), there exists $0 \leq \hat{\beta} \leq 1$ such that y is the unique outcome to problem (4) with $\beta = \hat{\beta}$.
- In practice, choosing a proper value for ρ can be problematic.

Combinatorial Method for Eliminating Weakly Dominated Solutions

- In the case of *biobjective linear integer programs* (BLIPs), we can employ combinatorial methods.
- Such a strategy involves implicitly enumerating alternative optimal solutions to $P(\beta)$.
- Weakly dominated outcomes are eliminated with cutting planes during the branch and bound procedure.
- Instead of pruning nodes that yield feasible outcomes immediately, we continue to search for alternative optima that dominate the current incumbent.
- To do so, we determine which of the two constraints

$$\begin{aligned} z &\geq \beta(y_1^* - y_1) \\ z &\geq (1-\beta)(y_2^* - y_2) \end{aligned}$$

from problem (1) is binding at $\hat{y}$.

Combinatorial Method for Eliminating Weakly Dominated Solutions (cont'd)

- Let ϵ_1 and ϵ_2 be such that if y_r is a new outcome between y^p and y^q, then $y_i^r \geq \min\{y_i^p, y_i^q\} + \epsilon_i$, for $i = 1, 2$.
- If the first constraint is binding, then the cut

$$y_1 \geq \hat{y}_1 + \epsilon_1$$

  is valid for any outcome that dominates $\hat{y}$.
- If the second constraint is binding, then the cut

$$y_2 \geq \hat{y}_2 + \epsilon_2$$

  is valid for any outcome that dominates $\hat{y}$.

Hybrid Methods

- In practice, the ACN method is fast, but choosing the proper value of ρ is problematic.
- Combinatorial methods are less susceptible to numerical difficulties, but are slower.
- Combining the two methods improves running times and reduces dependence on the magnitude of ρ.

Other Enhancements to the Algorithm

- In Step 2, any new outcome y^r will have $y_1^r > y_1^p$ and $y_2^r > y_2^q$.
- If no such outcome exists, then the subproblem solver must still re-prove the optimality of y^p or y^q.
- Then it must be the case that

$$\|y^* - y^r\|_\infty^{\beta_{pq}} + \min\{\beta_{pq}\epsilon_1, (1-\beta_{pq})\epsilon_2\} \leq \|y^* - y^p\|_\infty^{\beta_{pq}} = \|y^* - y^q\|_\infty^{\beta_{pq}}$$

- Hence, we can impose an a priori upper bound of

$$\|y^* - y^p\|_\infty^{\beta_{pq}} - \min\{\beta_{pq}\epsilon_1, (1-\beta_{pq})\epsilon_2\}$$

  when solving the subproblem $P(\beta_{pq})$.
- With this upper bound, each subproblem will either be infeasible or produce a new outcome.

Using Warm Starting

- We have been developing methodology for *warm starting* branch and bound computations.
- Because the WCN algorithm involves solving a sequence of slightly modified MILPs, warm starting can be used.
- Three approaches
  - Warm start from the result of the previous iteration.
  - Solve a "base" problem first and warm each subsequent problem from there.
  - Warm start from the "closest" previously solved subproblem.
- In addition, we can optionally save the global cut pool from iteration to iteration.

Implementation

- A variety of algorithms have been implemented as extensions to the SYMPHONY callable library.
- The subproblems are solved using a modified version of branch and cut.
  - The user specifies a second objective.
  - When using the WCN, SYMPHONY performs the required reformulation.
  - SYMPHONY can use either the ACN or the combinatorial method for eliminating weakly dominated solutions.
- Solver features
  - Can produce approximations to the Pareto set.
  - Implements bisection search, WCN, ACN, and hybrid ACN.
  - Can warm start subproblems.
  - Can maintain a global cut pool between iterations.
- Available from COIN-OR (`www.coin-or.org`).

