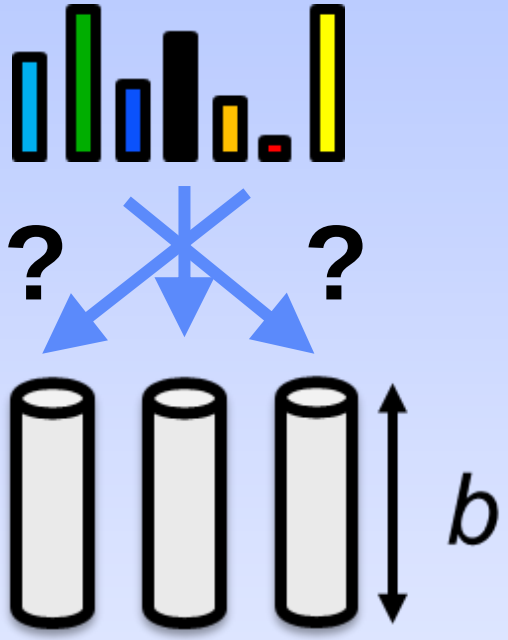
Application of constraint satisfaction algorithms for conditioning and packaging 160 control rod assemblies

Dr. Philip J. Harding,
Brenk Systemplanung GmbH

Packaging plan

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?

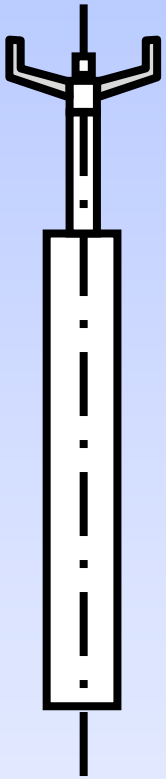


In practise, following aspects must be considered (**3-S**):

Size	Waste and container/cask specifications (activity(limits), mass(limits), …)
Space	Max. no. of free cask/container positions and max. no. of permitted simultaneously open casks/containers
Sequence	Conditioning process
	No. of changes (swaps) of casks/containers in conditioning facility

Control Rod Assemblies

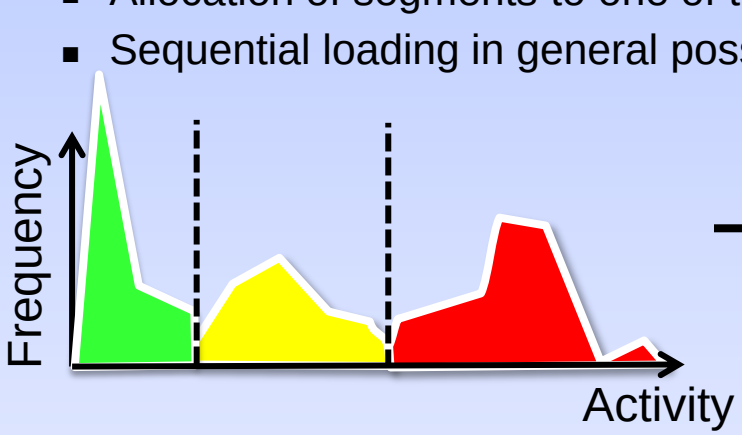
- A packaging plan for ca. 160 control rod assemblies of a boiling water reactor was to be prepared (mass: ca. 16 Mg)
- In advance: Measurement of dose rate on 9 segments of each assembly (=**dose rate segment**), calculation of activity
- Specification:Three types of casks:
  - 200-l drum:
  - MOSAIK® 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

