Three-Dimensional Bin Packing with Vertical Support

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Case study

- Large warehouses
- Mixed-case palletization
- No control over items' shape (strongly heterogeneous)
- Pallets wrapped during loading procedure

ERMES-X

Figure: Example of pit palletization (Schäfer Case Picking — SSI SCHÄFER)

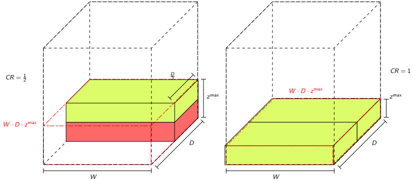


Figure: Cage ratio of two different bin configurations

Vertical Support

Definition

An item has vertical support if one of the following conditions hold:

- **Condition 1**: at least a percentage α_s of its base area is resting on other items
- **Condition 2**: at least 3 of its vertices are resting over other items and **Condition 1** holds with a lower percentage

Vertical Support

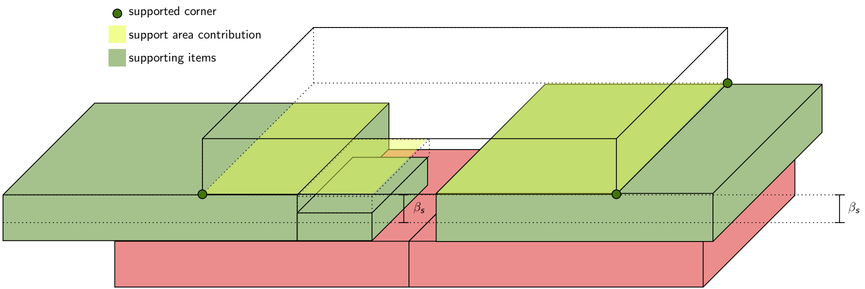


Figure: Representation of an item with conditions 1 and 2 of vertical support given $\alpha_s = 0.5, \beta_s$

Literature Review

- The problem is NP-Hard
- Exact methods only for small instances
- Existing 3D-BPP heuristics don't consider practical constraints
- Solutions for container loading and pallet loading problems are layer based

Conceptual Formulation

minimize	number of used bins
then, maximize	average cage ratio of the used bins
subject to	all items are assigned to one and only one bin
	all items are inside the bin's bounds
	no overlaps between items in the same bin
	all items have vertical support

MILP Proxy Model - Objective Function

minimize	number of used bins
then, maximize	average cage ratio of the used bins
subject to	all items are assigned to one and only one bin
	all items are inside the bin's bounds
	no overlaps between items in the same bin
	all items have vertical support

$$
\begin{array}{lll}
\min & \sum_{b \in B} (Hv_b + z_b^{max}) & \\
\text{s.t.} & \sum_{b \in B} u_{ib} + \sum_{b \in B} u_{jb} = 1 & \forall (i,j) \in I^{OR} \\
& u_{ib} \leq v_b & \forall i \in I, \forall b \in B \\
& v_b \geq v_c & \forall (b,c) \in B : b < c \\
& x_i + w_i \leq W & \forall i \in I \\
& y_i + d_i \leq D & \forall i \in I \\
& z_i + h_i \leq H & \forall i \in I \\
& (x_i + w_i) - x_j \leq W(1 - x_{ij}^p) & \forall i,j \in I \\
& x_j - (x_i + w_i) + 1 \leq W x_{ij}^p & \forall i,j \in I \\
& (y_i + d_i) - y_j \leq D(1 - y_{ij}^p) & \forall i,j \in I \\
& y_j - (y_i + d_i) + 1 \leq D y_{ij}^p & \forall i,j \in I \\
& (z_i + h_i) - z_j \leq H(1 - z_{ij}^p) & \forall i,j \in I \\
& z_j - (z_i + h_i) + 1 \leq H z_{ij}^p & \forall i,j \in I \\
& x_{ij}^p + x_{ji}^p + y_{ij}^p + y_{ji}^p + z_{ij}^p + z_{ji}^p \geq u_{ib} + u_{jb} - 1 & \forall i,j \in I, \forall b \in B \\
& z_b^{max} \geq (z_i + h_i) - H(1 - u_{ib}) & \forall i \in I, \forall b \in B
\end{array}
$$