Implementation: Code Sample

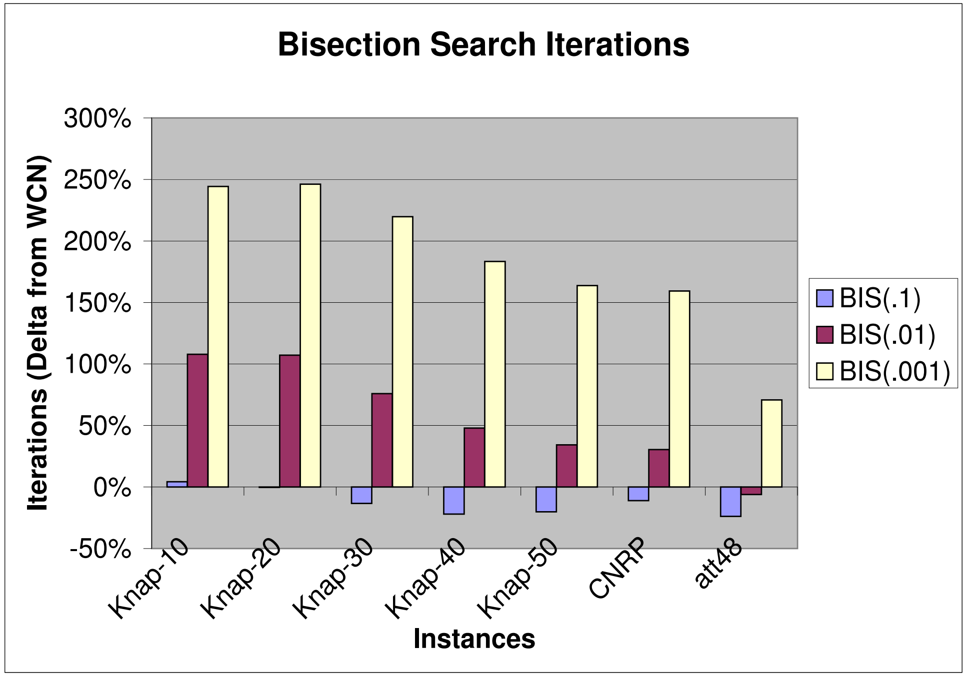
- Recall the example from earlier:

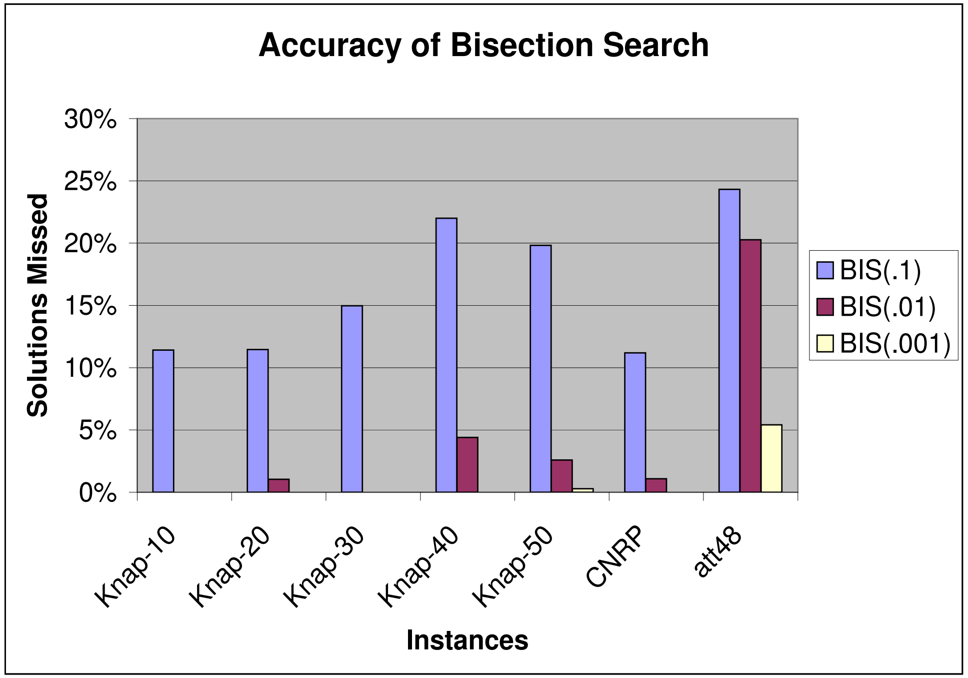
$$
\begin{aligned}
\text{vmax} \quad & [8x_1, x_2] \\
\text{s.t.} \quad & 7x_1 + x_2 \leq 56 \\
& 28x_1 + 9x_2 \leq 252 \\
& 3x_1 + 7x_2 \leq 105 \\
& x_1, x_2 \geq 0
\end{aligned}
$$

- The following code solves this model using SYMPHONY.