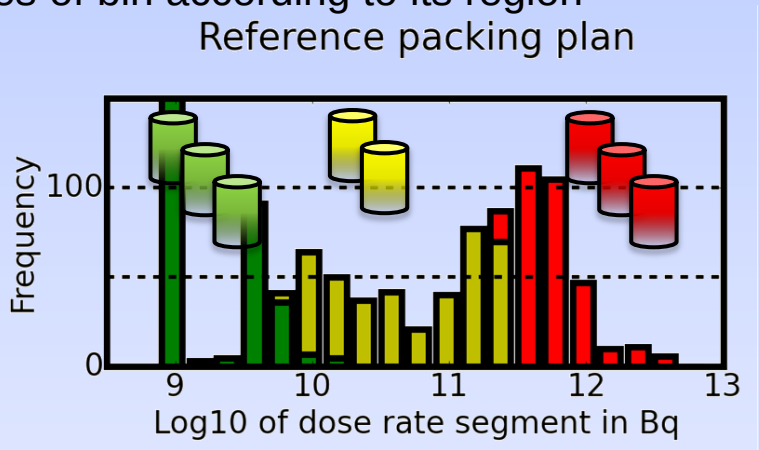


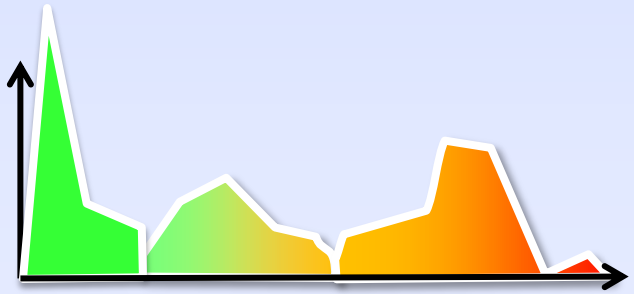
Sequence	Waste	Cask
1		1
2		1
3		1
4		1
5		2
6		2
7		1
8	…	1
9	…	3
…	…	…

