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Vorwort

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Darüber hinaus bietet die Reihe ein Forum für die Berichterstattung über die zahlreichen Kooperationsprojekte des Instituts mit Partnern aus Industrie und Wirtschaft.

Berichterstattung heißt hier Dokumentation des Transfers aktueller Ergebnisse aus mathematischer Forschungs- und Entwicklungsarbeit in industrielle Anwendungen und Softwareprodukte – und umgekehrt, denn Probleme der Praxis generieren neue interessante mathematische Fragestellungen.

Prof. Dr. Dieter Prätzel-Wolters
Institutsleiter

Kaiserslautern, im Juni 2001

A CONSTRAINT PROGRAMMING APPROACH FOR THE TWO-DIMENSIONAL RECTANGULAR PACKING PROBLEM WITH ORTHOGONAL ORIENTATIONS

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Abstract. We propose a constraint-based approach for the two-dimensional rectangular packing problem with orthogonal orientations. This problem is to arrange a set of rectangles that can be rotated by 90 degrees into a rectangle of minimal size such that no two rectangles overlap. It arises in the placement of electronic devices during the layout of 2.5D System-in-Package integrated electronic systems. Moffitt et al. [8] solve the packing without orientations with a branch and bound approach and use constraint propagation. We generalize their propagation techniques to allow orientations. Our approach is compared to a mixed-integer program and we provide results that outperform it.

Keywords. rectangular packing, orthogonal orientations, non-overlapping constraints, constraint propagation.

1. Introduction

Rectangular packing problems occur in many real world applications and challenge researchers from operations research, constraint programming, artificial intelligence and many more. We address the two-dimensional rectangular packing problem with orthogonal orientations (RPWO) which is to arrange rectangles that can be rotated by 90 degrees into a rectangular container such that no two overlap. Minimizing the container size is an $\mathcal{NP}$-hard combinatorial optimization problem.

Such a problem arises in 2.5D System-in-Package (SiP) layout design [9]. 2.5D SiP is a modern integration approach of heterogeneous electronic components on modules which are stacked or folded vertically. SiP integration meets modern requirements for miniaturized electronic systems, has a predicted growing market demand but still lacks standardized design automation tools. Figure 1 exemplarily illustrates two 2.5D SiP technologies.

The layout process is subdivided into a sequence of three optimization problems [10]. In the partitioning step the components are assigned to the vertically stacked modules. In the placement step the components are placed on each module side. The placement problem on each module involves a RPWO. The routing step includes the arrangement of the vertical interconnections and the routing within each module. Figure 2 illustrates the layout steps in SiP design.

We propose to layout an SiP with our novel prototype electronic design automation (EDA) tool called 3D SiP Expert. This tool uses a database of SiP layouts that are

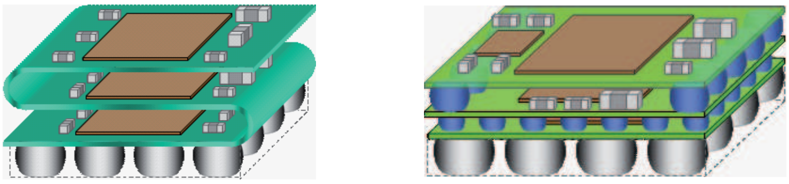


FIGURE 1. Two illustrations for SiPs: Integrated on a flexible bended substrate (left) and integrated on rigid modules electrically interconnected through conductive solder balls (right).

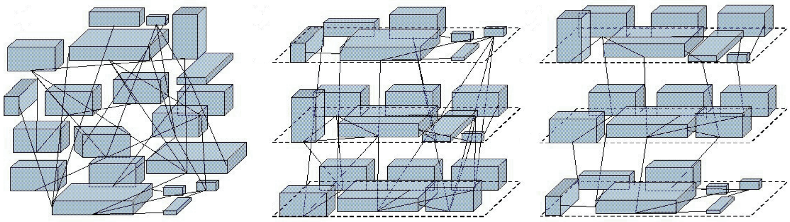


FIGURE 2. Layout process of SiPs: Paritioning of the components to modules; placement of the components on the module sides; routing through vertical interconnections and through the modules.

calculated in an offline phase. Then in an online phase, the engineer can use this tool to quickly navigate to the SiP layout of his interest. The designer can restrict and select values of multiple criteria like size, wiring, thermal and electrical properties of the SiP. This novel approach accelerates the layout process and avoids time consuming re-design cycles.

For the RWPO of the placement problem in SiP layout we need an adequate algorithmic method. A multitude of methods from metaheuristics, linear, mixed integer, nonlinear and constraint programming have been developed for rectangular packing [11, 2, 7, 6, 1]. However, the orientation is often disregarded and most of the approaches can not integrate important constraints arising in SiP design. Therefore, we extend the meta-constraint satisfaction problem (CSP) approach of Moffitt et al. [8]. Their branch and bound solves minimal area packing and uses constraint propagation.

We generalize the propagation algorithms for orientations and show the relation of the meta-CSP approach to mixed-integer programming (MIP). We compare our extended meta-CSP to an MIP and provide numerical results that outperform it. In conclusion, our approach solves RPWO and can be extended to address the wiring of SiP components in order to serve as algorithm of an SiP design automation tool.

The outline of the paper is as follows: In section 2 we introduce our notation and problem formulation, then discuss the meta-CSP model in section 3 and our generalization for orthogonal orientations in section 4. In section 5 we propose an MIP formulation and discuss its similarities to our approach. Then we provide numerical results in section 6 for our implementations, discuss them and conclude in section 7 with an outline for future work.

