Unified Arbitrary Rectilinear Block Packing and Soft Block Packing Based on Sequence Pair

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ABSTRACT

To the best of our knowledge, this is the first algorithm unifying arbitrary rectilinear block packing and soft block packing. Furthermore, this algorithm handles arbitrary convex or concave rectilinear block packing in the most efficient way compared to other sequence pair-based approaches. At the same time, the algorithm can handle rectangle soft block effectively. The concept of non-redundant constraint graph together with its algorithms play critical role in unifying the arbitrary rectilinear block packing and soft block packing. This general block packing tool builds the foundation for floorplanning with IP reuse. The experimental results demonstrate the efficiency and effectiveness of this general block packing.

Keywords: floorplan, block packing, soft block, rectilinear block, sequence pair, non-redundant constraint graph, related-vertics-grouped constraint graph, feasible slack, bottleneck path, simulated annealing.

I. Introduction

Due to the rapid scaling of circuit size and increasing complexity of IC design, design reuse has become of great interest of the design community. As the IP blocks to be reused are not often of rectangle shapes, good packing algorithm for floorplans with arbitrary rectilinear (hard) blocks is desired. On the other hand, as many blocks have not been detailedly designed in the early floorplanning stage, shape flexibility is to be exploited to improve the floorplanning quality, and good algorithm for floorplans with soft (rectangle) block is demanded. Several works have been done in each of the two areas ([1], [2], [3] for arbitrary rectilinear block packing; [4], [5] for soft block packing with general non-slicing structure), but no method accommodating both of the two aspects have been proposed so far. By addressing this problem, this paper makes the following major contributions: (1) It proposes a new technique for evaluating sequence pair; (2) It re-designs the rectilinear block packing algorithm and soft block packing algorithm and unifies them together, based on some existing techniques and more importantly, several new observations of the rectilinear/soft block packing properties; (3) It extends the existing stochastic moves to be more globally.

The following of this paper is organized as follows: Section II briefly introduces the sequence pair structure. Section III describes in details the new method of evaluating SP. Section IV and section V describe the rectilinear block packing and soft block packing algorithms, respectively. Section VI describes the extended stochastic moves. Section VII presents the experimental results and section IX gives some concluding remarks.

II. Sequence Pair (SP) Structure

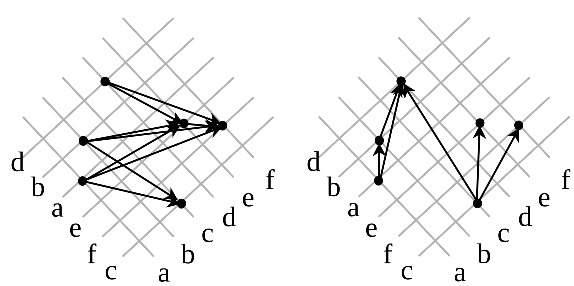
A sequence pair for a set of *n* rectangle blocks is a pair of permutations of the *n* block names [6]. For example, (*d b a e f c, a b c d e f*) is a sequence pair of the block set {*a, b, c, d, e, f*}.

The topological constraint between every pair of blocks *x*, *y* is defined as follows:

H-constraint: (.. *x* .. *y* .. , .. *x* .. *y* ..) ⇒ *x* is left of *y*

V-constraint: (.. *y* .. *x* .. , .. *x* .. *y* ..) ⇒ *x* is below *y*

Given a sequence pair, a compacted packing of the blocks can be obtained by using the directed acyclic H/V-constraint graphs G_h / G_v which are constructed faithfully to the H/V-constraint described above. That is to say, for every pair of blocks *x*, *y*, if *x* is left of *y*, we add an edge (*x*, *y*) to G_h; if *x* is below *y*, we add an edge (*x*, *y*) to G_v. Moreover, there is a source s_h / s_v connected to each leftmost / lowest block and a sink t_h / t_v connected to each rightmost / upmost block in G_h / G_v. Fig 1 shows an example. The weight of the each vertex in G_h / G_v is the width / height of the corresponding block. The X/Y-coordinate of each block can be determined by the length of the longest path from the source s_h / s_v to the corresponding vertex in G_h / G_v.



(a) G_h (b) G_v

Fig 1 Constraint Graphs of Sequence Pair

III. Non-redundant Constraint Graph

Sequence Pair defines a "left/right" or "below/above" relation between every pair of blocks. So the union of the complete horizontal constraint graph G_h and the complete vertical constraint graph G_v has $C(n, 2) = n(n\text{-}1)/2$ edges. A quick glance at the graphs in Fig 1 shows that some edges (e.g. (a, f) in G_h, (a, d) in G_v) are redundant. In general, a horizontal edge between two vertics v_i and v_j doe not need to be present if there is another path from v_i and v_j passing one or more other vertics. And we define such edge as *redundant edge*. Specifically, if there is an edge from v_i to v_k and from v_k to v_j, then the left/right constraint between v_i and v_j is implicitly endured by the transition. So the edge (v_i, v_j) can be removed without changing any constraint defined by the SP. A constraint graph with all redundant edges removed is called a *non-redundant constraint graph*.