MILP Proxy Model - Geometric Constraints 1

$$
\begin{aligned}
\min \quad & \sum_{b \in B} (Hv_b + z_b^{max}) & \\
\text{s.t.} \quad & \sum_{b \in B} u_{ib} + \sum_{b \in B} u_{jb} = 1 & \forall (i,j) \in I^{OR} \\
& u_{ib} \leq v_b & \forall i \in I, \forall b \in B \\
& v_b \geq v_c & \forall (b,c) \in B : b < c \\
& x_i + w_i \leq W & \forall i \in I \\
& y_i + d_i \leq D & \forall i \in I \\
& z_i + h_i \leq H & \forall i \in I \\
& (x_i + w_i) - x_j \leq W(1 - x_{ij}^p) & \forall i,j \in I \\
& x_j - (x_i + w_i) + 1 \leq Wx_{ij}^p & \forall i,j \in I \\
& (y_i + d_i) - y_j \leq D(1 - y_{ij}^p) & \forall i,j \in I \\
& y_j - (y_i + d_i) + 1 \leq Dy_{ij}^p & \forall i,j \in I \\
& (z_i + h_i) - z_j \leq H(1 - z_{ij}^p) & \forall i,j \in I \\
& z_j - (z_i + h_i) + 1 \leq Hz_{ij}^p & \forall i,j \in I \\
& x_{ij}^p + x_{ji}^p + y_{ij}^p + y_{ji}^p + z_{ij}^p + z_{ji}^p \geq u_{ib} + u_{jb} - 1 & \forall i,j \in I, \forall b \in B \\
& z_b^{max} \geq (z_i + h_i) - H(1 - u_{ib}) & \forall i \in I, \forall b \in B
\end{aligned}
$$

minimize	number of used bins
then, maximize	average cage ratio of the used bins
subject to	all items are assigned to one and only one bin
	all items are inside the bin's bounds
	no overlaps between items in the same bin
	all items have vertical support

MILP Proxy Model - Geometric Constraints 2

minimize	number of used bins
then, maximize	average cage ratio of the used bins
subject to	all items are assigned to one and only one bin
	all items are inside the bin's bounds
	no overlaps between items in the same bin
	all items have vertical support

$$\min \quad \sum_{b \in B} (Hv_b + z_b^{max})$$

$$\text{s.t.} \quad \sum_{b \in B} u_{ib} + \sum_{b \in B} u_{jb} = 1 \qquad \forall (i,j) \in I^{OR}$$

$$u_{ib} \leq v_b \qquad \forall i \in I, \forall b \in B$$

$$v_b \geq v_c \qquad \forall (b,c) \in B : b < c$$

$$x_i + w_i \leq W \qquad \forall i \in I$$

$$y_i + d_i \leq D \qquad \forall i \in I$$

$$z_i + h_i \leq H \qquad \forall i \in I$$

$$(x_i + w_i) - x_j \leq W(1 - x_{ij}^p) \qquad \forall i,j \in I$$

$$x_j - (x_i + w_i) + 1 \leq W x_{ij}^p \qquad \forall i,j \in I$$

$$(y_i + d_i) - y_j \leq D(1 - y_{ij}^p) \qquad \forall i,j \in I$$

$$y_j - (y_i + d_i) + 1 \leq D y_{ij}^p \qquad \forall i,j \in I$$

$$(z_i + h_i) - z_j \leq H(1 - z_{ij}^p) \qquad \forall i,j \in I$$

$$z_j - (z_i + h_i) + 1 \leq H z_{ij}^p \qquad \forall i,j \in I$$

$$x_{ij}^p + x_{ji}^p + y_{ij}^p + y_{ji}^p + z_{ij}^p + z_{ji}^p \geq u_{ib} + u_{jb} - 1 \qquad \forall i,j \in I, \forall b \in B$$

$$z_b^{max} \geq (z_i + h_i) - H(1 - u_{ib}) \qquad \forall i \in I, \forall b \in B$$