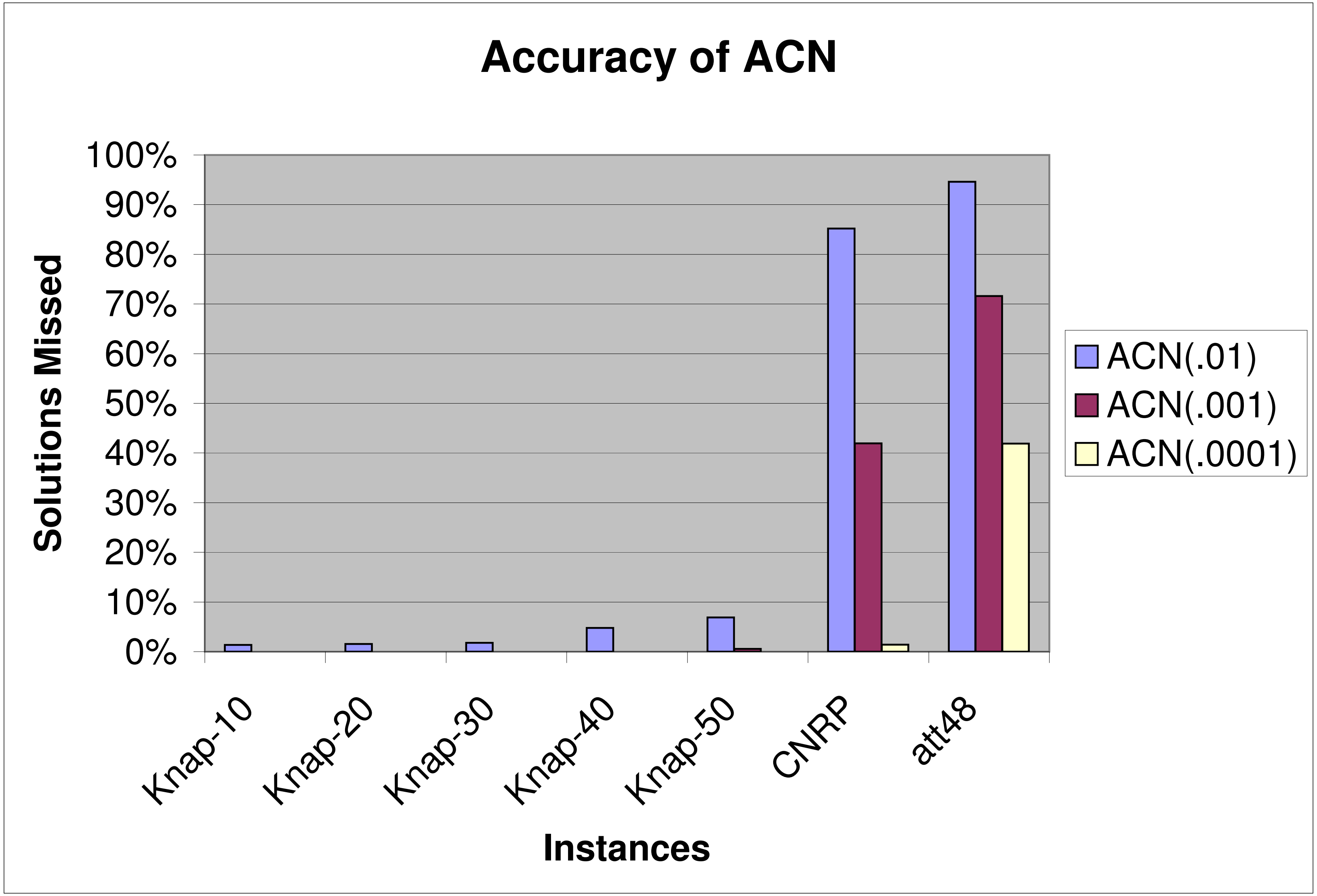
```
int main(int argc, char **argv)
{
   OsiSymSolverInterface si;
   si.parseCommandLine(argc, argv);
   si.setObj2Coeff(1, 1);
   si.loadProblem();
   si.multiCriteriaBranchAndBound();
}
```

