Creating Tests for a Family of Cost Aware Resource Constraints

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Objective: Develop scheduling tools for energy cost aware scheduling
Figure: Electricity Demand and Price, ROI, Comparing January and June data
So far our work has considered the core algorithms to include resource costs into scheduling constraints:

- **An energy cost aware cumulative.** BPPC’10, Bologna, Italy, June 2010.
- **Constraint-based scheduling for reducing peak electricity use.** CompSust’10, Boston, MA, June 2010.
- **A resource cost aware cumulative.** ModRef 2010, St Andrews, Scotland, September 2010.
- **A Family of Resource Constraints for Energy Cost Aware Scheduling.** CROCS 2010, St Andrews, Scotland, September 2010
We considered an extension of the *Cumulative* constraint.

We extended that work for other resource types: *Disjunctive, Parallel-Disjunctive, Machine Choice*.

We have proposed different algorithms to compute *lower bounds* on the resource cost of a schedule, and compared their theoretical and practical power.

The best results use an adaptation of the *linear programming model* for the cumulative constraint from \(^1\). Lower bounds better than 98% of the optimal value can be achieved.

*Reduced cost based filtering* based on these bounds can remove a significant number of domain values.

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However

- To validate and improve our findings we require test cases on which we can systematically test the performance of our methods.
- None of the existing resource constraint benchmarks includes a cost element.
- We want to evaluate the quality of different constraint implementations.
Therefore
- We created our own instance generator
- Written in Java
- Produces an XML instance format
- Can be directly integrated into Java code
- Available on the website of the authors
**CumulativeCost**

**Definition**

**Constraint** CumulativeCost expresses the following relationships:

\[ \forall 0 \leq t < p : \quad pr_t := \sum_{i|s_i \leq t < s_i + d_i} r_i \leq l \]  
(1)

\[ \forall 1 \leq i \leq n : \quad 0 \leq s_i \leq s_i < s_i + d_i \leq s_i + d_i \leq p \]  
(2)

\[ \text{ov}(t, pr_t, A_j) := \begin{cases} \max(0, \min(y_j + h_j, pr_t) - y_j) & x_j \leq t < x_j + w_j \\ 0 & \text{otherwise} \end{cases} \]  
(3)

\[ \forall 1 \leq j \leq q : \quad a_j = \sum_{0 \leq t < p} \text{ov}(t, pr_t, A_j) \]  
(4)

\[ \text{cost} = \sum_{j=1}^{q} a_j c_j \]  
(5)
An Example

Problem and Optimal Solution

<table>
<thead>
<tr>
<th>j</th>
<th>c_j</th>
<th>a_j</th>
<th>cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>4</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>

LP Solution

1 1 1 1 1
2 3 5 4 1
3 1 1 1 3
LB Lower Bound

\[ \text{lb} = \min \sum_{j=1}^{q} a_j c_j \]  \hspace{1cm} (6)

\[ \forall 0 \leq t < p : \quad pr_t \in [0, l] \]  \hspace{1cm} (7)

\[ \forall 1 \leq i \leq n, 0 \leq t < p : \quad y_{it} \in \{0, 1\} \]  \hspace{1cm} (8)

\[ \forall 1 \leq j \leq q, \forall x_j \leq t < x_j + w_j : \quad z_{jt} \in [0, h_j] \]  \hspace{1cm} (9)

\[ \forall 1 \leq j \leq q : \quad 0 \leq a_j \leq \overline{a}_j \leq w_j h_j \]  \hspace{1cm} (10)

\[ \forall 1 \leq i \leq n : \quad s_i = \sum_{t=0}^{p-1} ty_{it} \]  \hspace{1cm} (11)

\[ \forall 1 \leq i \leq n : \quad \sum_{t=0}^{p-1} y_{it} = 1 \]  \hspace{1cm} (12)

\[ \forall 0 \leq t < p : \quad pr_t = \sum_{1 \leq i \leq n} \sum_{t' \leq t < t' + d_i} y_{it'} r_i \]  \hspace{1cm} (13)

\[ \forall 0 \leq t < p : \quad pr_t = \sum_{j=1}^{q} z_{jt} \]  \hspace{1cm} (14)

\[ \forall 1 \leq j \leq q : \quad a_j = \sum_{t=x_j}^{x_j+w_j-1} z_{jt} \]  \hspace{1cm} (15)
The DisjunctiveCost constraint allows one task to be run on a machine at any time. We can describe the constraint by adding

$$\forall i, j | i \neq j : \quad s_i + d_i \leq s_j \lor s_j + d_j \leq s_i$$ (16)

to constraints (1) -(5).