MILP Proxy Model - Geometric Constraints 3

minimize	number of used bins
then, maximize	average cage ratio of the used bins
subject to	all items are assigned to one and only one bin
	all items are inside the bin's bounds
	no overlaps between items in the same bin
	all items have vertical support

$$
\begin{aligned}
\min \quad & \sum_{b\in B}(Hv_b + z_b^{max}) & \\
\text{s.t.} \quad & \sum_{b\in B} u_{ib} + \sum_{b\in B} u_{jb} = 1 & \forall (i,j) \in I^{OR} \\
& u_{ib} \leq v_b & \forall i \in I, \forall b \in B \\
& v_b \geq v_c & \forall (b,c) \in B : b < c \\
& x_i + w_i \leq W & \forall i \in I \\
& y_i + d_i \leq D & \forall i \in I \\
& z_i + h_i \leq H & \forall i \in I \\
& (x_i + w_i) - x_j \leq W(1 - x_{ij}^p) & \forall i,j \in I \\
& x_j - (x_i + w_i) + 1 \leq W x_{ij}^p & \forall i,j \in I \\
& (y_i + d_i) - y_j \leq D(1 - y_{ij}^p) & \forall i,j \in I \\
& y_j - (y_i + d_i) + 1 \leq D y_{ij}^p & \forall i,j \in I \\
& (z_i + h_i) - z_j \leq H(1 - z_{ij}^p) & \forall i,j \in I \\
& z_j - (z_i + h_i) + 1 \leq H z_{ij}^p & \forall i,j \in I \\
& x_{ij}^p + x_{ji}^p + y_{ij}^p + y_{ji}^p + z_{ij}^p + z_{ji}^p \geq u_{ib} + u_{jb} - 1 & \forall i,j \in I, \forall b \in B \\
& z_b^{max} \geq (z_i + h_i) - H(1 - u_{ib}) & \forall i \in I, \forall b \in B
\end{aligned}
$$

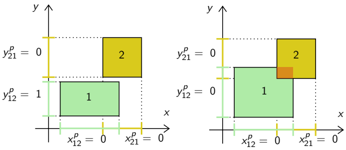


Figure: Precedences variables (2D case)

MILP Proxy Model - Vertical Support

minimize	number of used bins
then, maximize	average cage ratio of the used bins
subject to	all items are assigned to one and only one bin
	all items are inside the bin's bounds
	no overlaps between items in the same bin
	all items have vertical support

MILP Proxy Model - Closeness

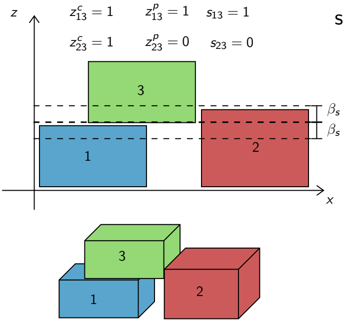


Figure: Closeness variables example

s.t.

$$
\begin{aligned}
& z_j - (z_i + h_i) \le \beta_s + H(1 - z^c_{ij}) && \forall (i,j) \in I : i \ne j \\
& z_j - (z_i + h_i) \ge -\beta_s - H(1 - z^c_{ij}) && \forall (i,j) \in I : i \ne j \\
& s_{ij} \le z^p_{ij} && \forall (i,j) \in I \\
& s_{ij} \le z^c_{ij} && \forall (i,j) \in I \\
& s_{ij} \ge z^p_{ij} + z^c_{ij} - 2 && \forall (i,j) \in I : i \ne j \\
& \sum_{j \in I} s_{ij} \le \sum_{b \in B} u_{ib} && \forall i \in I
\end{aligned}
$$