As the time of calculating the longest path for each block is linear to the number of edges in the graph, removing those redundant edges will result in a significant reduction of time in evaluating a SP. Next we will show how to build such non-redundant constraint graph G_h^* and G_v^* from a given SP in the time linear to the total number of edges in G_h^* and G_v^*.

Given a SP (Γ_+, Γ_-), we will build G_h^* and G_v^* simultaneously by finding all the immediate left-predecessors and below-predecessors for each block. As we know, if block a is left of or below block b, a precedes b in Γ_-. Therefore, for each block b, we only need to consider the blocks preceding b in Γ_-. And naturally we should process all the blocks in the order given by Γ_-. Without loss of generality, we assume that $\Gamma_- = (a_1\ a_2 \ldots a_n)$. Then the algorithm goes as follows:

First we see how to get a pair of redundancy-reduced constraint graph G_h' and G_v' which are equivalent to G_h and G_v in terms of the topological constraints they define.

(1) a_1 has no predecessor in G_h' or G_v';

(2) Suppose we are done for all a_k ($k<i$). Then for a_i:

i. let $j = i–1$;

ii. compare Γ_+ (a_i) (the index of block a_i in Γ_+) and Γ_+ (a_j) to decide whether a_j is left of or below a_i, and add an edge (a_j, a_i) to G_h' or G_v' accordingly. Suppose a_j is left of / below a_i. Then we check whether a_j has any predecessor in current G_v' / G_h'. If not, stops; otherwise, we pick up its below-predecessor / left-predecessor with the highest index in Γ_-, a_k. Let $j = k$, goto ii again.

Fig 2 Algorithm RRCG

Lemma 1 The constraint graph G_h' and G_v' output by algorithm RRCG is equivalent to the SP which it is built from in terms of topological constraints.

Proof As G_h' and G_v' are subsets of G_h and G_v, respectively, G_h' and G_v' do not alter any topological constraint defined by the corresponding SP. If we can prove that G_h' and G_v' do not reduce any topological constraint defined by the corresponding SP either, the proof is obviously done. For the latter, we only need to show that for any block a_i, it's reachable from any of the blocks preceding it in Γ_- in either G_h' or G_v', which means the topological relation between any pair of blocks is given by G_h' and G_v'.

Without loss of generality, we assume that $a_{i–1}$ is left of a_I, as shown in Fig 3(a). All blocks preceding a_i in Γ_- are either in region I or in region II of the constraint graph. As all blocks in region I can reach $a_{i–1}$ in G_h', they can also reach a_i in G_h' through the edge ($a_{i–1}$, a_i). Let us consider blocks in region II. If $a_{i–1}$ has no predecessor in G_v', then region II contains no block, we are done. Otherwise, let a_k be the predessor of $a_{i–1}$ in G_v' with largest index in Γ_-. a_k is either left of or below a_i.

(i) a_k is left of a_i : As shown in Fig 3(b), there is an edge (a_k, a_i) in G_h' according to the algorithm RRCG. All blocks in region II(a) can reach a_k in G_h', so they can also reach a_i in G_h' through the edge (a_k, a_i). Region II(b) must contain no block, otherwise a_k can not be the predessor of a_{i-1} in G_v' with largest index in Γ_-. We are left with Region II(c). The problem is reduced to a smaller size than that in Fig 3(a).

(ii) a_k is below a_i : As shown in Fig 3(c), there is an edge (a_k, a_i) in G_v' according to the algorithm RRCG. Again, region II(b) contains no block. All blocks in region II(c) can reach a_k in G_v', so they can also reach a_i through the edge (a_k, a_i). Now for region II(a). If a_k has no predecessor in G_h', then region II(a) contains no block, we are done. Otherwise, let a_j be the predecessor of a_k in G_h' with largest index in Γ_-, as shown in Fig 3(d). Again, a_j is either left of or below a_i. For the former case, we are left with region II(a)-1; for the latter case case, we are left with region II(a)-2. In both case the problem is reduced to a smaller size than that in Fig 3(c).

Therefore by deduction we can prove that any block preceding block a_i in Γ_- can reach it either by a horizontal path in G_h' or by a vertical path in G_v'.