In the LP/MIP model, we extend constraints (6) - (15) with the condition

$$\forall 0 \leq t < p : \quad \sum_{1 \leq i \leq n} \sum_{t' \leq t < t' + d_i} y_{it'} \leq 1$$ (17)
The **ParallelMachineCost** constraint consists of constraints (1) -(5) plus the constraints

\[ \forall 1 \leq k \leq b, \forall i, j | i \neq j : \quad m_i \neq m_j \vee s_i + d_i \leq s_j \vee s_j + d_j \leq s_i \]  

(18)

We can express this condition in the LP/MIP model by adding constraints of the form

\[ \forall 1 \leq k \leq d, \forall 0 \leq t < p : \quad \sum_{\{i|m_i=k\}} \sum_{t' \leq t < t' + d_i} y_{it'} \leq 1 \]  

(19)

to constraints (6) - (15).
Constraint **MachineChoiceCost** expresses the following relationships:

∀ 0 ≤ t < p : \( pr_t := \sum_{\{i|s_i\leq t < s_i+d_{im_i}\}} r_{im_i} \leq l \) (20)

∀ 1 ≤ i ≤ n : 0 ≤ \( s_i \) < \( s_i + d_{im_i} \) ≤ \( \overline{s_i} + d_{im_i} \) ≤ p (21)

\( ov(t, pr_t, A_j) := \begin{cases} \max(0, \min(y_j + h_j, pr_t) - y_j) & x_j \leq t < x_j + w_j \\ 0 & \text{otherwise} \end{cases} \) (22)

∀ 1 ≤ j ≤ q : \( a_j = \sum_{0 \leq t < p} ov(t, pr_t, A_j) \) (23)

\( \text{cost} = \sum_{j=1}^{q} a_j c_j \) (24)
The instance generator is available in the form of a Java jar file `CostInstance.jar` which can be downloaded from

http://4c.ucc.ie/~thadzic/CostInstance.jar

To create an instance, execute:

```
java -cp CostInstance.jar Instance <parameters>
```

where `<parameters>` are:
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>-instanceType</td>
<td>0 - CumulativeCost, 1 - DisjunctiveCost, 2 - ParallelMachineCost</td>
</tr>
<tr>
<td>-n</td>
<td>number of required tasks</td>
</tr>
<tr>
<td>-m</td>
<td>number of required areas</td>
</tr>
<tr>
<td>-d_max</td>
<td>maximum duration of a task</td>
</tr>
<tr>
<td>-r_max</td>
<td>maximum resource consumption of a task</td>
</tr>
<tr>
<td>-s_diff_portion</td>
<td>portion of the horizon restricting the start time domain</td>
</tr>
<tr>
<td>-util</td>
<td>utilization of the total available area</td>
</tr>
<tr>
<td>-cost_distr</td>
<td>cost distribution, 0 - explicitly given, 1 - random</td>
</tr>
<tr>
<td>-w</td>
<td>width of each area</td>
</tr>
<tr>
<td>-machineNo</td>
<td>number of machines for parallel machine instances</td>
</tr>
<tr>
<td>-randomSeed</td>
<td>initial random seed</td>
</tr>
<tr>
<td>-maxCost</td>
<td>maximal random cost of an area</td>
</tr>
<tr>
<td>-costFileName</td>
<td>a valid file name containing a vector of costs (or input &quot;no-file&quot;)</td>
</tr>
</tbody>
</table>
Let $p$ denote the horizon and $s_{max}$ denote $p \cdot s_{\text{diff\_portion}}$. Then the instance generator enforces:

$$0 \leq s_{\overline{i}} \leq s_i \leq s_{\overline{i}} \leq s_i + s_{max}$$

If $s_{\text{diff\_portion}}$ is set to a negative value then each task $i$ has a maximal feasible start-time interval $[0, p - d_i]$. 
Parameter: $\text{util}$