MILP Proxy Model - Discretized Vertical Support

Pre-Computed Parameter

$O(i, j, k, h)$

$O(i, j, 1, 2) = 1$

Variables

$s_{ijb}^{12} = 1$

$(x_j - x_i, y_j - y_i)$

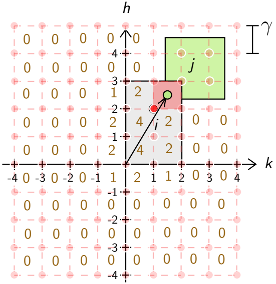


Figure: Space discretization

$$
\begin{aligned}
\text{s.t.} \quad & z_i \leq H(1 - g_i) && \forall i \in I \\
& \sum_{(k,h)\in\Delta, b\in B: O(i,j,k,h)\neq 0} s_{ijb}^{kh} \leq s_{ij} && \forall (i,j) \in I \\
& \sum_{(k,h)\in\Delta: O(i,j,k,h)\neq 0} s_{ijb}^{kh} \leq u_{ib} && \forall (i,j,b) \in I^B \\
& \sum_{(k,h)\in\Delta: O(i,j,k,h)\neq 0} s_{ijb}^{kh} \leq u_{jb} && \forall (i,j,b) \in I^B \\
& x_j - x_i \geq \gamma k - 2W(1 - s_{ijb}^{kh}) && \forall (k,h) \in \Delta, \forall (i,j,b) \in I^B : O(i,j,k,h) \neq 0 \\
& x_j - x_i \leq \gamma (k+1) + 2W(1 - s_{ijb}^{kh}) && \forall (k,h) \in \Delta, \forall (i,j,b) \in I^B : O(i,j,k,h) \neq 0 \\
& y_j - y_i \geq \gamma h - 2D(1 - s_{ijb}^{kh}) && \forall (k,h) \in \Delta, \forall (i,j,b) \in I^B : O(i,j,k,h) \neq 0 \\
& y_j - y_i \leq \gamma (h+1) + 2D(1 - s_{ijb}^{kh}) && \forall (k,h) \in \Delta, \forall (i,j,b) \in I^B : O(i,j,k,h) \neq 0 \\
& \sum_{(k,h)\in\Delta, b\in B, j\in I: i\neq j \wedge O(i,j,k,h)\neq 0} O(i,j,k,h) s_{jib}^{kh} \geq \alpha_s w_i d_i - w_i d_i g_i && \forall i \in I
\end{aligned}
$$

Overview

Composed of:

- Constructive heuristic (Support Planes)
- Beam-Search

Each node is a partial solution, starts from the empty solution

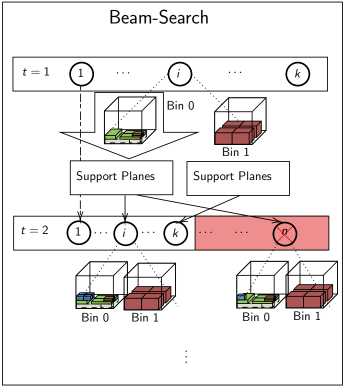


Figure: Conceptual representation of the proposed heuristic

Support Planes

- Operates on a single bin
- Items generate planes
- Planes have obstacles or support items
- Insertions on the lowest possible planes
- Exploits a modified 2D-BPP heuristic
- No explicit layers

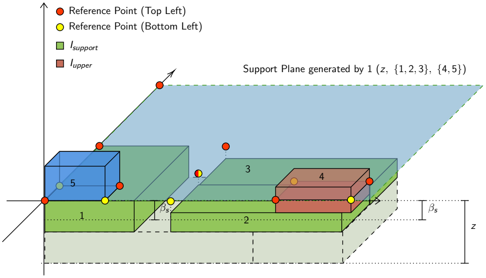
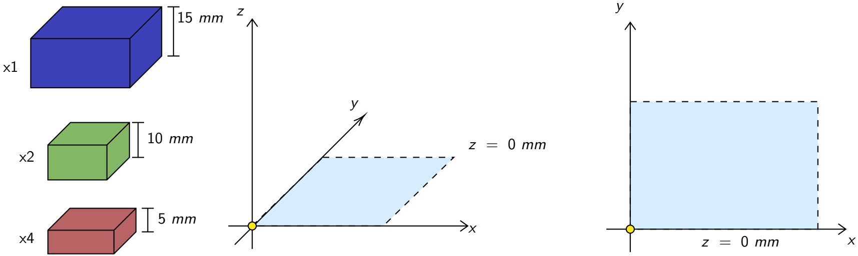
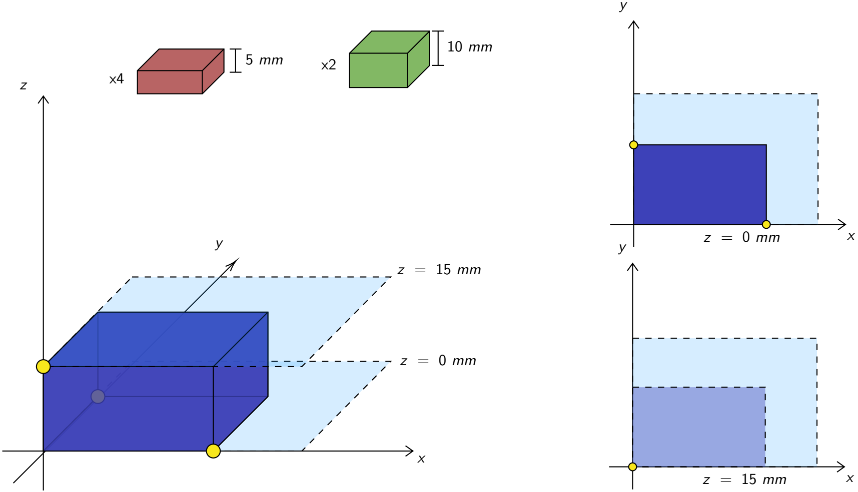