2. Problem Formulation

We denote $\mathcal{R} := \{r_1, \dots, r_n\}$ as rectangle set with index set $\mathcal{I} := \{1, \dots, n\}$; $w_i, h_i \in \mathbb{N}$ represent the width and height, $x_i, y_i \in \mathbb{R}^{\geq 0}$ the coordinates of the lower left corner and $o_i \in \{0, 1\}$ models the orientation of rectangle r_i; $W, H \in \mathbb{R}^{\geq 0}$ represent the width and height of the container with upper bounds $W_{\max}, H_{\max}$. We formulate RPWO as minimal half perimeter packing problem with linear objective $f := W + H$:

$$
\begin{array}{llll}
\text{(RPWO)} & \min\ f & \text{subject to} & \\
(1) & x_i + s_i^x \leq W, & W \leq W_{\max}, & \\
(2) & y_i + s_i^y \leq H, & H \leq H_{\max}, & \\
(3) & (1-o_i)w_i + o_i h_i = s_i^x, & o_i w_i + (1-o_i)h_i = s_i^y, & \forall i \in \mathcal{I}, \\
(4) & (x_i + s_i^x \leq x_j) \vee (x_j + s_j^x \leq x_i) & & \\
 & \vee\ (y_i + s_i^y \leq y_j) \vee (y_j + s_j^y \leq y_i), & & \forall i,j \in \mathcal{I}, i<j, \\
(5) & x_i \geq\ 0, & y_i \geq 0, & \forall i \in \mathcal{I}.
\end{array}
$$

(1-2) ensure the rectangle containment, (3) define the size of the oriented rectangles, (4) make sure that no two overlap by arranging them left (d_{iLj}), right (d_{iRj}), below (d_{iBj}) or above (d_{iAj}) of each other and (5) are the non-negativity constraints for the coordinates of the rectangles.

3. Meta-CSP Model

In [8] minimal area rectangular packing with fixed orientations is approached. Instead of searching x_i, y_i, meta-variables C_{ij} are introduced for each non-overlapping constraint. C_{ij} ranges in domain $D(C_{ij}) := \{d_{iLj}, d_{iRj}, d_{iBj}, d_{iAj}\}$ and represents the geometric relation between r_i and r_j. The search tree is branched over the C_{ij} and pruned with constraint propagation. Propagation uses incrementally maintained graphs that describe a partial solution. Figure 3 shows a complete solution and the corresponding packing of the rectangles.

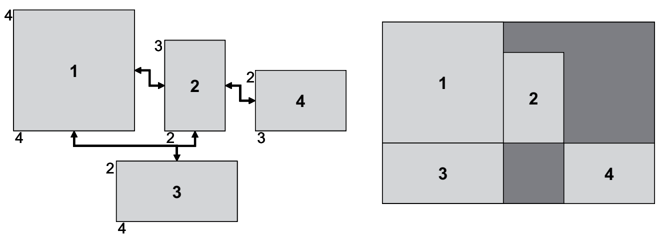


FIGURE 3. Example for a complete meta-CSP solution and the corresponding packing.

A partial packing for a subset $\mathcal{S}$ of $\mathcal{R}$ is described by two sets of inequalities $u + s \leq v$, $\mathcal{C}_h$ for the horizontal and $\mathcal{C}_v$ for the vertical geometric relations. $\mathcal{C}_h$ and $\mathcal{C}_v$ are encoded in two weighted directed graphs G_h and G_v that represent the left and below precedences of r_i and r_j. The vertices of both graphs represent the rectangles and the edges represent the horizontal or vertical precedences of the rectangles. The weights of the edges from j to i are given by the size $-s$ of rectangle r_i. The edges are weighted with the negative sizes of the rectangles in order to illustrate the graph algorithms canonically. Also for a better illustration, we introduce both a source vertex $n+1$ with outgoing edges to each rectangle vertex i with the rectangle size $-s$ as edge weight and a sink vertex 0 with incoming edges from each rectangle vertex i with edge weight 0. Figure 4 shows G_h and G_v for the example in figure 3.

Then, $\mathcal{C}_h$ ($\mathcal{C}_v$) is consistent if and only if G_h (G_v) has no negative cycle. Negative cycles can be detected in polynomial time by checking for negative entries on the main diagonal of the all-pairs shortest path matrix A_h (A_v) of G_h (G_v) [4]. A_h and A_v are maintained

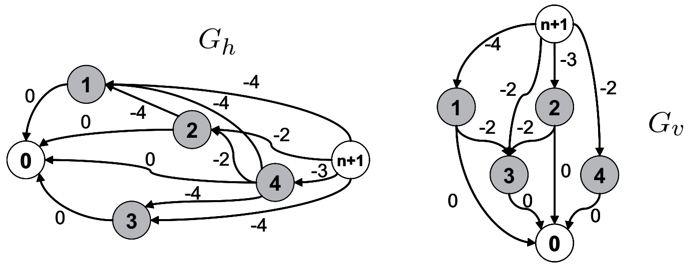


FIGURE 4. Precedence graphs for the example in figure 3.

during search and updated with the Floyd-Warshall algorithm in $O(n^3)$. In figure 5 we provide the all-pairs shortest path matrices for the example in figure 3.

$$A_h = \begin{pmatrix} \infty & \infty & \infty & \infty & \infty & \infty \\ 0 & \infty & \infty & \infty & \infty & \infty \\ -4 & -4 & \infty & \infty & \infty & \infty \\ 0 & \infty & \infty & \infty & \infty & \infty \\ -6 & -6 & -2 & -4 & \infty & \infty \\ -9 & -9 & -5 & -4 & -3 & \infty \end{pmatrix} \qquad A_v = \begin{pmatrix} \infty & \infty & \infty & \infty & \infty & \infty \\ -2 & \infty & \infty & -2 & \infty & \infty \\ -2 & \infty & \infty & -2 & \infty & \infty \\ 0 & \infty & \infty & \infty & \infty & \infty \\ 0 & \infty & \infty & \infty & \infty & \infty \\ -6 & -4 & -3 & -5 & -2 & \infty \end{pmatrix}$$

FIGURE 5. All-pairs shortest path matrices for the example in figure 3.