An integer value between 0 and 100 designating the percentage of the required $\textit{utilization}$. For $\text{CumulativeCost}$ and $\text{ParallelMachineCost}$ the instance generator enforces:

$$l = \frac{\sum_{i=1}^{n} d_i \cdot r_i}{\text{util} \cdot p}$$  \hspace{1cm} (25)

where $l$ is a maximal resource level. For $\text{DisjunctiveCost}$ the generator enforces:

$$p = \frac{\sum_{i=1}^{n} d_i}{\text{util}}.$$  \hspace{1cm} (26)

Note that due to rounding to integer values, exact utilization levels might not be achieved.
Parameter: cost_distr

- For *random cost distribution* (cost_distr=1), we select a cost for each area from interval \([0, \text{maxCost} - 1]\).
- For *explicitly given costs* (cost_distr=0), we cyclically repeat vector of costs given in the file costFileName. For example, for a vector of costs 10, 20, 30 and \(m = 5\) areas, we generate costs 10, 20, 30, 10, 20.
- For *explicitly given costs* (cost_distr=0) and no external file (costFileName = "no-file") we use default, hardcoded vector of electricity costs which consists of 48 values, covering 24 hour period for a particular day on the Irish electricity market.
<?xml version="1.0" encoding="UTF-8" standalone="yes"?>
<instance resource-limit="6" horizon="21"
xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
xsi:noNamespaceSchemaLocation="resourcecost.xsd"/>
<tasks number="5">
  <task id="0" start_min="4" start_max="4" duration="3" resource="2"/>
  <task id="1" start_min="1" start_max="5" duration="4" resource="5"/>
  <task id="2" start_min="8" start_max="8" duration="6" resource="5"/>
  <task id="3" start_min="0" start_max="10" duration="3" resource="2"/>
  <task id="4" start_min="3" start_max="9" duration="3" resource="3"/>
</tasks>
<areas number="7">
  <area id="0" x="0" y="0" width="3" height="6" cost="14"/>
  <area id="1" x="3" y="0" width="3" height="6" cost="11"/>
  <area id="2" x="6" y="0" width="3" height="6" cost="7"/>
  <area id="3" x="9" y="0" width="3" height="6" cost="7"/>
  <area id="4" x="12" y="0" width="3" height="6" cost="0"/>
  <area id="5" x="15" y="0" width="3" height="6" cost="7"/>
  <area id="6" x="18" y="0" width="3" height="6" cost="7"/>
</areas>
<machines number="2">
  <machine id="0" tasks="2 4 3"/>
  <machine id="1" tasks="0 1"/>
</machines>
Figure: The XML schema, describing the output format of the output XML file.
Existing Benchmarks for Resource Constraints

To the best of our knowledge, this is the first generator of scheduling instances involving cost-aware resources

A number of scheduling instances were collected previously:

- Patterson: A Comparison of Exact Approaches for Solving the Multiple Constrained Resource, Project Scheduling Problem, 1984
- Alvarez et al: Heuristic algorithms for resource-constrained project scheduling: A review and an empirical analysis, 1989
- Taillard: Benchmarks for basic scheduling problems, 1993
- Kolisch et al: Characterization and generation of a general class of resource-constrained project scheduling problems, 1995
- Baptiste and Le Pape: Constraint propagation and decomposition techniques for highly disjunctive and highly cumulative project scheduling problems, 2000
The most comprehensive instance generator is presented in the body of work by Kolisch et al.

- Authors introduce instance generator ProGen for the general class of project scheduling instances.
- The generator produces multi-modal instances over multiple resources.
- Tightness of precedence relationships is controlled by generating the activity-on-node network.
- Scarcity level of resource is controlled through a resource strength, \( RS \in [0, 1] \).