Figure: An example of a support plane generated by item 1

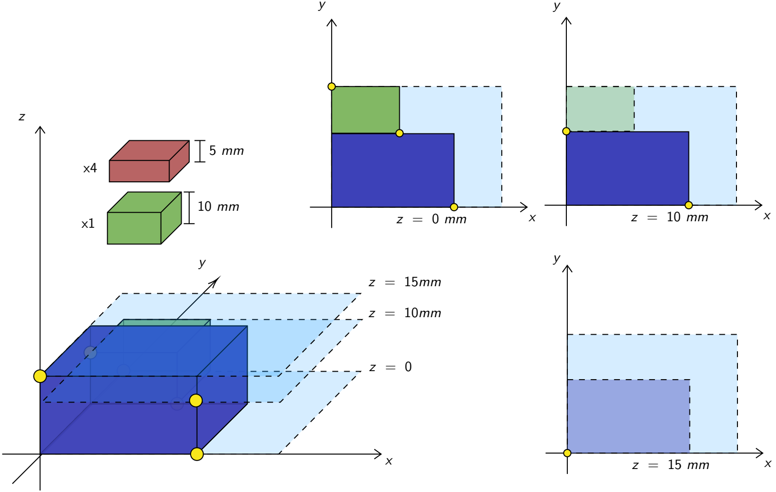
Support Planes



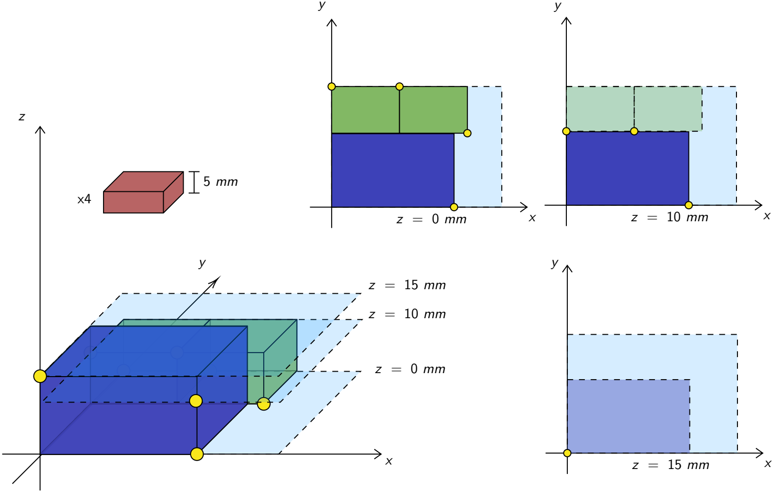
Support Planes



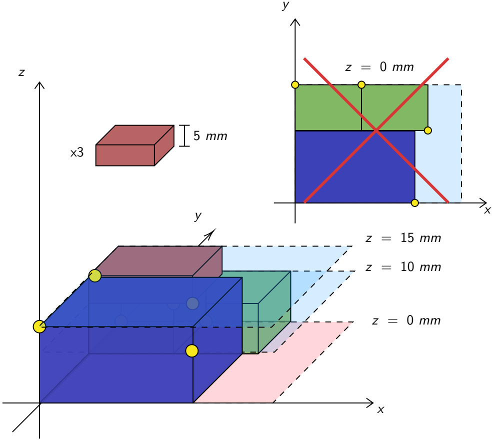
Support Planes

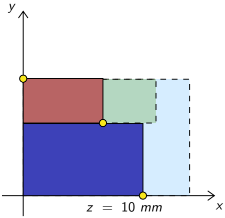


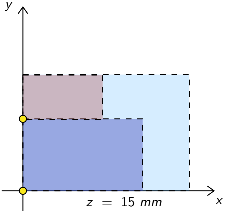
Support Planes



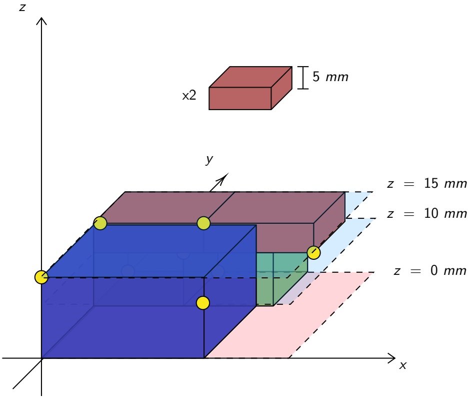
Support Planes

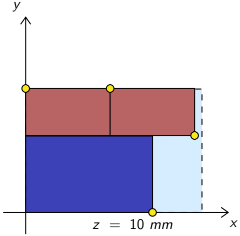


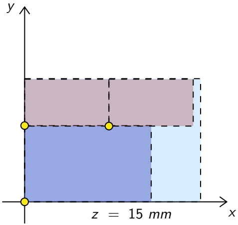




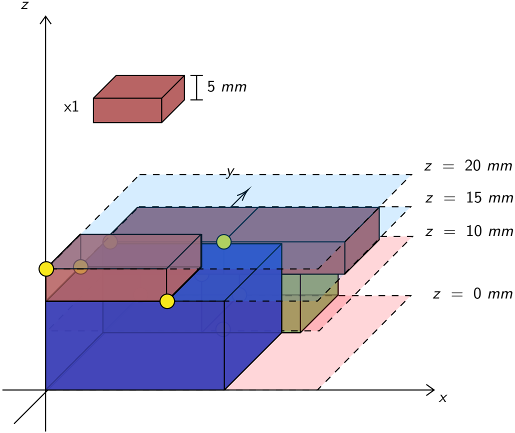
Support Planes

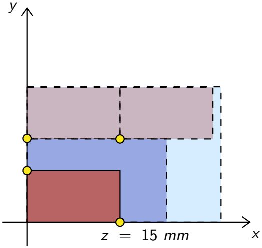


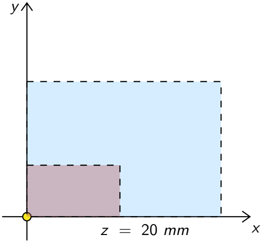




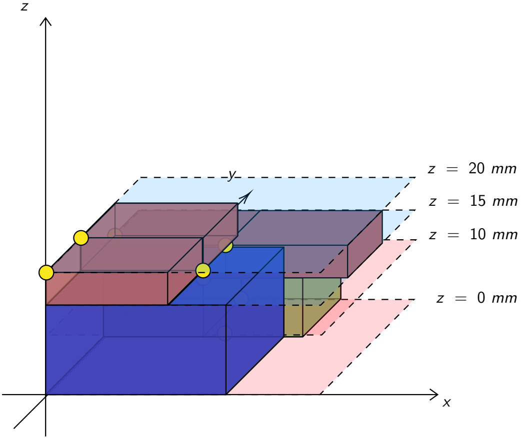
Support Planes

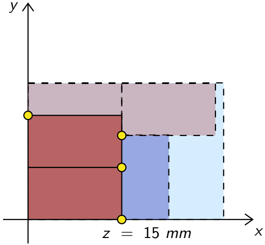


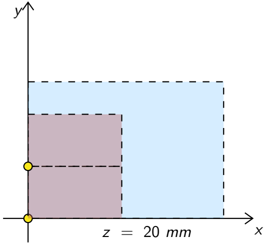




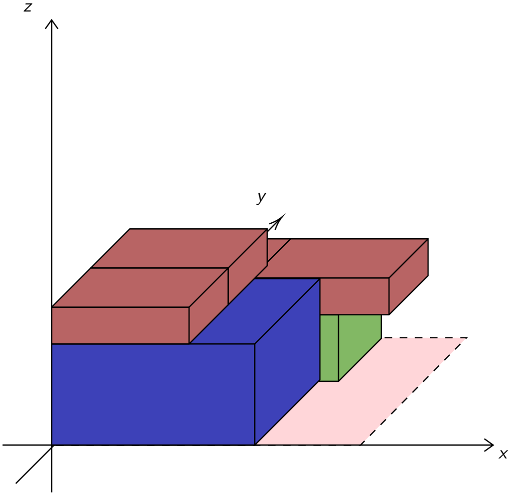
Support Planes







Support Planes



Beam Search

- Iteratively builds a solution