Whenever a meta-variable C_{ij} is consistently instantiated with a horizontal disjunct during search, the distance graph G_h is extended with an edge between vertex i and j and Floyd-Warshall is applied to update A_h. Both G_v and A_v are updated analogously whenever C_{ij} is instantiated with a vertical disjunct.

The acyclic directed graphs G_h and G_v can be used to determine lower bounds for both the rectangle coordinates x_i, y_i and the width W and height H of the container. The negative shortest path length from vertex i to vertex 0 gives the lower bound. Stating these conditions with the help of the all-pairs shortest path matrices A_h and A_v we obtain the following lower bounds,

$$-A_h(i,0) \leq x_i, \qquad -A_v(i,0) \leq y_i,\ \forall i \in \mathcal{I}, \tag{6}$$

$$-A_h(n+1,0) \leq W,\ -A_v(n+1,0) \leq H. \tag{7}$$

Therefore, we also have a lower bound for our objective f, i.e.

$$-A_h(n+1,0) - A_v(n+1,0) \leq f, \tag{8}$$

where equality holds once all C_{ij} are instantiated.

Besides using G_h, G_v, A_h, A_v for getting the rectangle coordinates and dimensions of the container, these data structures allow us to efficiently detect inconsistency early and to apply several specific propagation techniques. We discuss some techniques in the following and refer to [8] for a detailed description. With G_h, G_v, A_h, A_v the following propagation techniques are applied in $O(1)$ during search:

Forward checking (FC) removes inconsistent values of C_{ij} with respect to a partial assignment. To check if value $\{d : u + s \leq v\} \in D(C_{ij})$ is consistent, $A(i,j)$ must not be less than s. The propagation rules for FC are as follows:

$$\forall C_{ij} \ : \ (D(C_{ij}) = \emptyset \Rightarrow \text{fail}) \tag{9}$$

$$\forall C_{ij} \ : \ (\exists d \in D(C_{ij}) : A(i,j) < s \Rightarrow (D(C_{ij}) \leftarrow D(C_{ij}) \setminus \{d\})) \tag{10}$$

Removal of subsumed variables (RS) assigns C_{ij} transitively implied by C_{ik} and C_{kj}. A value $\{d : u + s \leq v\} \in D(C_{ij})$ of C_{ij} is satisfied if and only if the shortest path from r_j to r_i is smaller than $-s$. The propagation rule for RS is as follows:

$$\forall C_{ij} \quad : \quad (\exists d \in D(C_{ij}) : A(j,i) \leq -s \Rightarrow C_{ij} = d) \tag{11}$$

In figure 6 we illustrate how negative cycles are detected by FC and in figure 7 how subsumed variables are detected by RS.

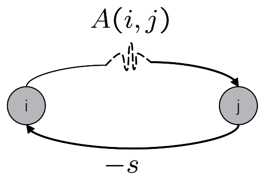


FIGURE 6. Negative cycle detection with forward checking.

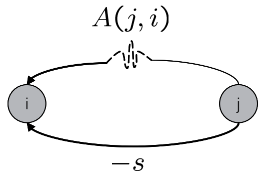


FIGURE 7. Detection of subsumed variables.

Detecting cliques of displacement (DC) is another pruning technique. Partial solutions with cliques consisting of pairwise, horizontally or vertically, aligned rectangles whose alignment exceeds the container, lead to a dead-end. A greedy heuristic is applied to a horizontal and vertical displacement graph to detect such cliques early.

Furthermore, to avoid symmetric solutions, symmetry breaking before and during the search is applied in the branch and bound of [8]. A dynamic most constrained variable first heuristic orders C_{ij} of large rectangle pairs first. Those relations of C_{ij} that require the minimal increase in area are selected first. In case of a tie, the relation $\{d : u + s \leq v\}$ with the least amount of slack $A(i,j) - s$ is selected.

4. META-CSP MODEL WITH ORIENTATION

To introduce orientations into the meta-CSP model, we generalize the pruning techniques FC, RS and DC. When an o_i is not assigned, we either use the minimal $\underline{s}_i = \min(w_i, h_i)$ or maximal side lengths $\overline{s}_i = \max(w_i, h_i)$ of r_i for propagation. Figure 8 illustrates the concept of our generalization. When an o_i is assigned, we use s_i^x, s_i^y analogously to the meta-CSP model.

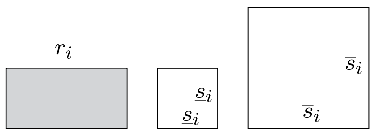


FIGURE 8. Minimal and maximal square for rectangle r_i that are used in our generalization of the propagation techniques.

We apply $\underline{s}_i$ for FC and $\overline{s}_i$ for RS. The generalized propagation rules are as follows:

$$\forall C_{ij} \quad : \quad (\exists d \in D(C_{ij}) : A(i,j) < \underline{s}_i \Rightarrow C_{ij} \neq d)\,, \tag{12}$$

$$\forall C_{ij} \quad : \quad (\exists d \in D(C_{ij}) : A(j,i) \leq -\overline{s}_i \Rightarrow C_{ij} = d)\,. \tag{13}$$

For DC, we also apply $\underline{s}_i$ of r_i with uninstantiated o_i.