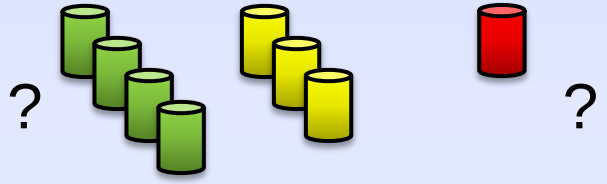
Previous vs. New Approach

- 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

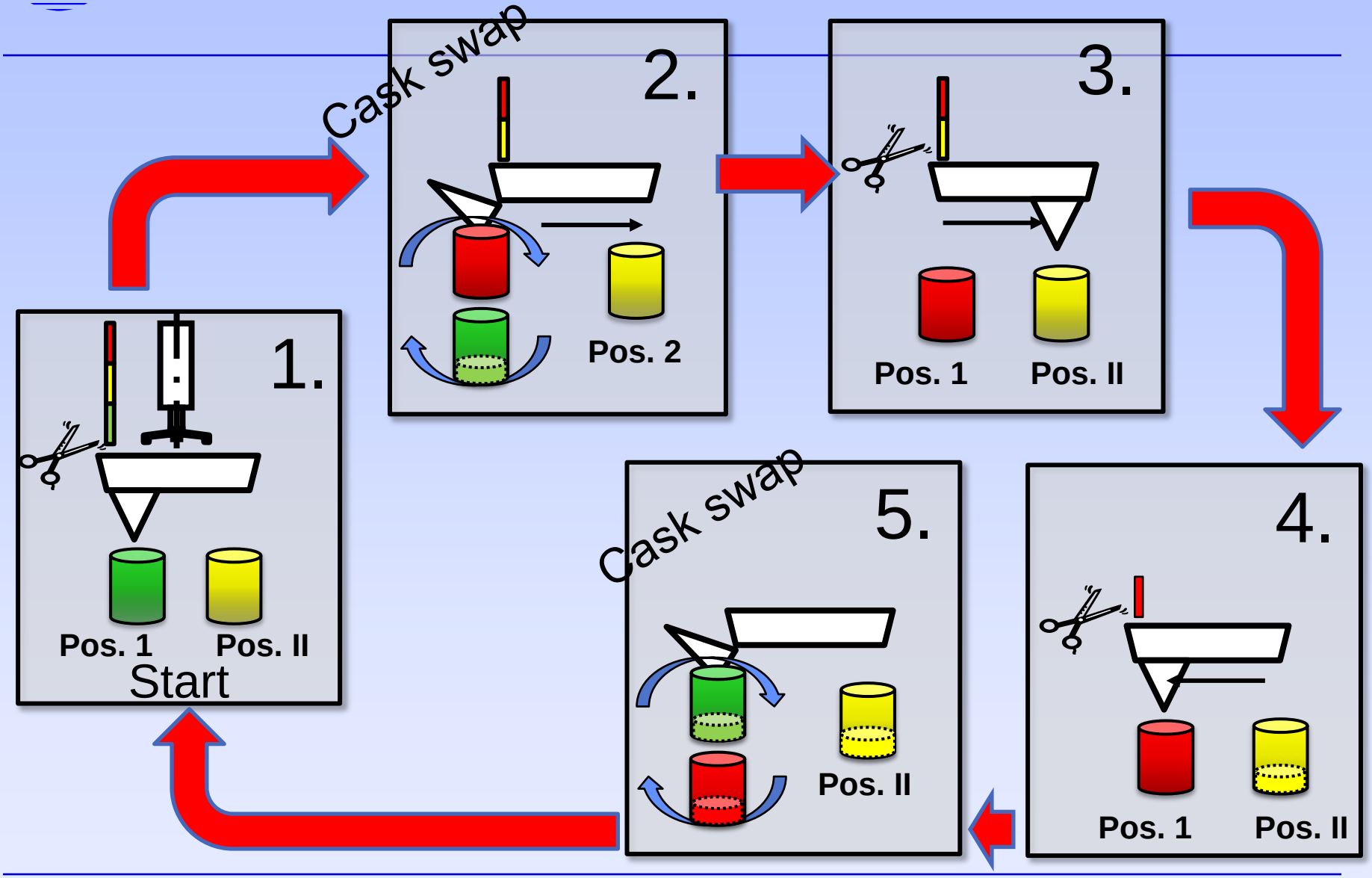








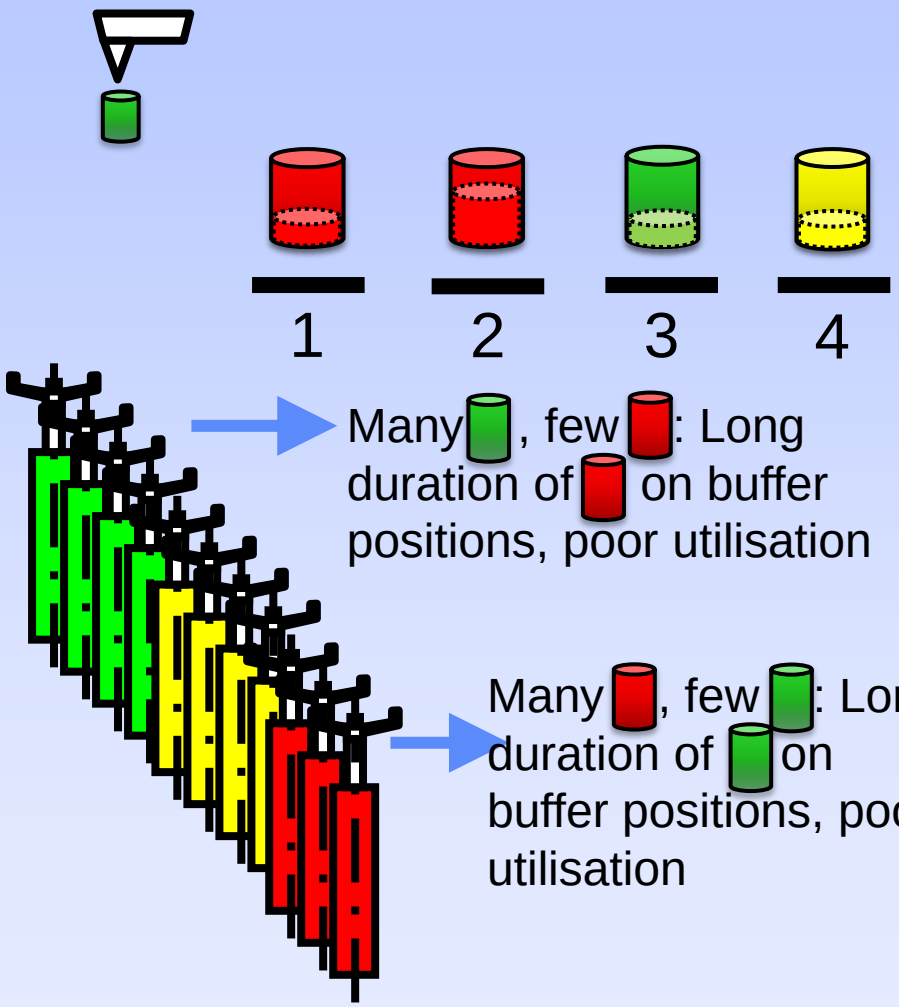
Conditioning sequence



Correlations

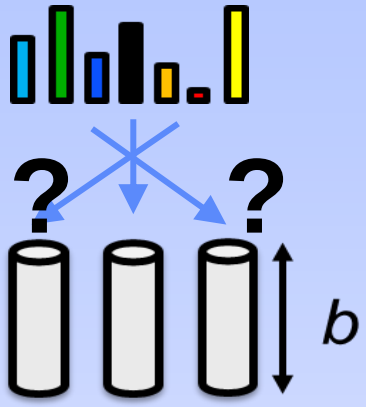
- The higher the desired utilisation, the more cask swaps are in general necessary

- Sequence influences max. no. of simultaneously open casks



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, , …, $m_n \leq b$ be allocated to *k* bins of capacity *b* so that the number of bins is minimised?

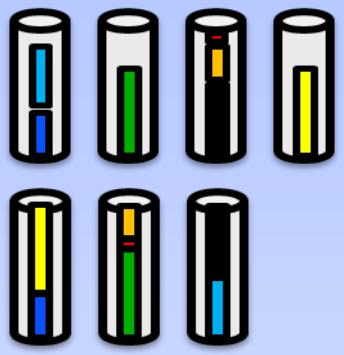


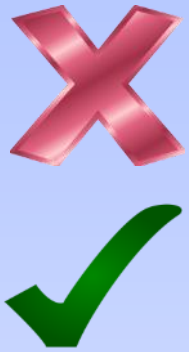
$$\exists\, f : \{1, \ldots, n\} \rightarrow \{1, \ldots, k\}, \text{such that } \forall\, j \coloneqq 1, .., k \ \sum_{f(i)=j} m_i \leq b$$

- 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

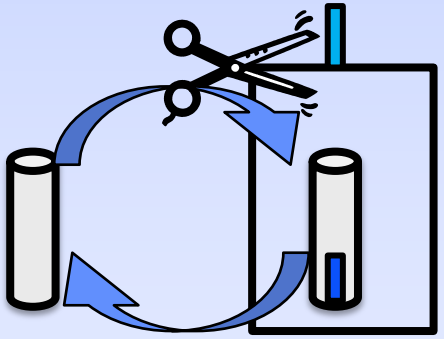
Planning goals

- 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) — classical
- Compliance with given max. no. of simultaneously open casks (related to no. of buffer positions) — Non-classical

„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 — classical
- Reduction of no. of swaps as far as possible
- *Variance of activity of surcharged casks* — Non-classical