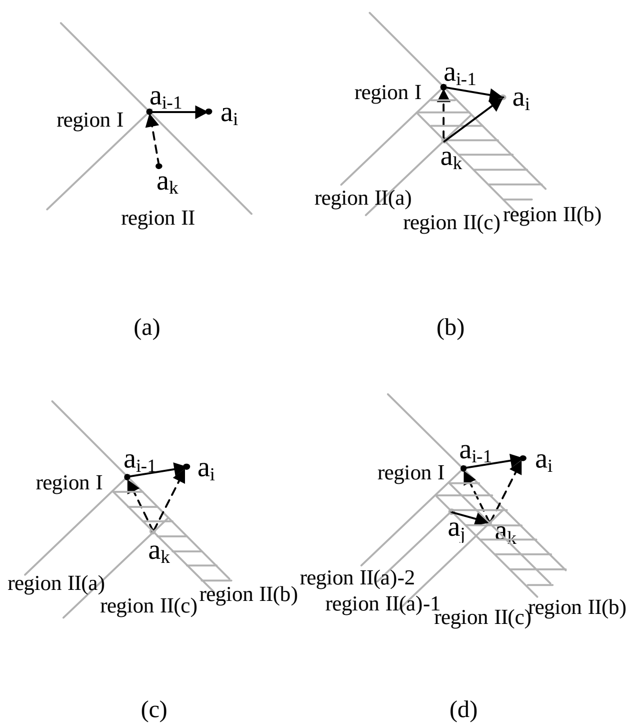


Fig 3 Illustration of Proof for Lemma 1 (A solid line represents a horizontal edge and a dashed line represents a vertical edge)

By the algorithm RRCG, we can obtain a pair of graphs G_h' and G_v' equivalent to but smaller than G_h and G_v. But it may still contain some redundant edges in the case shown in Fig 4. Block *f* is left of block *h*; block *c* is *f*'s rightmost below-predecessor in G_v' and *c* is below *h*; *b* is *c*'s upmost left-predecessor in G_h'. As *b* may be left of *f*, in which case *b* can reach *h* through the path from *b* to *f* and the the edge (*f*, *h*), so edge (*b*, *h*) may be a redundant edge.

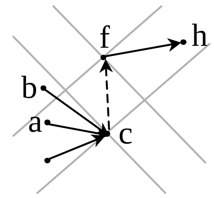


Fig 4 Illustration of Selecting Predecessors

To avoid adding an edge (b, h) in $G_h{}'$ in such case, we modify the algorithm RRCG and get the non-redundant constraint graph G_h^* and G_v^* as follows:

(1) a_1 has no predecessor in G_h^* or G_v^*;
(2) Suppose we are done for all a_k ($k<i$). For a_i:
i. let $j = i-1$, last_dir = no_def, last_blk = no_def;
ii. compare Γ_+ (a_i) and Γ_+ (a_j) to decide whether a_j is left of or below a_i, add an edge (a_j, a_i) to G_h^* or G_v^*, and record the direction of this iteration as 'h' or 'v' accordingly. If the direction of last iteration is not 'no_def' and is different from the direction of this iteration, then modify the reference-block to be the a_j of last iteration. Suppose a_j is left of/below a_i. Then we check whether a_j has any predecessor in current G_v^*/ G_h^* which is not below/left-of the reference-block (if the reference-block is no_def, we just ignore this requirement). If not, stops; otherwise, we pick up the one among them with the highest index in Γ_-, a_k. Let $j = k$, goto ii again.

Fig 5 Algorithm NRCG

Lemma2 The constraint graph G_h^* and G_v^* output by algorithm NRCG is equivalent to the SP which it is built from in terms of topological constraints.

This is easy to prove following the line of thought in the proof of Lemma 1. The details are omitted here due to the limit of space.

Lemma3 Algorithm NRCG does not produce any redundant edge in either G_h^* or G_v^*.

Proof Take the example in Fig 4. Suppose $a_i = h$, $a_j = c$ now and block a is block c's left-predecessor in G_h^* which is not left-of (i.e. is below) block f with the largest index in Γ_-. Suppose no redundant edge has been produced so far, then the edge (a, h) is not redundant either, in either of the two cases:
(i) a is left of h. If edge (a, h) is redundant in G_h^*, there must be another block g such that the path from a to g and the path from g to h already exist in G_h^*. As the reference block f is the last block before changing direction again, all blocks visited after f (up till c) are below h. So block g can not be any of them; g is not f either, for a is below f. So g must have higher index in Γ_- than f, and be either right of or above f. g can not be right f, otherwise (f, h) is redundant. g can not be above f either, otherwise g is above a the same as f. So block g can not exist, and edge (a, h) is not redundant.
(ii) a is below h. If edge (a, h) is redundant in G_v^*, there must be another block g such that the path from a to g and the path from g to h already exist in G_v^*. g is not c, for c is right of a. So g must have higher index in Γ_- than c, and be either right of or above c. g can not be above c, otherwise (c, h) is redundant. g can not be right of c either, otherwise g is right of a the same as c. So block g can not exist, and edge (a, h) is not redundant.

Lemma 4 Algorithm NRCG output G_h^* and G_v^* in time linear to $(|E_h^*| + |E_v^*|)$.

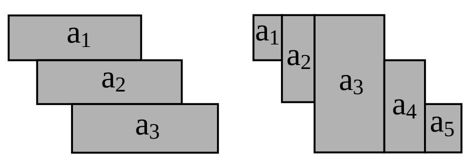
Proof The main operations in this algorithm are comparisons of two blocks' indics in Γ_+ to decide their topological relation. Each comparison belongs to either of the two classes: (1) It leads to an edge to be added to G_h^* or G_v^*; (2) It is used in selecting a proper left/below-predecessor of a block to continue the process, but does not yield an edge in G_h^* or G_v^*. The total number of comparisons in the 1st class is obviously the total number of edges in G_h^* and G_v^*. It can be proved that the total number of comparisons in the 2nd class is no more than the total number of edges in G_h^* and G_v^*, for there is an injection from the set of comparisons in the 2nd class to the set of edges in G_h^* and G_v^*. The detailed proof is omitted here due to the limit of space.

