Application of constraint satisfaction algorithms for conditioning and packaging 160 control rod assemblies

Dr. Philip J. Harding,
Brenk Systemplanung GmbH
Packaging plan:

- What **types** of casks or containers are required?
- How **many** of each type?
- What is the best **allocation** of waste to a cask or container?
- How can a viable **sequence** of packaging be identified?

In practice, the following aspects must be considered (3-S):

<table>
<thead>
<tr>
<th>Size</th>
<th>Waste and container/cask specifications (activity(limits), mass(limits), …)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space</td>
<td>Max. no. of free cask/container positions and max. no. of permitted simultaneously open casks/containers</td>
</tr>
<tr>
<td>Sequence</td>
<td>Conditioning process</td>
</tr>
<tr>
<td></td>
<td>No. of changes (swaps) of casks/containers in conditioning facility</td>
</tr>
</tbody>
</table>
Control Rod Assemblies

- A packaging plan for ca. 160 control rod assemblies of a boiling water reactor was to be prepared (mass: ca. 16 Mg)
- In advance: Measurement of dose rate on 9 segments of each assembly (=dose rate segment), calculation of activity
- Specification: Three types of casks:
  - 200-l drum:
  - MOSAIK® II-15, thin cladding of Pb
  - MOSAIK® II-15, thick cladding Pb
- The three cask types have different specifications with respect to payload, activity and/or specific activity
- For this calculation, two options were specified with exact no. of casks (per type) each
**Previous vs. New Approach**

- High bandwidth of specific activity
  - → trivial packaging plan impossible
- Usual „back of the envelope“ approach:
  - Two (specific) activity parameters → three (specific) activity regions
  - Allocation of segments to one of the three types of bin according to its region
  - Sequential loading in general possible

---

Dr. Philip J. Harding, Brenk Systemplanung GmbH

8 Feb. 2017
Conditioning sequence

1. Start
   - Pos. 1
   - Pos. II

2. Cask swap
   - Pos. 1
   - Pos. II
   - Pos. 2

3. Cask swap
   - Pos. 1
   - Pos. II

4. Cask swap
   - Pos. 1
   - Pos. II

5. Cask swap
   - Pos. II
   - Pos. II

8 Feb. 2017
Dr. Philip J. Harding, Brenk Systemplanung GmbH
Correlations

- The higher the desired utilisation, the more cask swaps are in general necessary.

- Sequence influences max. no. of simultaneously open casks.

Many, few: Long duration of on buffer positions, poor utilisation
The classical bin packing problem

- The problem at hand is a well known problem in the area of combinatorial optimisation, the **bin packing problem**.
  - How can $n$ weights $m_1, m_2, \ldots, m_n \leq b$ be allocated to $k$ bins of capacity $b$ so that the number of bins is minimised?

  $$\exists f: \{1, \ldots, n\} \rightarrow \{1, \ldots, k\}, \text{such that } \forall j := 1, \ldots, k \sum_{f(i) = j} m_i \leq b$$

- The bin packaging problem is one of the NP-hard problems, just as e.g. the travelling salesman problem

- No analytical solution known, but a number of well known approaches
Planning goals

- Minimisation of the costs of the casks used, highest possible utilisation

- A few swaps as possible to minimise execution time (and therefore personnel costs, dose)
Boundary conditions of planning goals

„Strong“ conditions

Violation leads to termination

- Compliance with limits depending on cask type (mass, (specific) activity)
- Compliance with given max. no. of simultaneously open casks (related to no. of buffer positions)

„Weak“ Conditions

Violation possible, but the less the better

- Costs for used casks are to be as low as possible
  - The fewer the better, the cheaper the better
- Reduction of no. of swaps as far as possible
- Variance of activity of surcharged casks

8 Feb. 2017
Dr. Philip J. Harding, Brenk Systemplanung GmbH
Extension of the classical bin packing problem

- **Adapt** the classical bin packing problem:
  - Instead of one limit (‘weight‘), need **two+** limits
  - Add items **sequentially** to bins to mimick process

- **Adapt** score function of classical problem:
  - For every realisation, calculate **number of simultaneously open bins** and include in score
  - For every realisation, **calculate number of swaps** and include in score (need conditioning process)
  - *For every realisation*, **variance of activity of surcharged casks is calculated and included in score**
  - …

For every realisation (**sequence** and **allocation**), the real cost of the campaign must be evaluated
# Structure of costs