To strengthen propagation we propose new pruning techniques that incorporate the orientations. We assign o_i of r_i which only fits into the container with a certain o_i. The rules for exceeding $W_{\max}$ are as follows, analogous rules follow for the lower bound $\underline{y}_i$ and $H_{\max}$:

$$\forall i \in \mathcal{I} : (\underline{x}_i + h_i > W_{\max} \Rightarrow o_i = 0)\,, \tag{14}$$

$$(\underline{x}_i + w_i > W_{\max} \Rightarrow o_i = 1)\,. \tag{15}$$

In a similar way we assign o_i of r_i which can only precede r_j with a certain o_i. The rule for the left precedence (d_{iLj}) is as follows, analogous rules follow for the other geometric relations:

$$\forall i, j \in \mathcal{I}, i < j : (C_{ij} = d_{iLj} \wedge \underline{x}_i + h_i > \overline{x}_j \Rightarrow o_i = 0)\,, \tag{16}$$

$$(C_{ij} = d_{iLj} \wedge \underline{x}_i + w_i > \overline{x}_j \Rightarrow o_i = 1)\,. \tag{17}$$

Conversely, an instantiated o_i is propagated on $\overline{x}_i, \overline{y}_i$:

$$\begin{aligned} o_i = 0 \Rightarrow \overline{x}_i &\leftarrow \min(\overline{x}_i, W_{\max} - w_i)\,, \\ \overline{y}_i &\leftarrow \min(\overline{y}_i, H_{\max} - h_i)\,. \end{aligned} \tag{18}$$

Again, an analogous rule is applied for the instantiation $o_i = 1$.

Furthermore, we propose a symmetry breaking technique which imposes a lex-leader constraint on equal sized rectangles by removing one horizontal and one vertical geometric relation of the corresponding C_{ij}. An example for a lex-leader constraint and three equal sized rectangles is illustrated in figure 9.

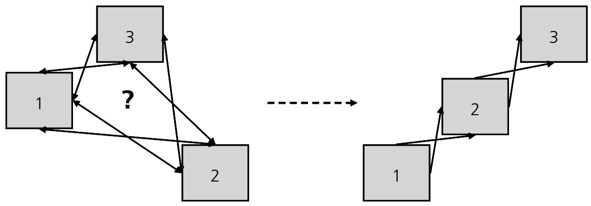


FIGURE 9. Illustration of the lex-leader constraint for three equal sized rectangles. In the domains of C_{12}, C_{13} and C_{23} one horizontal and one vertical disjunct is removed.

In addition to the meta-variables C_{ij} we have to search the orientations o_i. With our generalization we can instantiate C_{ij} and o_i order-independently. We instantiate o_i and o_j right after the meta-variable C_{ij} has been assigned. We call this order (C_{ij}, o_i, o_j). This ordering only marginally weakens propagation compared to ordering the o_i first, which is called the standard order (o, C) here.

To strengthen our exhaustive search method we initialize it with an upper bound on f. We obtain the bound from a feasible solution constructed by a greedy best-fit packing heuristic.

Our heuristic tries to pack all rectangles into a given container with fixed width and height. The half perimeter of the container is initially set to $W + H = \lfloor 2\sqrt{\sum_{i \in \mathcal{I}} w_i h_i} \rfloor$ and is iteratively incremented until a feasible packing of all rectangle is found. In every iteration different width and height pairs are tried for a given half perimeter of the container.

The greedy heuristic packs one rectangle at a time. Each subsequent rectangle r_i is packed at insertion positions where one corner of r_i and its adjacent sides touch other rectangles or the container sides. Our insertion position generalizes the normal position defined in [3] for two-dimensional bin packing problems.

Instead of ordering the rectangles statically, our algorithm dynamically chooses the next best pair of rectangle and insertion position. Similar to the touching perimeter algorithm in [5] we prefer insertion positions where the inserted rectangle shares as many sides as possible with already packed rectangles.

5. Mixed-integer Formulation

Now we formulate RWPO as a mixed-integer program. Therefore, we have to resolve the disjunctive non-overlapping constraints (4) through a big-M relaxation and auxiliary variables $z_{ij}^k \in \{0,1\}, k = 1,\dots,4$:

$$\begin{aligned}
(19)\qquad & x_i + s_i^x \le x_j + (1 - z_{ij}^1)W_{\max},\\
& y_i + s_i^y \le y_j + (1 - z_{ij}^3)H_{\max},\\
& x_j + s_j^x \le x_i + (1 - z_{ij}^2)W_{\max},\\
& y_j + s_j^y \le y_i + (1 - z_{ij}^4)H_{\max},\\
(20)\qquad & 1 \ge z_{ij}^1 + z_{ij}^2,\\
& 1 \ge z_{ij}^3 + z_{ij}^4,\\
(21)\qquad & 1 \le z_{ij}^1 + z_{ij}^2 + z_{ij}^3 + z_{ij}^4,\ \forall i,j \in \mathcal{I}, i < j.
\end{aligned}$$

The constraints (19) represent the linear disjuncts of the non-overlapping constraints (4), the constraints (20) assure that at most one horizontal and at most one vertical geometric relation is implied and the constraints (21) assure that at least one geometric relation between any rectangle pair is implied.

The resulting MIP model and the meta-CSP model are similar in different ways. We discuss some similarities in the following.

Definition 1. *The Critical Path Problem is to find the longest path from any source s to any sink t in a directed acyclic graph $G(V,E)$.*

Lemma 2. *The determination of lower bounds for W and H in the meta-CSP model is equivalent to the solution of critical path problems of the following form:*

$$\max(x_{n+1}) \text{ such that } x_j - x_i \le -s_j^x, \forall (i,j) \in E_h,$$

and

$$\max(y_{n+1}) \text{ such that } y_j - y_i \le -s_j^y, \forall (i,j) \in E_v.$$

Proof. Given the property that $G(V,E)$ is a directed acyclic graph the longest path problem can be solved as shortest path problem with non-positive edge weights. The critical path problem for a directed acyclic graph $G(V,E)$ with the source s, the sink t and non-negative edge weights c_{ij} can be formulated as the following dual of a shortest path linear program [12]: $\max(\pi_t - \pi_s)$ such that *shortest path optimality conditions* hold: $\pi_j - \pi_i \le c_{ij}$, $\forall (i,j) \in E$. The claim holds for $\pi_t := x_{n+1}, \pi_s := x_0 = 0, \pi_i := x_i, \pi_j := x_j, c_{ij} := -s_j^x, E := E_h$ and $\pi_t := y_{n+1}, \pi_s := y_0 = 0, \pi_i := y_i, \pi_j := y_j, c_{ij} := -s_j^y, E := E_v$, respectively. □

We now show that solving the linear relaxation of a partial solution s with fixed orientations in the MIP model has the same effect on the objective as solving the longest path problems for the directed acyclic graphs of the partial solution within the meta-CSP model. Hence, both models provide the same lower bound for the objective function f.