Apart from reducing the evaluation time remarkably, the main significance of this approach lies in that it makes it very convenient for building the related-vertics-grouped constraint graph in the following rectilinear block packing algorithm and finding a bottleneck path in the following soft block packing algorithm (both of which are critical steps in the corresponding algorithms) and therefore serves as the basis of the whole unified rectilinear/soft block packing algorithm.
For convenience we will refer to the non-redundant constraint graphs G_h^* and G_v^* as G_h and G_v in the following sections.

IV. Efficient Arbitrary Rectilinear Block (Convex & Concave) Packing

1. Fundamentals of rectilinear block packing

Up to the present the rectilinear block packing problem is dealt with mostly by partitioning each rectilinear block A into a set of rectangle sub-blocks, representing them individually, and packing the mixture of these rectangle sub-blocks and original rectangle blocks by some existing rectangle packing algorithms. Fig 6(a) and Fig 6(b) give examples of horizontal partitioning and vertical partitioning, respectively. A representation of a rectilinear packing by SP is therefore a pair of permutations of all the unit block (rectangle sub-block or original rectangle block) names.



(a) (b)

Fig 6 H/V-partition of A Rectilinear Block

Certain measures need to be taken to guarantee the relative positions of sub-blocks of a same rectilinear block so that this rectilinear block can keep its original shape after the packing process (a SP satisfying this need is called a feasible SP). A most notable measure is to apply the three necessary sufficient conditions of the feasibility of SP, as proposed in [1].
Condition-1: For any H-partitioned / V-partitioned block A, the permutation pair of A equals the H-Pair / V-Pair of A.
Condition-2: Any two unit blocks $a_i, a_j \in A$ are not interrupted by a unit block $c \notin A$.
Condition-3: Any two pairs of unit blocks $a_i, a_j \in A$ and $b_p, b_q \in B$, $A \neq B$, (a_i, a_j) separates (b_p, b_q) in the first or second sequence.

Where the unit block relations "interrupt" and "separate" are defined as:

• Given three unit blocks a_i, $a_j \in A$ and $c \notin A$, if c is between a_i and a_j in both sequences, e.g. (a_i c a_j, a_i c a_j), we call *c interrupts* a_i and a_j.

• Given two pairs of unit blocks a_i, $a_j \in A$ and b_p, $b_q \in B$, $A \neq B$, if in the $1^{st}/2^{nd}$ sequence: a_i .. a_j .. b_p .. b_q or b_p .. b_q .. a_i .. a_j, we (a_i, a_j) and (b_p, b_q) as *separates* of each other in the $1^{st}/2^{nd}$ sequence.

2. Packing rectilinear blocks based on a related-vertics-grouped constraint graph

In SP-based rectilinear block packing, as SP only defines the topological constraints among all the unit blocks (including both original rectangle blocks and rectangle sub-blocks of rectilinear blocks), the constraint graph built from SP doesn't contain information about how the sub-blocks of a same rectilinear block should be placed relative to each other. Therefore the packing obtained from such constraint graph needs a post-process alignment to adjust the positions of the unit blocks such that the relative positions of each rectilinear block's sub-blocks conform to its initial shape and the topological constraints among all unit blocks are preserved. Such separate compaction and alignment makes it difficult for shape optimization of floorplans containing rectilinear blocks. In the following we will show how to bypass this difficulty by a new method of rectilinear packing, where we construct a pair of smaller sized non-redundant constraint graphs G_h' and G_v' from the original non-redundant constraint graphs G_h and G_v, and calculate the position of each rectangle/rectilinear block based on this G_h' and G_v'. G_h' and G_v' not only give the topological constraints among all the unit blocks, but also implies the relative positions of the sub-blocks of a same rectilinear block.

We get G_h' and G_v' by grouping all vertics in G_h and G_v representing sub-blocks of a same rectilinear block together and representing the whole rectilinear block by a single vertex in G_h' and G_v'. Therefore we call them *related-vertics-grouped constraint graphs*. The edges in G_h' will be obtained in the following way:

For each edge (v_p, v_q) in G_h,

(i) If both v_p and v_q represent original rectangle blocks a and b, we add an edge (a, b) in G_h' and the weight remains the same;

(ii) If v_p represents a sub-block a_i of rectilinear block A, v_q represents an original rectangle block b, we add an edge (A, b) in G_h' if it's not present in G_h' yet, and the weight is $dx(a_i)+w(a_i)$; otherwise, we update the weight of the existing edge with $max(old\_weight, dx(a_i)+w(a_i))$. Where $dx(a_i)$ is the horizontal distance from the bottom-left corner of a_i to the bottom-left corner of the bounding box of A under current orientation of A, $w(a_i)$ is the width of a_i;