<table>
<thead>
<tr>
<th>Weak costs (WC)</th>
<th>Strong costs (SC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass surcharge: ( \sim k^* (m-m_0)^2 ) for ( m &gt; m_0 )</td>
<td></td>
</tr>
<tr>
<td>Activity surcharge: ( \sim k^* (a-a_0)^2 ) für ( a &gt; a_0 )</td>
<td></td>
</tr>
<tr>
<td>Exceeding the permitted no. of simultaneously open casks: 10,000 c.u. per cask</td>
<td></td>
</tr>
<tr>
<td>Swap: 2 c.u.</td>
<td></td>
</tr>
</tbody>
</table>

\[(Variance\ of\ activity\ of\ surcharged\ casks: k \cdot \sigma^2)\]

\[c.u.:\ cost\ unit\ (virtual\ currency)\]
Development of strong and weak costs

Dynamic behaviour of strong costs during calculation

- Strong costs [c.u.]
  - Monotonously decreasing!
  - Valid SC = 0
  - Valid solution

Dynamic behaviour of weak costs during calculation

- Weak costs [c.u.]
  - WC are not m.d.
  - SC decrease at the expense of WC!
<table>
<thead>
<tr>
<th>Name of segment</th>
<th>Cask name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Segment 1</td>
<td>Cask 1</td>
</tr>
<tr>
<td>Segment 2</td>
<td>Cask 2</td>
</tr>
<tr>
<td>Segment 3</td>
<td>Cask 3</td>
</tr>
<tr>
<td>Segment 4</td>
<td>Cask 4</td>
</tr>
</tbody>
</table>

Graphic representation
Histogramm of activity (per bin type)

Reference packing plan

Mathematically optimised packing plan

: segments of higher activity are being placed in „lower“ type casks -> higher utilisation!
Results

<table>
<thead>
<tr>
<th>Description of option</th>
<th>Utilisation of activity</th>
<th>Utilisation of activity</th>
<th>Utilisation of mass (all bin types)</th>
<th>Relative std. dev. of activity of surcharged</th>
<th>Violation of strong boundary conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Option 1</td>
<td>Few, many</td>
<td>99 %</td>
<td>73 %</td>
<td>95 %</td>
<td>0.02 %</td>
</tr>
<tr>
<td></td>
<td>Some surcharged</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Option 2</td>
<td>Many, few</td>
<td>99 %</td>
<td>83 %</td>
<td>97 %</td>
<td>N/A</td>
</tr>
</tbody>
</table>

**Significant reduction** of no. of swaps:

- The reference packaging plan yielded 100 assemblies whose segments were allocated to 3 bin types: 2 swaps per assembly
- Optimised planning yields **10 fewer** of these assemblies: No swap necessary for them! -&gt; save ~20 swaps!
Sneak preview: Optimising the storage in a, say, storage facility of national interest

- Storage of delivered waste packages in Waste Package Type Groups (WPTG): Up to two types of waste package of different number but defined waste package type sequence, e.g.:
  - 6 Konrad-Container (KC) type I followed by 3 KC II
  - 13 cast iron cylindrical waste casks (GB) type III followed by 20 GB I
  - (2 - 3 dozen other possible WPTG)
- 11 types of waste packages altogether
- Can only store in one of two open WPTG at any one time
- Several boundary conditions on coarsely and finely grained maintenance intervals sometimes force the storage in one particular (open) WPTG
Sneak preview: Optimising the storage in a, say, storage facility of national interest

- Delivery of waste package type sequence cannot be guaranteed,
  - but: Sequence can be changed in facility -> incur dose and cost!
- For reasons of averaging, some of these waste packages must be placed in *one specific* WPTG

How organise the sequences of WPTG and required waste package sequence changes to ensure cost-minimal storage for any given delivery realisation?

-> Development of a lightweight software package capable of identifying a cost-minimal storage realisation of >1000 waste packages for any given delivery realisation in the order of minutes (Completion: 23.12.2016)
Conclusion

- First demonstration of an automated calculation of a packaging plan for a real campaign, acceptance by client
- Generation of packaging plans of 160 activated control rod assemblies with many complex boundary conditions, optimised **sequence** and **allocation**
- **Proven reduction** of total costs of campaign
- Change of cask and waste specification possible at any time, rapid generation of new plan (~minutes)
- Well suited for other packaging problems (e.g. storage logistics), extension of no. of limits