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*
  - *…*

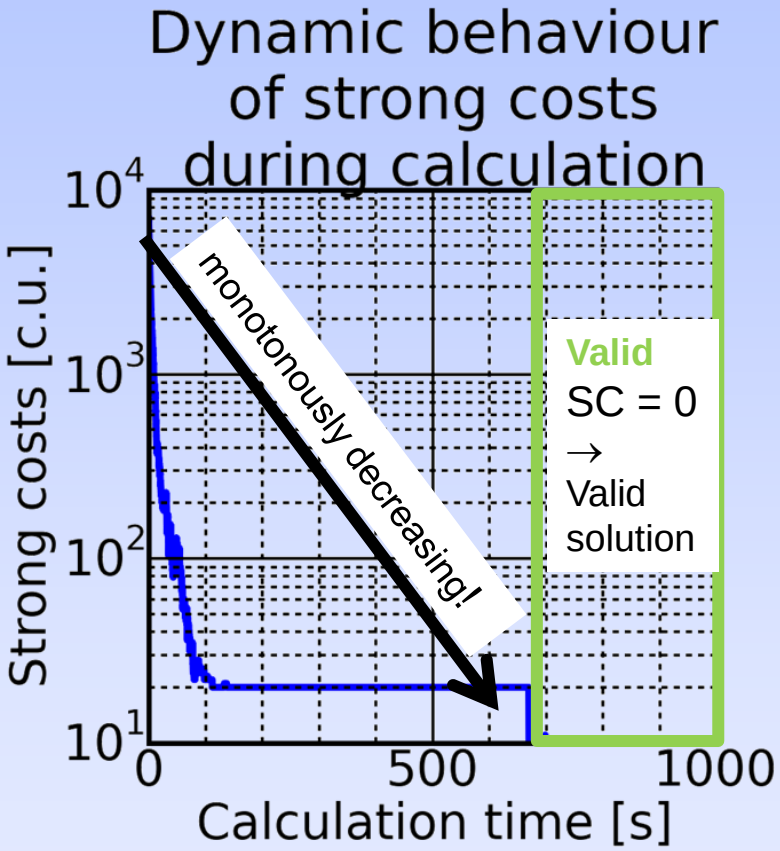
For every realisation (**sequence** and **allocation**), the real cost of the campaign must be evaluated