(iii) If v_p represents represents an original rectangle block b, v_q represents a sub-block a_i of rectilinear block A, we add an edge (b, A) in G_h' if it's not present in G_h' yet, and the weight is $w(b)–dx(a_i)$; otherwise, we update the weight of the existing edge with $max(old\_weight, w(b)–dx(a_i))$;

(iv) If v_p represents a sub-block a_i of rectilinear block A, v_q represents a sub-block b_j of another rectilinear block B, we add an edge (A, B) in G_h' if it's not present in G_h' yet, and the weight is $dx(a_i)+w(a_i)–dx(b_j)$; otherwise, we update the weight of the existing edge with $max(old\_weight, dx(a_i)+w(a_i)–dx(b_j))$;

(v) If v_p and v_q represent two sub-blocks a_i and a_j of a same rectilinear block A, we add an edge (A, A) in G_h' if if it's not present in G_h' yet and the weight $dx(a_i)+w(a_i)–dx(a_j)$ is not zero.

Then, we add an edge from the horizontal s_h source to every block in G_h' and the weight is zero. This is not significant in rectangle block packing, but it's indispensable here. It is to prevent the coordinate of any block from being negative. Look at the example show in Fig 7. As b is left of a_2,

b is left of A in G_h'. Therefore b's x-coordinate is calculated before A. As b's x-coordinate is zero and A's relative position to b is negative, A's x-coordinate is going to be negative without an edge (s_h, A) in G_h' with weight zero.

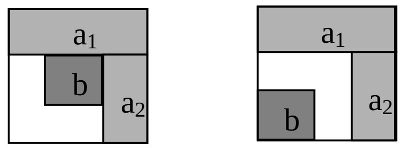


Fig 7 Illustration of Why Edges Connected to Source is Needed

The edges in G_v' can be obtained similarly.
After G_h' and G_v' are drawn, we derive corresponding horizontal and vertical topological orders from them, and then we can get the location of each block (either rectangle or rectilinear) by applying the longest path algorithm to G_h' and G_v' in such orders.

Lemma 5 The algorithm described above can achieve simultaneous compaction and alignment for rectilinear block packing.

Proof As we treat each rectilinear block as a whole, obviously the relative positions among sub-blocks of a same rectilinear block have been taken care of. Now let's prove that G_h' and G_v' have preserved the topological constraints contained in G_h and G_v. There must be no doubt about operation (i). Operations (ii), (iii) and (iv) are illustrated in Fig 8 (a), (b) and (c), respectively. In (a), there is an edge (a_1, b) in G_h, which means b must be right of a_1. Therefore the bottom-left corner of b must be right of the bottom-left corner of a_1 by the amount of at least $w(a_1)$. This is equivalent to the constraint that the bottom-left corner of b must be right of the bottom-left corner of the rectilinear block A by the amount of at least $dx(a_1)+w(a_1)$, for the bottom-left corner of every sub-block a_i to the bottom-left corner of the whole rectilinear block is always a constant $dx(a_i)$. In (b), there is an edge (b, a_2) in G_h, which means a_2 must be right of b. Therefore the bottom-left corner of a_2 must be right of the bottom-left corner of b by the amount of at least $w(b)$. This is equivalent to the constraint that the bottom-left corner of the rectilinear block A must be "right of" the bottom-left corner of block b by the amount of at least $w(b)–dx(a_2)$ for the reason as stated for Fig 8(a). Note that this value may be negative, which means rectilinear block A can be left of block b by the amount of at most $|w(b)–dx(a_2)|$. Combining the two facts together, we can easily defer the formula in (iv). And case (v) is similar to (iv). The operation in (v) is useful only for checking the feasibility of the corresponding SP. If the SP is feasible, no edge is added in (v), otherwise, a positive self-circle is added indicating the infeasibility of the SP.
And once we have this pair of related-vertics-grouped constraint graph G_h' and G_v', and the corresponding horizontal and vertical topological orders, we can apply the longest path algorithm to them just the same as in rectangle block packing, and get the x/y-coordinate of each rectilinear/rectangle block accordingly.

This constraint graph can also easily tell whether the corresponding sequence pair is feasible:

Lemma 6 A sequence pair is feasible if and only if its corresponding related-vertics-grouped constraint graphs G_h' and G_v' contain no positive circle.

The detailed proof is omitted here due to the limit of space. This lemma is valid for the cases of both convex and concave rectilinear block packing. For convex rectilinear block packing, it is equivalent to the three necessary and sufficient conditions given by [1] as described in the previous sub-section. Condition-1 is satisfied if and only if either $G_h{}'$ or $G_v{}'$ contains no self-circle. Condition-2 and condition-3 are satisfied if and only if either $G_h{}'$ or $G_v{}'$ contains no circle among any two or more blocks.