Computational Results: WCN versus Bisection Search

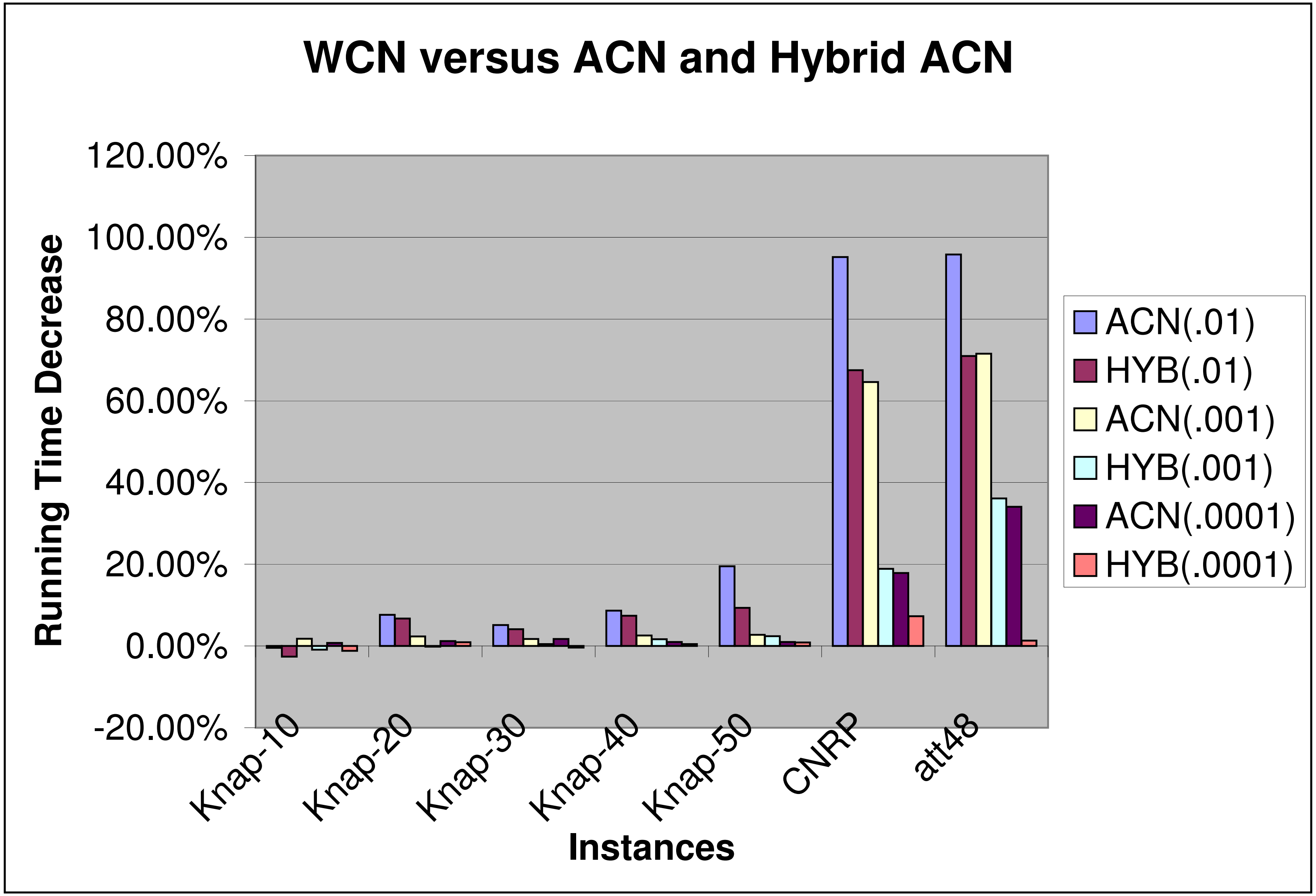




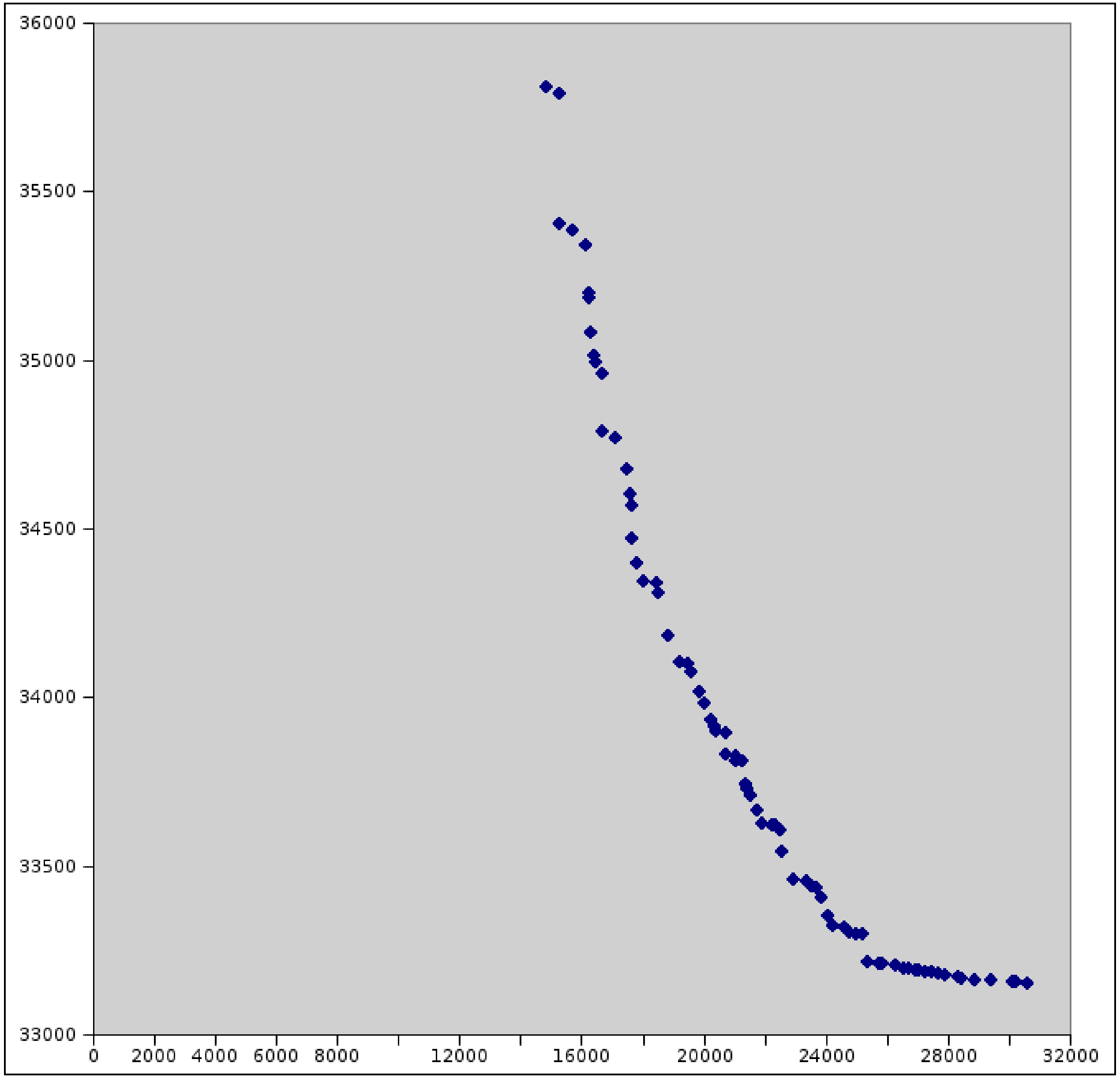
Computational Results: Accuracy of ACN



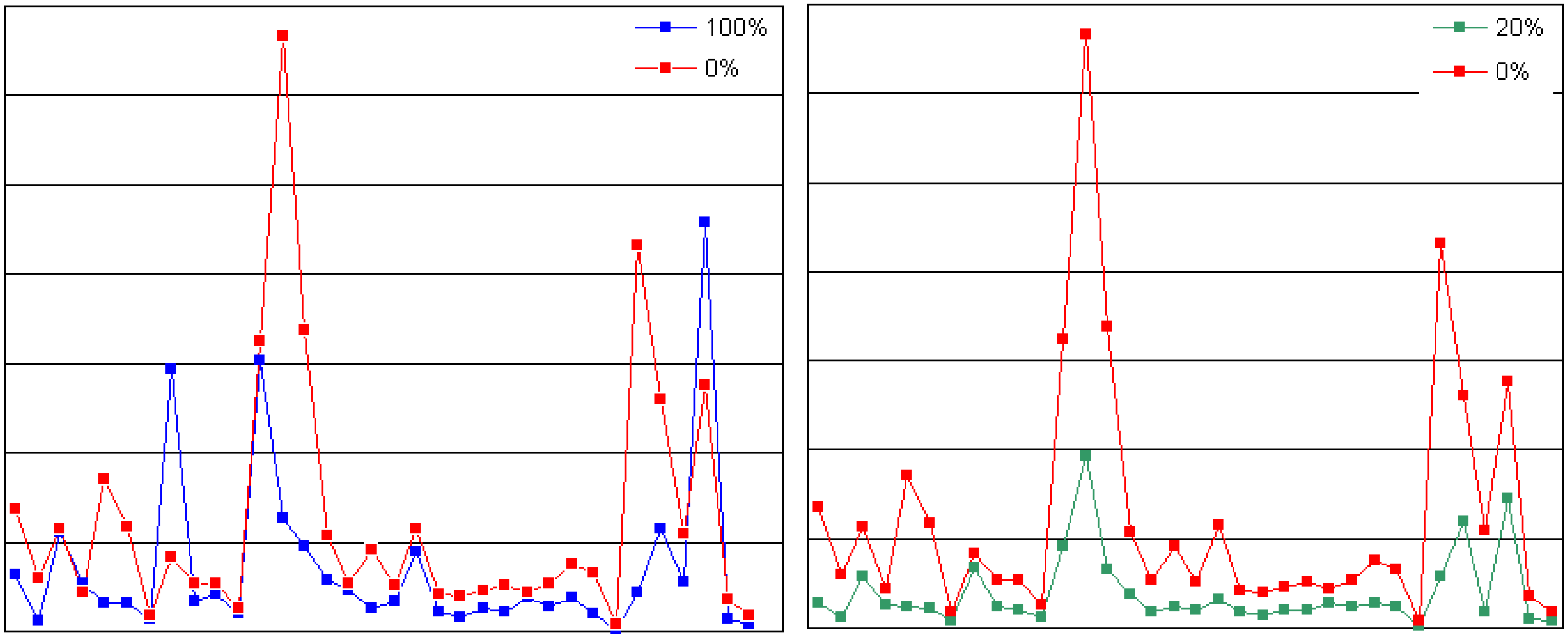
Computational Results: Running Time Comparison



Example: Pareto Outcomes for att48



Computational Results: Using Warm Starting to Solve CNRP Instances



These are results using SYMPHONY to solve CNRP instances with two different warm starting strategies.

Parallelizing the WCN Algorithm

- Enumerating the entire Pareto set can be extremely difficult for hard combinatorial problems.
- The WCN algorithm is, however, naturally parallelizable.
- A simple master-worker implementation
  - The master keeps a queue of subproblems to be solved.
  - When a worker becomes free, the master picks a subproblem off the queue and sends it to the worker.
  - The worker returns either
    * Message that the subproblem is infeasible (a new breakpoint).
    * Two new subproblems to be added to the queue.
  - Continue until the queue is empty.
- This algorithm is a perfect candidate for solving on the computational grid.
  - It is coarse-grained and asynchronous.
  - Subproblem descriptions consist of only a few parameters.
  - Only the list of breakpoints and solutions generated so far are needed to restart.