Theorem 3. *Let s be a partial solution for RWPO with fixed orientations, i.e. without loss of generality $o_i = 0, \forall i \in \mathcal{I}$. Then the objective function value $f^{LP}(s)$ for the linear relaxation for s in the MIP model is equal to the objective function value $f^{CP}(s)$ resulting from the critical path problems for the graphs $G_h(V,E_h)$ and $G_v(V,E_v)$ for s in the meta-CSP model, i.e.,*

$$f^{LP}(s) = f^{CP}(s).$$

Proof. Given the partial solution s we have the following remaining linear relaxation for s in the MIP:

$$\begin{aligned}
&(22) && \min\ f \quad , \text{ subject to} && \\
&(23) && x_i + w_i \le W, && \forall i \in \mathcal{I}, \\
&(24) && W \le W_{\max}, && \\
&(25) && y_i + h_i \le H, && \forall i \in \mathcal{I}, \\
&(26) && H \le H_{\max}, && \\
&(27) && x_i + w_i \le x_j, && \forall (i,j) : z_{ij}^1 = 1, \\
&(28) && x_j + w_j \le x_i, && \forall (i,j) : z_{ij}^2 = 1, \\
&(29) && y_i + h_i \le y_j, && \forall (i,j) : z_{ij}^3 = 1, \\
&(30) && y_j + h_j \le y_i, && \forall (i,j) : z_{ij}^4 = 1, \\
&(31) && x_i + w_i \le x_j + (1 - z_{ij}^1) W_{\max}, && \forall (i,j) : z_{ij}^1 \ne 1, \\
&(32) && x_j + w_j \le x_i + (1 - z_{ij}^2) W_{\max}, && \forall (i,j) : z_{ij}^2 \ne 1, \\
&(33) && y_i + h_i \le y_j + (1 - z_{ij}^3) H_{\max}, && \forall (i,j) : z_{ij}^3 \ne 1, \\
&(34) && y_j + h_j \le y_i + (1 - z_{ij}^4) H_{\max}, && \forall (i,j) : z_{ij}^4 \ne 1, \\
&(35) && 1 \le z_{ij}^1 + z_{ij}^2 + z_{ij}^3 + z_{ij}^4, && \\
&(36) && z_{ij}^1 + z_{ij}^2 \le 1, && \\
&(37) && z_{ij}^3 + z_{ij}^4 \le 1, && \forall i,j \in \mathcal{I}, i < j, \\
&(38) && x_i \ge 0, && \\
&(39) && y_i \ge 0, && \forall i \in \mathcal{I}.
\end{aligned}$$

The containment constraints (23-26) and the non-negativity constraints (38-39) can be disregarded in the following, as these constraints are equivalent in the MIP and meta-CSP model.

First, we show that $f^{\mathrm{LP}}(s) \le f^{\mathrm{CP}}(s)$. Given the solution s in the meta-CSP model with $f^{\mathrm{CP}}(s)$, we transform the directed acyclic graphs $G_h(V, E_h)$ and $G_v(V, E_v)$ to shortest path linear programs for W and H as described in proof of Lemma 2. These two independent shortest path problems can be subsumed to one linear program which is equivalent to the dual linear program given by the objective (22) and the constraints (27-30). Let $Z_{IP} := \{z_{ij}^k : \text{integral in s}\}$ be all fixed binary variables that correspond to edges in the graphs of the meta-CSP model and $Z_{LP} := \{z_{ij}^k : \text{fractional in s}\}$ be all binary variables that are not integral yet.

In order to show that $f^{\mathrm{LP}}(s) \le f^{\mathrm{CP}}(s)$, it remains to prove that we can consistently assign values to Z_{LP} that satisfy constraints (31-37) without increasing the objective function $f^{\mathrm{LP}}(s)$. Without loss of generality, we can either assume $w_i + w_j \le W$ or assume $h_i + h_j \le H$ because otherwise there is no solution for the given W and H. For the horizontal direction and the constraints (31,32,36) we distinguish three cases for any rectangle pair (r_i, r_j) where $z_{ij}^k \in Z_{LP}, k \in \{1, 2\}$, the analogous argumentation holds for the vertical direction, $z_{ij}^k \in Z_{LP}, k \in \{3, 4\}$ and the constraints (33,34,37):

(1) The assignment Z_{IP} implies $x_i + w_i \le x_j$. In this case, we can consistently extend Z_{IP} with $z_{ij}^1 = 1, z_{ij}^2 = 0$ to satisfy the constraints (31,32,36) without increasing $f^{\mathrm{LP}}(s)$.

(2) The assignment Z_{IP} implies $x_j + w_j \leq x_i$. We can extend Z_{IP} with $z^1_{ij} = 0, z^2_{ij} = 1$ and satisfy the constraints (31,32,36) without increasing $f^{\mathrm{LP}}(s)$.