- Each node is a feasible packing
- Exploits support planes
- Different placement modes
- Explores k best placements

Optimizations

- Duplicates removal
- Fast overlap checks
- Memory management

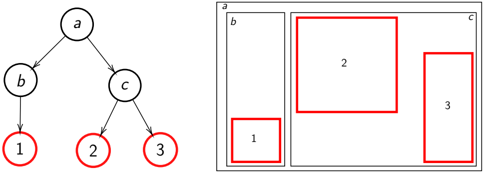


Figure: AABB Tree

Computational Experiments

Table: Average execution time of literature results with bin gap

Heuristic		Execution Time (s)				Bin Gap (%)
		$n = 50$	$n = 100$	$n = 150$	$n = 200$	
PM	$k = 1$	0.05	0.11	0.28	0.55	4.57
	$k = 5$	0.08	0.39	1.02	2.16	4.32
	$k = 10$	0.15	0.74	1.98	4.12	4.29
	$k = 20$	0.29	1.45	3.89	8.07	4.05
	$k = 50$	0.72	3.63	9.72	20.47	3.95
PS	$k = 1$	0.04	0.18	0.51	1.08	4.35
	$k = 5$	0.12	0.74	2.19	4.79	4.01
	$k = 10$	0.23	1.43	4.19	9.39	3.94
	$k = 20$	0.47	2.81	8.48	18.93	3.74
	$k = 50$	1.15	6.74	21.03	45.78	3.52
BRKGA-VD		17.13	80.63	190.50	369.75	0.00

Computational Experiments