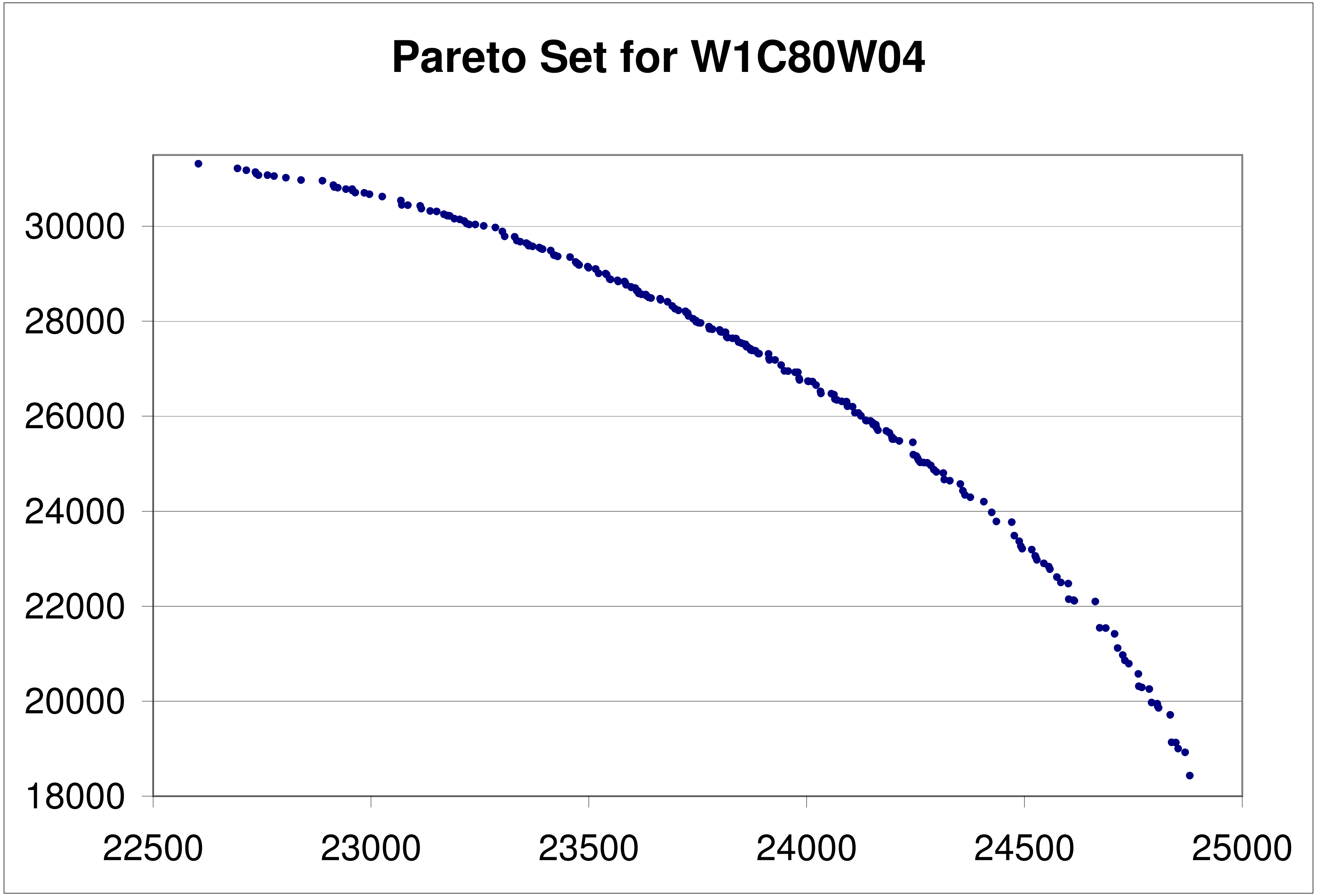
Implementing the Parallel WCN Algorithm

- The algorithm was parallelized using MWBlackBox, a tool for deploying simple master-worker algorithms on the computational grid.
- MWBlackBox is built on top of Condor, a unique full-featured task management system.
- Condor is used to remotely run a subproblem solver implemented using the SYMPHONY callable library.
- Required methods
  - `get_userinfo()`: Specify file locations
  - `setup_initial_tasks()`: Find utopia point
  - `act_on_completed_task()`: Generate new subproblems
  - `printresults()`: Print final results