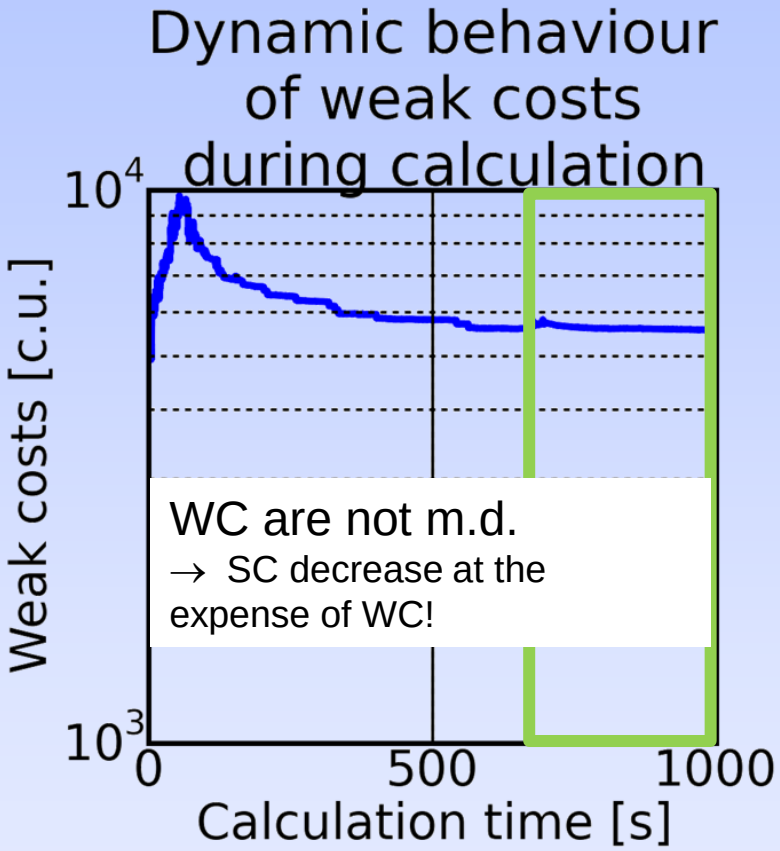
Structure of costs

Weak costs (WC) 	Strong costs (SC) 
 : 100 c.u.	Mass surcharge: ~k*(m-m_0)^2 for m>m_0
 : 80 c.u.	Activity surcharge: ~k*(a-a_0)^2 für a>a_0
 : 5 c.u.	Exceeding the permitted no. of simultaneously open casks: 10.000 c.u. per cask
Swap: 2 c.u.	
(Variance of activity of surcharged casks: $k \cdot \sigma^2$)	

c.u.: cost unit (virtual currency)