Table: Summary of case study tests

	PS			**PM**		
k	**TT (ms)**	**B**	**CR (%)**	**TT (ms)**	**B**	**CR (%)**
1	423.87	1.37	65.87	65.18	1.31	**70.70**
5	1,597.54	1.34	69.19	185.22	1.29	**73.08**
10	2,627.52	1.32	70.35	344.90	1.27	**73.56**
20	5,373.79	1.34	70.78	620.95	1.27	**74.57**
50	14,203.10	1.31	72.11	1,279.96	1.29	**74.61**
100	26,934.21	1.31	73.23	2,340.37	1.26	**75.36**
200	48,944.90	1.30	73.89	4,465.78	1.25	**76.39**

Computational Experiments

Table: Case study experiments trade off between average execution times and average cage ratio

k	**PS**		**PM**	
	CR* – CR (%)	**TT – TT* (ms)**	**CR* – CR (%)**	**TT – TT* (ms)**
1	10.56	358.69	5.73	0.00
5	7.24	1,532.36	3.35	120.04
10	6.08	2,562.34	2.87	279.72
20	5.65	5,308.61	**1.85**	**555.77**
50	4.32	14,137.92	**1.82**	**1,214.78**
100	3.20	26,869.03	1.07	2,275.19
200	2.54	48,879.72	0.04	4,400.60

Results & Future Developments