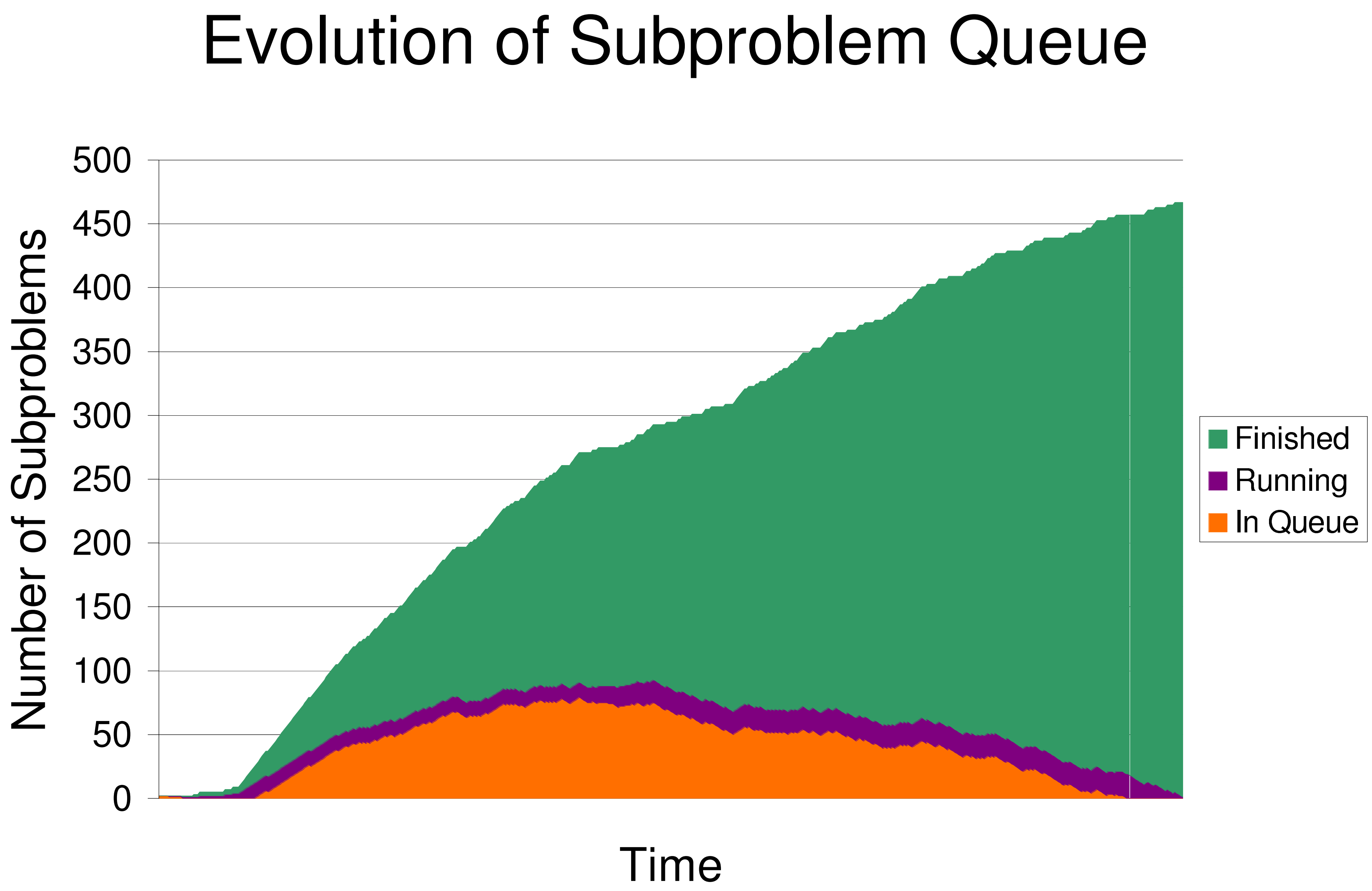
Scalability Issues

- The scalability issues are very similar to parallel branch and bound.
  - There is a queue of independent tasks to be done.
  - Each task may generate two child tasks, but there is no way of knowing a priori what the tree of tasks will look like.
  - The order of processing the tasks does not matter for correctness, but can greatly affect parallel performance.
- The main scalability factors
  - The number of outcomes and their distribution.
  - How fast the queue grows in the beginning and shrinks at the end.
  - If warm starting or a global cut pool is used, the processing order may also affect subproblem solution time.
- To test scalability of the basic algorithm, we solved 32 instances of the multicriteria knapsack problem with different numbers of available processors.