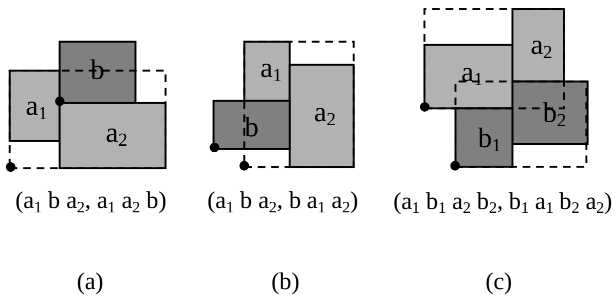


Fig 8 Simultaneous Compaction and Alignment

This rectilinear block packing approach is very critical to the unified rectilinear/soft block packing system. Compared to the approach in [1], it achieves simultaneous compaction and alignment, and therefore solves the dilemma between post-alignment of rectilinear blocks and shape optimization of soft blocks. Compared to the approach in [3], first, it decreases the size of the problem by reducing the total number of vertics in the constraint graph instead of increasing the problem size by increasing the total number of edges in the constraint graph as done in [3]. Second, and more importantly, although [3] achieves simultaneous compaction and alignment too, it still represents the sub-blocks of a rectilinear block individually in the constraint graph; in contrast our approach represents the rectilinear block as a whole by one vertex and therefore the rectilinear block can be treated virtually as a rectangle block in the soft block packing. This makes it very easy to integrate rectilinear block packing with soft block packing.

V. Enhanced Soft Block Packing

1. Fundamentals of soft block packing

The soft block packing problem is to optimize packing topology as well as the block shapes to achieve minimum total packing area. The key issue is how to optimize the block shapes for a given topology. An attractive approach for this is proposed by [4], where the block shapes are gradually adjusted to reduce the overall height and overall width alternatively and monotonously for a given topology. This strategy is illustrated by Fig 9.

A greedy algorithm is applied to perform each step of overall height reduction and overall width reduction based on a metric called *slack*. For the SP structure, the horizontal slack of a block b can be given as:

$$sl_b = l(s_h, t_h) - l(s_h, v_i) - l(v_i, t_h) - w(b)$$

where s_h and t_h are the horizontal source and sink, respectively; and v_i is the vertex representing block b in G_h. A block whose horizontal / vertical slack is zero is called *h-critical / v-critical* block.

The horizontal maximal slack $sl_b{}'$ of a block b can be obtained by increasing the height of b until it becomes v-critical.

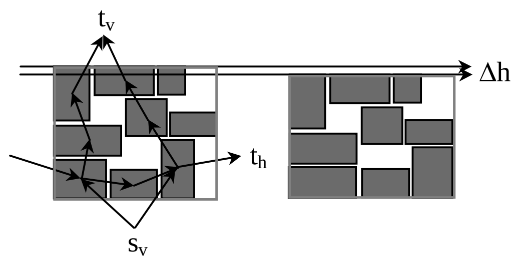


Fig 9 An Example of Reducing Overall Packing Height
Without Increasing Overall Packing Width

The following sufficient condition is used to meet the non-width-increase requirement:

$$\sum_{b \in p_h} \Delta w_b \leq sl'(p_h) \tag{1}$$

where the *maximal slack of a horizontal path p* is defined as:

$$sl'(p) = \min_{b \in p} sl_b'$$

And according to this sufficient condition (1), the horizontal source-to-sink path to yield maximum overall height reduction without overall width increase (denoted as bottleneck path) can be found as a path with maximum $\frac{sl'(p_h)}{num(p_h)}$, where *num(p_h)* denotes the number of blocks on the path.

Then the shape of each block on the bottleneck path will be adjusted according to the following formula:

$$\Delta w_b = sl'(p_h) \times \frac{w_b / h_b}{\sum_{b' \in p_h} w_{b'} / h_{b'}} \tag{2}$$

The height of each block will be reduced by approximately equal amount and so does the overall height.

The monotonous height reduction and width reduction will be carried out alternatively until no further reduction can be made.

2. Our algorithm

Our soft block packing follows the basic strategy presented in [4]. Yet we make certain improvement and a very important enhancement as described in the following.

Firstly, as we observed that among all blocks on a horizontal path, only those v-critical blocks are critical to the reduction of the overall height, so we only adjust the shapes of those v-critical blocks and leave the non-v-critical blocks alone. Experiments prove that by doing so we are able to obtain a greater amount of height reduction in an iteration in most cases.

As the maximal slack of each v-critical block is the same as its slack, the concept of maximal slack is no longer needed here. Instead, as soft packing is usually under certain aspect ratio constraint, we introduce another metric *feasible slack* to reflect this constraint. The horizontal feasible slack of a block *b* is:

$$sl_f(b) = \min(sl_b, w_m(b) - w(b))$$

where $w_m(b)$ is the maximum width of the block which is imposed by the minimum aspect ratio constraint; $w(b)$ is the current width of the block b.
Accordingly we substitute formula (1) in the above for the following sufficient condition of non-width-increase:

Sufficient Condition 1
$$\sum_{b\in p_h}^{\text{b is v-critical}} \Delta w_b \le sl_f(p_h) \tag{3}$$

where the *feasible slack of a horizontal path p* is defined as:

$$sl_f(p) = \min_{b\in p}^{\text{b is v-critical}} sl_f(b)$$

Also accordingly we can find the bottleneck path as a path with maximum $\frac{sl_f(p_h)}{num(p_h)}$, where $num(p_h)$ denotes the number of all v-critical blocks on the path.
Then we can adjust the shape of each v-critical block on the bottleneck according to the following formula:

$$\Delta w_b = sl_f(p_h) \times \frac{w_b / h_b}{\sum_{b'\in p_h}^{b' \text{ is v-critical}} w_{b'} / h_{b'}} \tag{4}$$

And we can carry out overall height reduction and overall width reduction alternatively until no further reduction can be made.