(3) The assignment Z_{IP} implies $x_i + w_i > x_j$ and $x_j + w_j > x_i$. The constraint (31) can be transformed to inequality $z^1_{ij} \leq 1 - \frac{x_i+w_i-x_j}{W_{\max}}$. The constraint (32) can be transformed to inequality $z^2_{ij} \leq 1-\frac{x_j+w_j-x_i}{W_{\max}}$. As $x_i+w_i > x_j$ and $x_j+w_j > x_i$ both the terms $\frac{x_i+w_i-x_j}{W} \geq \frac{x_i+w_i-x_j}{W_{\max}}$ and $\frac{x_j+w_j-x_i}{W} \geq \frac{x_j+w_j-x_i}{W_{\max}}$ range in $(0, 1)$. Adding the two transformed constraints results in $z^1_{ij} + z^2_{ij} \leq 2 - \frac{w_i+w_j}{W_{\max}}$. The term $\frac{w_i+w_j}{W} \geq \frac{w_i+w_j}{W_{\max}}$ ranges in $(0, 1]$ as we can assume $w_i + w_j \leq W$ without loss of generality. Hence, by assigning $z^1_{ij} = 1 - \frac{x_i+w_i-x_j}{W}$ and $z^2_{ij} = \min(1 - \frac{x_j+w_j-x_i}{W}, \frac{x_i+w_i-x_j}{W})$ we satisfy the constraints (31,32,36) without increasing $f^{\mathrm{LP}}(s)$.

Any combination of case (1) or (2) for the horizontal direction with any case of the vertical direction satisfies constraint (35). Also, any combination of case (1) or (2) for the vertical direction with any case of the horizontal direction satisfies constraint (35). Combining case (3) for the horizontal direction with case (3) for the vertical direction also satisfies constraint (35) for the following reasons:

- Suppose $\frac{x_i+w_i-x_j}{W} \leq 1 - \frac{x_j+w_j-x_i}{W}$ and $\frac{y_i+h_i-y_j}{H} \leq 1 - \frac{y_j+h_j-y_i}{H}$. Then $z^1_{ij} + z^2_{ij} + z^3_{ij} + z^4_{ij} = 2 > 1$.
- Suppose $\frac{x_i+w_i-x_j}{W} > 1 - \frac{x_j+w_j-x_i}{W}$ and $\frac{y_i+h_i-y_j}{H} \leq 1 - \frac{y_j+h_j-y_i}{H}$. Then $z^1_{ij} + z^2_{ij} + z^3_{ij} + z^4_{ij} = 3 - \frac{w_i+w_j}{W} > 1$.
- Suppose $\frac{x_i+w_i-x_j}{W} \leq 1 - \frac{x_j+w_j-x_i}{W}$ and $\frac{y_i+h_i-y_j}{H} > 1 - \frac{y_j+h_j-y_i}{H}$. Then $z^1_{ij} + z^2_{ij} + z^3_{ij} + z^4_{ij} = 3 - \frac{h_i+h_j}{H} > 1$.
- Suppose $\frac{x_i+w_i-x_j}{W} > 1 - \frac{x_j+w_j-x_i}{W}$ and $\frac{y_i+h_i-y_j}{H} > 1 - \frac{y_j+h_j-y_i}{H}$. Then $z^1_{ij} + z^2_{ij} + z^3_{ij} + z^4_{ij} = 4 - \frac{w_i+w_j}{W} - \frac{h_i+h_j}{H} > 1$.

Hence, constraint (35) is always satisfied and any consistent assignment to Z_{LP} does not increase $f^{\mathrm{LP}}(s)$.

Now, we show that $f^{\mathrm{CP}}(s) \leq f^{\mathrm{LP}}(s)$. Given the partial solution s in the MIP model with $f^{\mathrm{LP}}(s)$ we can disregard any variable of Z_{LP} and the constraints (31-37) without increasing $f^{\mathrm{LP}}(s)$. We concentrate on the linear program given by the variables Z_{IP} and build up the graphs G_h and G_v of the meta-CSP model. An edge $e = (j, i)$ with edge weight $-w_i$ is introduced in G_h whenever the corresponding variable $z^1_{ij} = 1$. An edge $e = (i, j)$ with edge weight $-w_j$ is introduced in G_h whenever the corresponding variable $z^2_{ij} = 1$. Also, we introduce the source $n + 1$ and sink 0 as well as their in- and outgoing edges as described in section 3. In an analogous way the graph G_v is build with regard to the variables z^3_{ij} and z^4_{ij}. Let $P_h = (n + 1, \ldots, i, \ldots, 0)$ be a longest path in G_h and let $L(P)$ its length. Then the following inequalities hold,

$$x_i + w_i \leq x_j, \forall (i, j) \in P_h.$$

This implies $0 \leq x_0 + \sum_{i\in P_h\setminus\{n+1\}} w_i = \sum_{i\in P_h\setminus\{n+1\}} w_i = L(P_h) \leq x_{n+1} \leq W$. Therefore, the inequality $W \geq L(P_h)$ holds. The same argumentation holds for the graph G_v and we get the inequality $H \geq L(P_v)$. It follows that $f^{\mathrm{LP}}(s) \geq W + H \geq L(P_h) + L(P_v) = f^{\mathrm{CP}}(s)$.

In conclusion, $f^{\mathrm{LP}}(s) \leq f^{\mathrm{CP}}(s)$ and $f^{\mathrm{CP}}(s) \leq f^{\mathrm{LP}}(s)$ imply that $f^{\mathrm{LP}}(s) = f^{\mathrm{CP}}(s)$. □

Corollary 4. *It is useless to integrate the linear relaxation of the MIP model as a slave lower bound generator within a master meta-CSP model, as both models provide the same lower bound.*

6. Numerical Results

We implemented our extended meta-CSP approach with the generalized techniques in Ilog Solver 6.5 and the MIP model in Ilog Cplex 11.1. For a fair comparison we applied the same symmetry breaking in both models. We tested the models on problem instances of size $n = 5, \ldots, 27$ with rectangles whose sizes are inspired by electronic devices typically found in SiPs. The details of the test instances are specified in the appendix. We impose a runtime limit of 600 CPU seconds.

Table 1 shows that the variable ordering (o, C) and (C_{ij}, o_i, o_j) lead to similar runtimes in many cases. However, for $n = 10$ and $n = 15$ the runtimes are significantly faster for our variable ordering (C_{ij}, o_i, o_j).