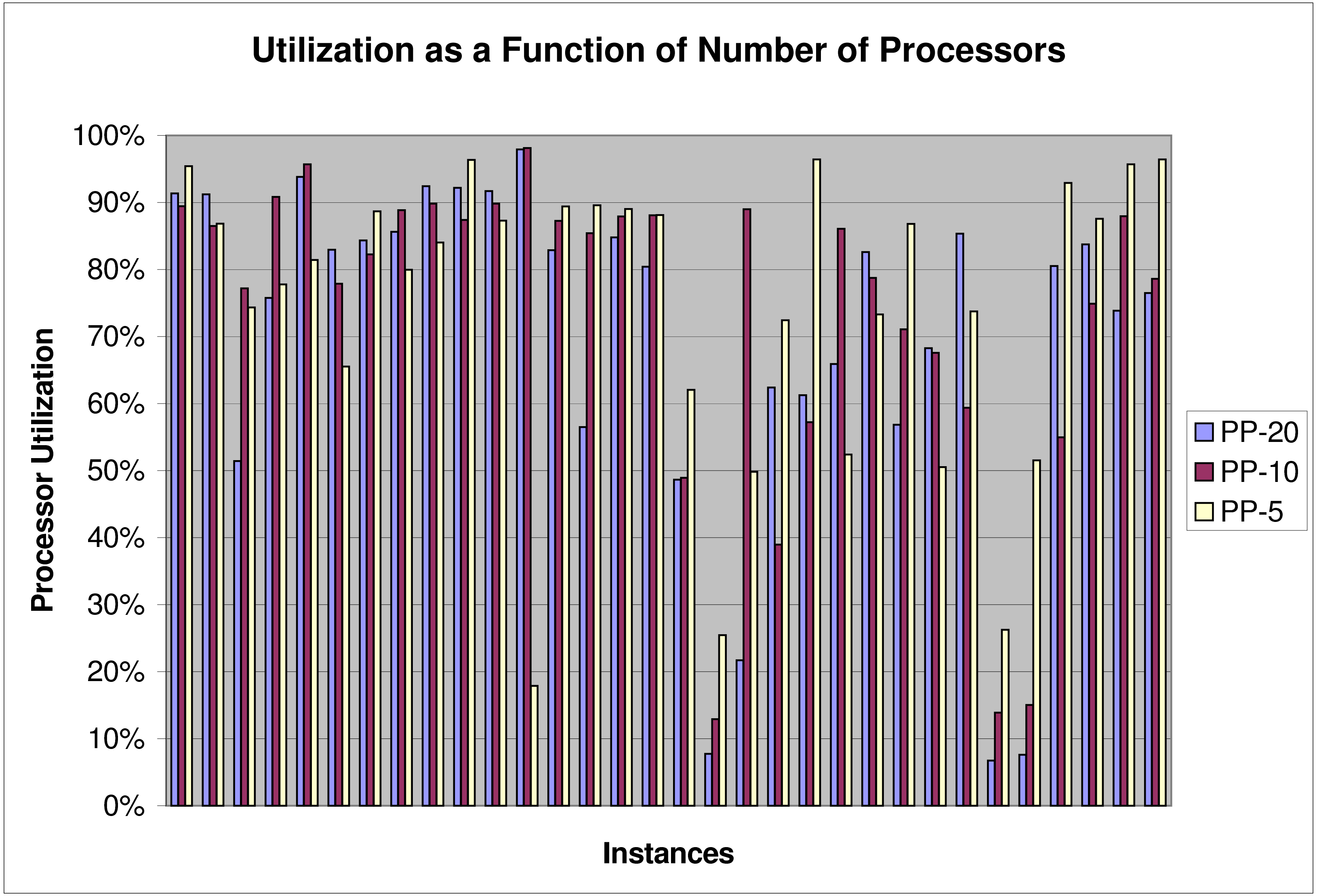
Example: Pareto Set for W1C80W04



Example: Queue Size for W1C80W04



Computational Results: Processor Utilization



Future Work: Improving Parallel Performance

- Limiting ramp-up and ramp-down time
  - Solution of subproblems can itself be parallelized when the queue is small.
  - Searching the widest intervals first may help populate the queue more quickly.
  - Subintervals could be allocated to processors a priori without solving any initial subproblems
- More asynchronicity can be introduced by allowing each worker to search an entire interval recursively.
- Maintaining warm starting information
  - For very large instances, warm starting can help a lot.
  - However, this means the subproblem descriptions will become much larger.
  - One option is to store the warm starts locally.
- Cuts can be shared through the use of a global cut pool.

Conclusion

- Generating the complete set of Pareto outcomes is a challenging computational problem.
- We presented a new algorithm for solving biobjective mixed-integer programs.
- The algorithm is
  - asymptotically optimal,
  - generates exact breakpoints,
  - has good numerical properties, and
  - can exploits modern solution techniques.
- We have shown how this algorithm is implemented in the SYMPHONY MILP solver framework.
- Future work
  - Improvements to warm starting procedures
  - Improvements to the parallelization scheme
  - More than two objective

More Information

- SYMPHONY
  - Prepackaged releases can be obtained from `www.BranchAndCut.org`.
  - Up-to-date source is available from `www.coin-or.org`.
  - Available Solvers
    - Generic MILP
    - Traveling Salesman Problem
    - Vehicle Routing Problem
    - Mixed Postman Problem
    - Biobjective Knapsack Solver
    - Set Partitioning Problem
    - Matching Problem
    - Network Routing
- For references and further details, see *An Improved Algorithm for Biobjective Integer Programming*, to appear in Annals of OR, available from

  `www.lehigh.edu/~tkr2`

- Overviews of multiobjective integer programming
  - Climaco (1997)
  - Ehrgott and Gandibleux (2002)
  - Ehrgott and Wiecek (2005)