But something is missing here for both the initial algorithm and the improved algorithm. Look at the example in Fig 10 (Note that the sources and sinks are omitted here). It can be observed that a horizontal path (such as (e, d)) is not sure to intersect with a vertical path (such as (a, b, c)) on a block. So not every horizontal source-to-sink path contains a block on every vertical longest path. And therefore not every horizontal source-to-sink path is qualified as a horizontal bottleneck path. We will find out a condition for such qualification in the following.
If a horizontal source-to-sink path p_h does not intersect with a vertical longest path p_v on any block, then there must be some edge (e.g. (e, d)) on p_h (e.g. (e, d)) crossing some edge (e.g. (b, c)) on p_v (e.g. (b, c)) as shown in the example. We will show that in such case there are only two possible combinations how vertics e and d is located relative to vertics b and c.

Lemma 7 If a horizontal edge (e, d) crosses a vertical edge (b, c), then e, d can only have two combinations of locations relative to b, c: (i) e is in (7) and d is in (6); (ii) e is in (5) and d is in (8).

Proof Firstly, neither e nor d could be in region (1) or (2), otherwise (e, d) could not have crossed (b, c);
Secondly, neither e nor d could be in region (9), otherwise there should not have been an edge between b and c because any block in region (9) would make (b, c) a redundant edge.
Thirdly, if e is in region (3), e is left of b and c, then d could only be in region (4), (6) or (8), for otherwise (e, d) could not have crossed (b, c). But in any of the three cases, d is transitively right of e through either b or c and therefore (e, d) would have become redundant and could not have existed. Therefore e could not be in region (3); similarly d could not be in region (4);
Fourthly, if e is in region (5), then d could not be in region (6), otherwise d is transitively right of e through b and therefore (e, d) could not have existed; similarly if e is in region (7), then d could not be in region (8).

For case (i) in lemma 7, *e* is above *b* and *d* is below *c*. As (*b*, *c*) is a v-critical edge, *b*'s lower boundary must lie on the same horizontal line as *c*'s upper boundary. Therefore $y(e_{lower}) \geq y(b_{upper}) = y(c_{lower}) \geq y(d_{upper})$, and *e* and *d* can not have overlap in y-direction, as in the example below. (Note that *e* and *d* is not considered as having overlap in y-direction if *e*'s lower boundary lies on the same horizontal line as *d*'s upper boundary). Similarly, and *e* and *d* can not have overlap in y-direction for case (ii).
Thereby we can give a sufficient condition of a horizontal path p_h intersecting every vertical longest path on a block:

Sufficient Condition 2 Every two adjacent blocks on a horizontal path p_h must have overlap in y-direction.

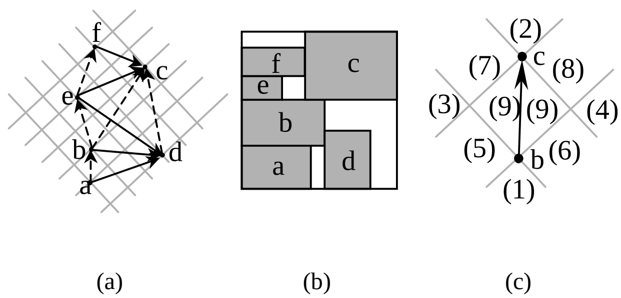


Fig 10 Two Possible Combinations of Positions of Block *e*, *d*

Based on this sufficient condition, we can modify the algorithm described above accordingly. First we give two definitions: If there is an edge (*a*, *b*) in G_h, we say that *a* is *b*'s *topological predecessor*; if *a* and *b* furthermore have overlap in y-direction, then we say that *a* is also *b*'s *geometrical predecessor*. Then we make the following modifications: (1) Not only any block with no topological predecessor/successor, but also any block with no geometrical predecessor/successor, could be the beginning/end of a bottleneck path. (2) For every block *b* except the beginning of a horizontal source-to-sink path, we calculate its $sl_f(v_i)$ and $num(v_i)$ only based on its geometrical predecessors, where v_i is the vertex representing *b* in the constraint graph, $sl_f(v_i)$ is the feasible slack of the piece of path on the whole path from the beginning up to v_i.

VI. Searching The Solution Space by Global Moves

Based on the three necessary and sufficient conditions as described in section IV-1, [1] defines three kinds of stochastic moves and corresponding adaption procedure.