In comparison, we could classify our generator as producing cost-aware, single-modal instances over a single resource, without precedence relationships. Instead, our generator uses restricted start times (\( s\_diff\_portion \)) and utilization parameter (\( \text{util} \)) to control the tightness and the scarcity level.
We are integrating our code into the *JSR-331: Constraint Programming API*. We extended a standard standard *Resource* class with *ResourceWithCost* class that supports a cost-declaring method:

```java
Var setCost(int x1, int x2, int y1, int y2, int cost)
```
Our Working Example in JSR-331

Problem and Optimal Solution

\[ j \leftarrow \begin{array}{c} 2 \\ 1 \\ 3 \end{array} \quad c_j \leftarrow \begin{array}{c} 3 \\ 2 \\ 2 \end{array} \quad a_j \leftarrow \begin{array}{c} 5 \\ 4 \\ 0 \end{array} \quad \text{cost} = 15 \]
setStart(0);
setEnd(5);

Activity T1 = activity("Task1", 1);
Activity T2 = activity("Task2", 2);
Activity T3 = activity("Task3", 1);
post(T1, ">=", 2);
post(T2, ">=", 1);

ResourceWithCost myResource = new ResourceWithCost(this, 3);
T1.requires(myResource, 2);
T2.requires(myResource, 2);
T3.requires(myResource, 3);

int [] x1 = {0,1,2,3,4};
int [] x2 = {1,2,3,4,5};
int [] y1 = {0,0,0,0,0};
int [] y2 = {3,3,3,3,3};
int [] cost = {1,2,4,3,0};
utilVars = new Var[5];
for (int i = 0; i < utilVars.length; i++) {
    utilVars[i] = myResource.setCost(x1[i], x2[i], y1[i], y2[i], cost[i]);
}
Var totalCost = scalProd(cost, utilVars);
Instance instance;

public void createInstance() {
    int instanceType = 0;
    int n = 50;
    int m = 10;
    int d_max = 7;
    int r_max = 5;
    double s_diff_portion = 0.5;
    int util = 50;
    int cost_distr = 1;
    int units_per_area = 1;
    int machineNo = 1;
    long randomSeed = 123456;
    int max_cost = 10;
    String costFileName = new String("no−file ");

    instance = new Instance(instanceType, n, m, d_max, r_max,
            s_diff_portion, util, cost_distr,
            units_per_area, machineNo, randomSeed,
            max_cost, costFileName);
}

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```java
setStart(0);
setEnd(instance.p);

ArrayList<Activity> Tasks = new ArrayList<Activity>();
for (int i = 0; i < instance.task.length; i++) {
    Activity Ti = activity("Task_" + i, instance.task[i].d);
    post(Ti, ">=", instance.task[i].s_min);
    post(Ti, "<=", instance.task[i].s_max);
    Tasks.add(Ti);
}

ResourceWithCost myResource = new ResourceWithCost(this, instance.l);

for (int i = 0; i < instance.task.length; i++) {
    Tasks.get(i).requires(myResource, instance.task[i].r);
}
```
utilVars = new Var[instance.area.length];
int[] areaUnitCosts = new int[instance.area.length];
for (int i = 0; i < utilVars.length; i++) {
    int x1 = instance.area[i].x;
    int x2 = instance.area[i].x + instance.area[i].w;
    int y1 = instance.area[i].y;
    int y2 = instance.area[i].y + instance.area[i].h;
    int cost = instance.area[i].c;
    areaUnitCosts[i] = cost;
    utilVars[i] = myResource.setCost(x1, x2, y1, y2, cost);
}

Var totalCost = scalProd(areaUnitCosts, utilVars);
Conclusions

- We created an instance generator for cost-aware scheduling problems
- Generator produces instances in XML format
- It can be integrated directly into Java code
- Publicly available at http://4c.ucc.ie/∼thadzic/CostInstance.jar
- Currently being integrated into the JSR-331 Constraint Programming API