Development of strong and weak costs

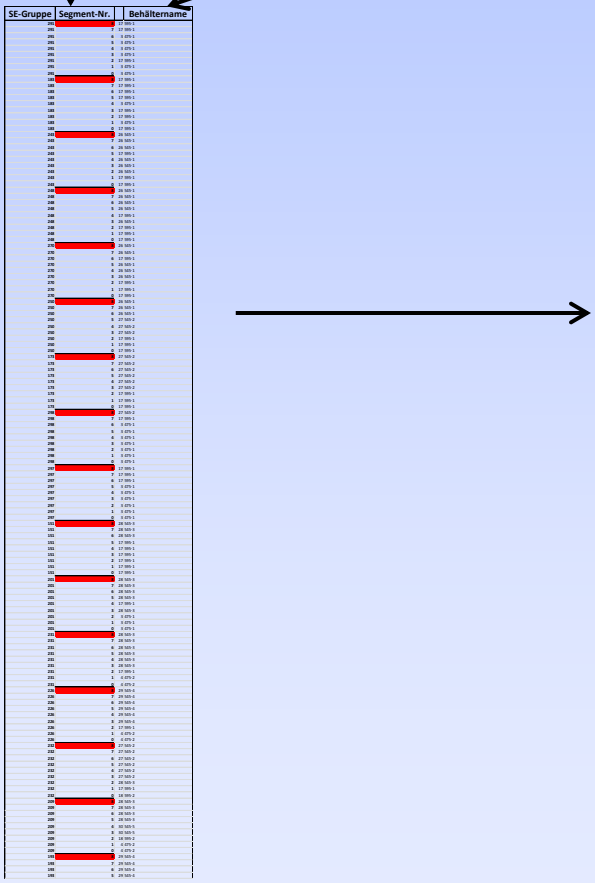




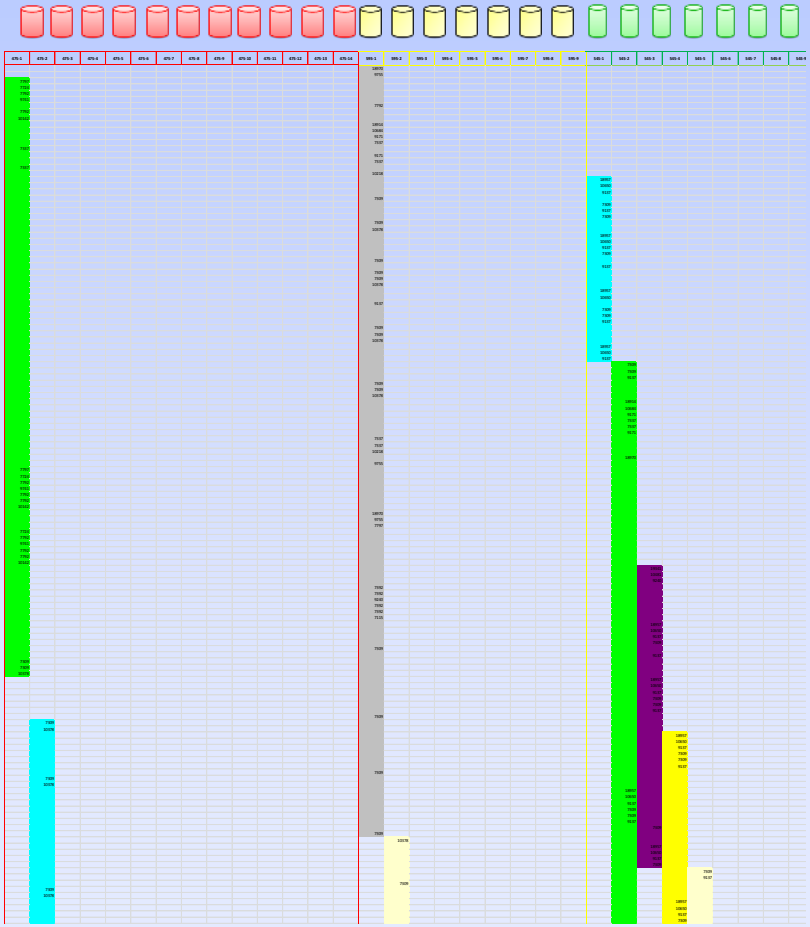
Output

Name of segment

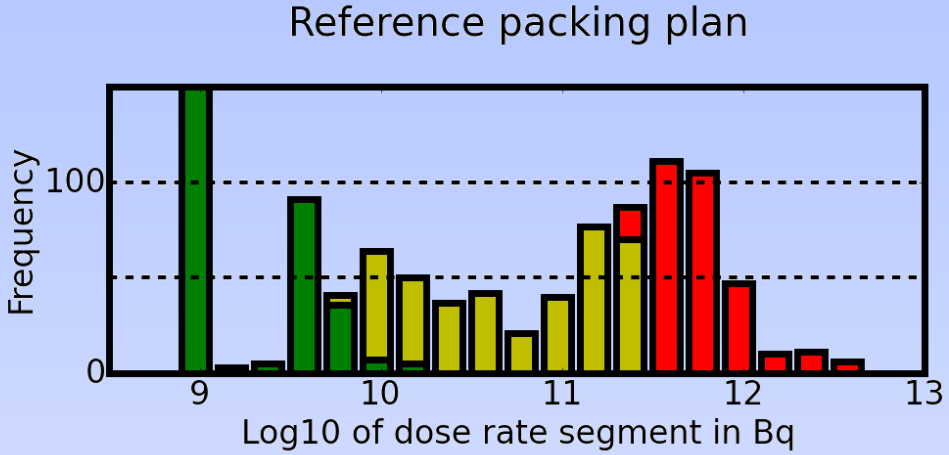
Cask name

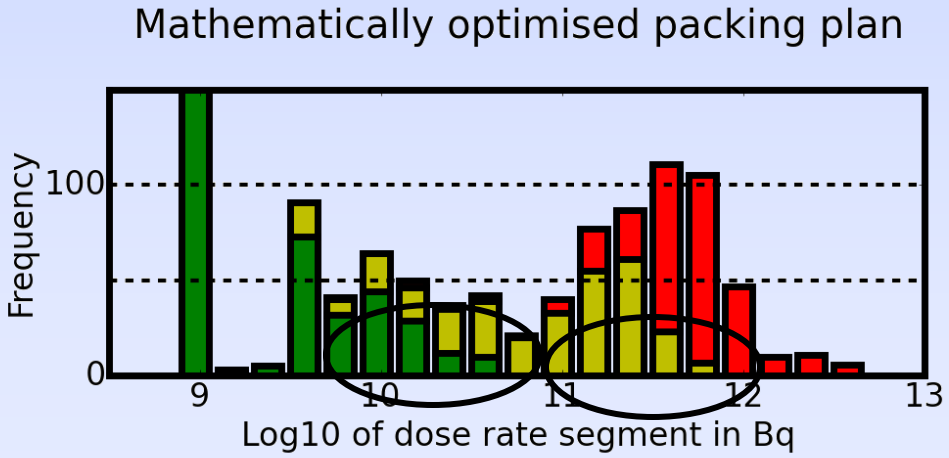


Graphic representation



Histogramm of activity (per bin type)





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

Results

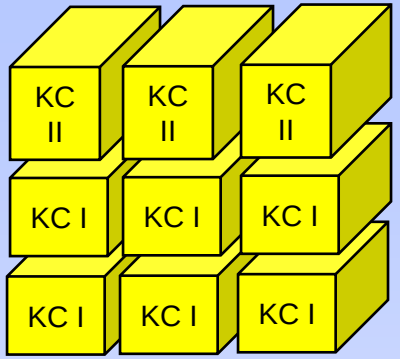
	Description of option	Utilisation of activity	Utilisation of activity	Utilisation of mass (all bin types)	Relative std. dev. of activity of surcharged	Violation of strong boundary conditions
Option 1	Few , many Some surcharged	99 %	73 %	95 %	0.02 %	No