Rotation: randomly pick up a macro block (rectilinear or rectangle) $A = \{a_1\ a_2 \ldots a_m\}$ and rotate it by 90 in the clockwise direction. The sequence pair is accordingly changed by switching unit block a_i with a_{m+1-i}, $i \in [1, n]$, in Γ_+ (when changing *A* from an H-partitioned orientation to a V-partitioned orientation) or in Γ_- (when it is the other way round).
Γ_+-mutation: randomly pick up two adjacent unit blocks $a \in A$ and $b \in B$ ($A \neq B$) in Γ_+ and exchange them.
Γ_--mutation: randomly pick up two adjacent unit blocks $a \in A$ and $b \in B$ ($A \neq B$) in Γ_- and exchange them.

These moves and adaption procedure defined by [1] are attractive for adoption in the case concave rectilinear blocks are not present, due to its quick and easy operation. Therefore with the absence of concave rectilinear blocks we would make our stochastic search by following the same line as [1]. In [1], the Γ_+-mutation and Γ_--mutation are restricted to exchanging of blocks between two adjacent blocks in either Γ_+ or Γ_-. In our approach, we extend Γ_+-mutation and Γ_--mutation to exchanging of blocks between two blocks in either Γ_+ or Γ_- with any distance under certain restrictions.

Γ_+-mutation: randomly pick up two unit blocks $a \in A$ and $b \in B$ ($A \neq B$) in Γ_+ such that no other unit blocks belonging to the either A or B are in between. Exchange a and b in Γ_+.
Γ_--mutation: randomly pick up two unit blocks $a \in A$ and $b \in B$ ($A \neq B$) in Γ_- such that no other unit blocks belonging to the either A or B are in between. Exchange a and b in Γ_-.

Like in [1], the Γ_+-mutation/Γ_--mutation may result in the violation of Condition-2 or Condition-3 defined by [1] under certain circumstances. So each Γ_+-mutation / Γ_--mutation will be followed by a check of feasibility of the resultant SP and an adaption in the case of infeasibility. The details are omitted here due to the limit of space.

VII. Assembly Everything Together

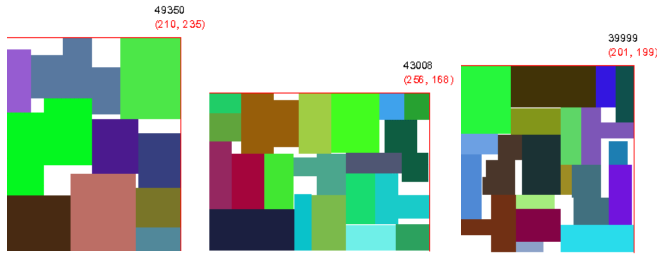
Because all the topological constraints and relative position constraints have been nicely captured in the related-vertics-grouped constraint graph $G_h{}'$ and $G_v{}'$, and every rectilinear block is represented as one vertex, just as if it was a rectangle block. So carrying out soft block packing on floorplans with rectilinear blocks will not be any more complicated than on those without rectilinear blocks. We only need to set the rectilinear blocks' horizontal/vertical feasible slack to zero to indicate they are hard blocks and can then perform the soft block packing as if no rectilinear block is present.
The whole algorithm uses simulated annealing mechanism to search for an optimal topology in the feasible solution space of sequence pairs of all the unit blocks. The key operations at each step of the simulated annealing is making a move and evaluating the resultant sequence pair.

Making a move including the following steps:
(1) Select a move and make it;
(2) Check the feasibility of the resultant SP if the move is Γ_+-mutation or Γ_--mutation;
(3) Adapt the SP if it's infeasible.

Evaluating a SP including the following steps:
(1) Construct the non-redundant constraint graph G_h and G_v which include all unit blocks for this SP;
(2) Construct the corresponding sub-blocks-grouped constraint graph $G_h{}'$ and $G_v{}'$;
(3) Perform soft block packing based on $G_h{}'$ and G_v;
(4) Calculate the cost of the packing output by (3).

VIII. Experiment Results

We have implemented the algorithm in C++(STL) with a Java interface and tested in on a SUN ULTRA-450 workstation. Fig 3.11(a), (b), (c) shows the packing results of 3 randomly generated sets of blocks. Set (a) is a packing of 10 blocks, 2 of them are rectilinear blocks. Either Set (a) or (c) is a packing of 20 blocks, 4 of them are rectilinear blocks. All the rectangle blocks are soft blocks whose shapes are optimized during the packing process. It takes no more than several minutes to get such a packing for any of the three cases.



(a) (b) (c)

Fig 3.11 Experimental Results

IX. Concluding Remarks

In this paper, we proposes a new technique of evaluating sequence pair; We presents a new method of simultaneous compaction and alignment for rectilinear block packing; We make a key observation for soft block packing problem and give a enhanced soft block packing algorithm; And most importantly, we unifies the rectilinear block packing and soft block packing into a whole system for the first time; Also, we give an extension of stochastic moves to search the solution space more effectively.

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