Runtime CPU sec.		
n	(C_{ij}, o_i, o_j)	(o, C)
5	0,07	0,09
6	0,11	0,09
7	0,34	0,44
8	5,34	5,95
9	0,31	0,84
10	7,23	32,86
11	–	–
12	–	–
13	125,69	104,39
14	–	–
15	349,98	–

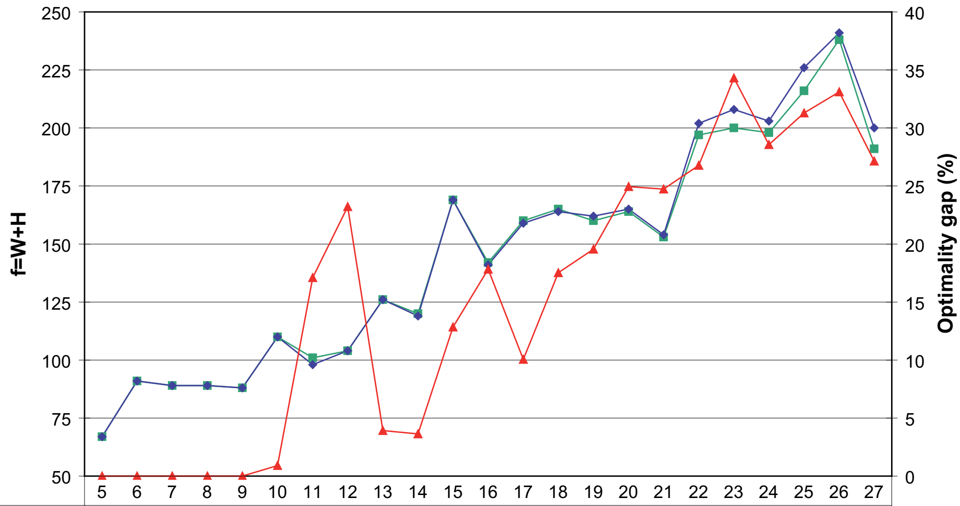
Table 1. Runtimes (<600 CPU sec.) to prove optimality for the variable ordering (C_{ij}, o_i, o_j) and (o, C) with our extended meta-CSP approach.

Runtime CPU sec.		
n	meta-CSP	MIP
5	0,07	0,03
6	0,11	0,44
7	0,34	9,42
8	5,34	175,98
9	0,31	19,69
10	7,23	–
11	–	–
12	–	–
13	125,69	–
14	–	–
15	349,98	–

Table 2. Runtimes (<600 CPU sec.) to prove optimality with our extended meta-CSP approach and with our mixed-integer program.

Table 2 shows that our approach outperforms the MIP in proving optimality. This is due to good initial upper bounds for f from the greedy heuristic and constraint propagation which shrinks the search tree. Our approach is significantly faster than the MIP which already fails for $n \geq 10$ to find optimal solutions or to prove optimality. Our approach also solves to optimality for $n = 10, 13, 15$ within the runtime limit. The solution quality is comparable for $n \leq 21$ but solutions of our approach are considerably better for $n \geq 22$ (see figure 10).

Furthermore, we tested our approach on a real world electronic circuit called eGrain, a tiny, autonomous and functional unit with flexible communication possibilities. eGrain is developed at the Fraunhofer Institute for Reliability and Microintegration (IZM), Berlin, and integrated as an SiP. Figure 11 illustrates the resulting placement of our approach. The greedy heuristic finds this placement after 83,19 CPU seconds and the exhaustive search could not further improve it within the runtime limit.



	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
meta-CSP	67	91	89	89	88	110	101	104	126	120	169	142	160	165	160	164	153	197	200	198	216	238	191
MIP	67	91	89	89	88	110	98	104	126	119	169	141	159	164	162	165	154	202	208	203	226	241	200
MIP Gap	0	0	0	0	0	0,9	17	23	3,9	3,6	13	18	10	18	20	25	25	27	34	29	31	33	27

Number of rectangles

FIGURE 10. Values for f and optimality gap for the MIP.

7. Conclusion

We extend the meta-CSP approach to RWPO where orientations are allowed. Therefore, we are flexible enough to instantiate the C_{ij} and o_i in any order and propagate between C_{ij}, o_i, x_i and y_i whenever possible. We show that the meta-CSP approach is similar to an MIP formulation but produces a smaller search tree due to constraint propagation.

In future work we will introduce a second objective for the wiring of the SiP components in order to use it for SiP design automation.

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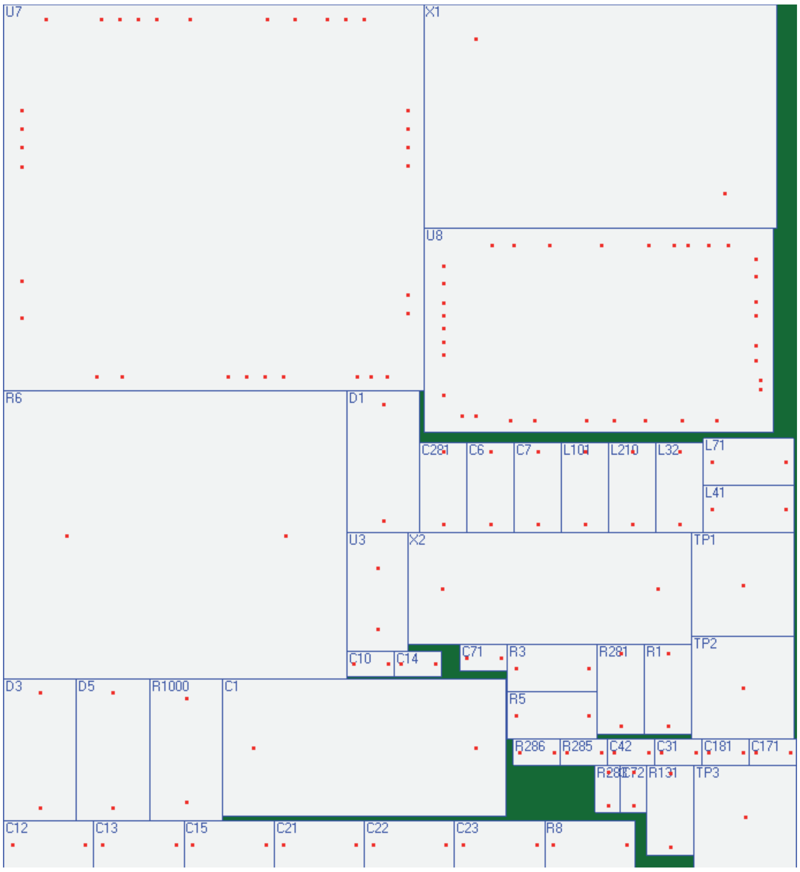