Option 2	Many , few	99 %	83 %	97 %	N/A	No

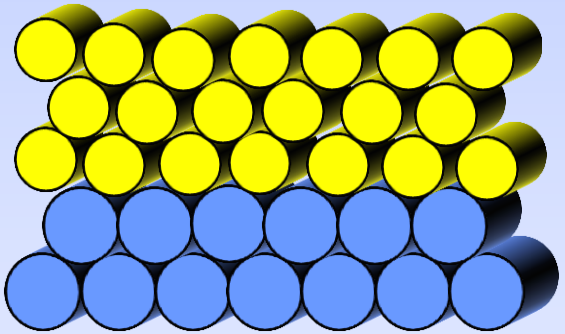
Significant reduction of no. of swaps:

- 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! **-> save ~20 swaps!**

Sneak preview: Optimising the storage in a, say, storage facility of national interest

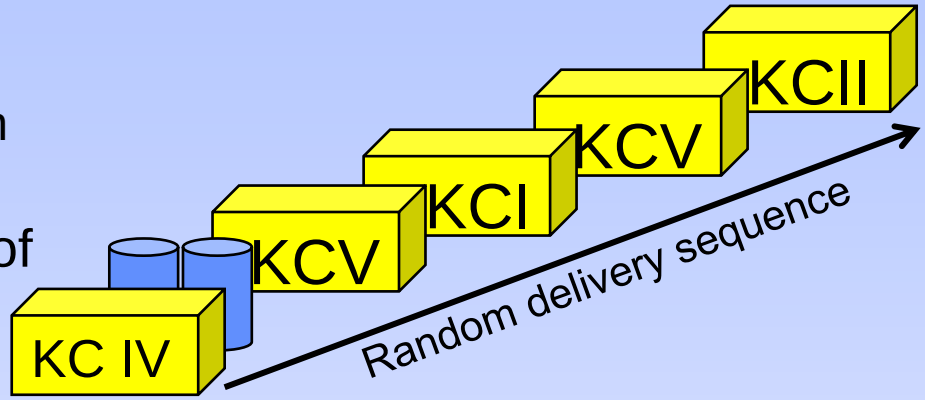
- Storage of delivered waste packages in Waste Package Type Groups (WPTG): Up to two types of waste package of different number but defined waste package type sequence, e.g.:
  - 6 Konrad-Container (KC) type I followed by 3 KC II
  - 13 cast iron cylindrical waste casks (GB) type III followed by 20 GB 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