FIGURE 11. Placement of our extended meta-CSP approach for the SiP eGrain.

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Appendix A

In table 3 we list the test instances used in the computational evaluation of our methods.

n	List of rectangles $r_i = (w_i, h_i)$
5	(23,16),(10,20),(10,20),(8,16),(10,20)
6	(16,18),(5,10),(14,28),(14,28),(14,28),(14,28)
7	(23,14),(10,20),(9,18),(10,20),(14,28),(14,28),(9,18)
8	(24,13),(13,26),(10,20),(9,18),(13,26),(9,18),(9,18),(10,20)
9	(12,24),(8,16),(8,16),(15,30),(15,30),(8,16),(8,16),(6,12),(6,12)
10	(13,15),(26,19),(9,18),(12,24),(12,24),(9,18),(12,24),(12,24),(14,28),(14,28)
11	(24,11),(18,15),(9,18),(9,18),(9,18),(11,22),(11,22),(9,18),(9,18),(13,26),(9,18)
12	(11,21),(16,19),(10,20),(10,20),(9,18),(10,20),(11,22),(9,18),(11,22),(9,18),(10,20),(11,22)
13	(47,47),(14,25),(29,13),(5,10),(5,10),(5,10),(5,10),(5,10),(9,18),(9,18),(5,10),(5,10),(9,18)
14	(41,41),(16,13),(19,11),(22,26),(5,10),(5,10),(8,16),(5,10),(5,10),(8,16),(8,16),(6,12),(5,10),(5,10)
15	(52,52),(24,21),(27,27),(13,14),(6,12),(13,26),(13,26),(13,26),(13,26),(13,26),(13,26),(6,12),(13,26),(6,12),(6,12)
16	(47,47),(15,16),(19,26),(17,11),(8,16),(8,16),(7,14),(9,18),(8,16),(8,16),(9,18),(9,18),(8,16),(8,16),(9,18),(7,14)
17	(49,49),(16,17),(27,21),(22,21),(7,14),(7,14),(8,16),(7,14),(15,30),(8,16),(7,14),(8,16),(7,14),(8,16),(15,30),(15,30),(7,14)
18	(52,52),(12,28),(28,27),(15,23),(8,16),(7,14),(7,14),(12,24),(12,24),(8,16),(7,14),(8,16),(12,24),(8,16),(7,14),(8,16),(8,16),(12,24)
19	(52,52),(26,17),(13,22),(24,12),(17,20),(10,20),(10,20),(8,16),(7,14),(7,14),(7,14),(8,16),(10,20),(7,14),(10,20),(10,20),(10,20),(7,14),(8,16)
20	(44,44),(26,27),(20,17),(11,18),(21,18),(10,20),(10,20),(11,22),(11,22),(10,20),(8,16),(11,22),(8,16),(11,22),(11,22),(8,16),(8,16),(8,16),(11,22),(8,16)
21	(42,42),(20,20),(14,11),(25,12),(13,12),(8,16),(8,16),(12,24),(8,16),(8,16),(8,16),(8,16),(8,16),(12,24),(8,16),(8,16),(12,24),(8,16),(8,16),(8,16),(12,24)
22	(51,51),(29,20),(24,11),(25,12),(22,13),(14,28),(14,28),(15,30),(15,30),(15,30),(5,10),(5,10),(14,28),(15,30),(15,30),(5,10),(15,30),(14,28),(5,10),(5,10),(15,30),(14,28)
23	(40,40),(18,29),(17,25),(29,19),(13,29),(23,22),(11,22),(15,30),(11,22),(11,22),(11,22),(15,30),(11,22),(15,30),(15,30),(11,22),(11,22),(15,30),(11,22),(15,30),(11,22),(11,22),(11,22)
24	(49,49),(25,18),(20,13),(10,21),(26,11),(16,28),(12,24),(13,26),(13,26),(11,22),(13,26),(11,22),(12,24),(13,26),(11,22),(12,24),(13,26),(13,26),(12,24),(11,22),(11,22),(12,24),(11,22),(11,22)
25	(49,49),(42,42),(22,16),(29,27),(13,16),(19,21),(23,24),(10,20),(15,30),(15,30),(15,30),(15,30),(7,14),(7,14),(10,20),(10,20),(10,20),(15,30),(10,20),(15,30),(10,20),(7,14),(7,14),(15,30),(7,14)
26	(45,45),(46,46),(29,23),(29,25),(11,17),(15,27),(24,18),(14,28),(12,24),(14,28),(14,28),(14,28),(14,28),(12,24),(14,28),(14,28),(12,24),(14,28),(14,28),(14,28),(12,24),(12,24),(14,28),(14,28),(12,24),(12,24)
27	(51,51),(40,40),(11,24),(23,10),(12,17),(22,13),(16,13),(6,12),(6,12),(6,12),(15,30),(6,12),(7,14),(7,14),(15,30),(7,14),(7,14),(6,12),(6,12),(6,12),(7,14),(7,14),(7,14),(15,30),(15,30),(15,30),(6,12)

Table 3. Test instances for the computational evaluation.

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