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PAPER *Special Section on Discrete Mathematics and Its Applications*

Air-Pressure Model and Fast Algorithms for Zero-Wasted-Area Layout of General Floorplan*

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SUMMARY A floorplan is a partition of a rectangle into subrectangles, each of which is associated with a module. Zero-wasted-area layouts are known to exist when the height and width of modules are constrained only by the area, and several methods have been proposed for deriving such layouts. However, because these methods are global and indirect, they are inherently slow. We propose a new algorithm which simulates the air-pressure mechanics. It begins with a layout, which is not necessarily feasible, and iterates the movement of one wall at a time to the force-balancing position. The key issue is that it is guaranteed that every movement makes a current layout approach a zero-wasted-area layout by the measure of energy which is defined here. Experimental results on the example in several literatures and artificially made complex examples showed very fast convergence. The algorithm is evolved to methods which move all the walls simultaneously, resulting in a further speed enhancement.

key words: *floorplan, layout, area optimization, air-pressure, zero-wasted-area*

1. Introduction

In VLSI layout design, floorplanning determines the total performance of VLSI circuits where a floor-rectangle is partitioned into subrectangles, each of which is associated with a module. Among the various optimization targets, the primary goal, and the subject of the present paper, is the minimization of the area of the resultant layout.

The floor-rectangle is partitioned by a set of horizontal and vertical line segments which do not intersect each other but which end at the orthogonal segments. These line segments, including the boundaries of the floor-rectangle, are here called the *walls*. Where it is necessary to distinguish among walls, the four boundary walls of the floor-rectangle will be referred to as *outer walls* and the others as *inner walls*. A maximal subregion containing no inner walls forms a rectangle referred to as the *room*. These definitions are illustrated in Fig. 1.

A minimum area layout is pursued under the two types of constraints, the topological and physical constraints.

The topological constraint is the incidence relation between walls and rooms. A wall and a room are said to be *incident* if the wall is a boundary of the room. The incidence relation is significant for its practical implication: A wall in a layout is considered to represent a straight channel in routing. A floorplan topology must have been designed so that the terminals of those modules that are incident to a wall will be easily connectable via the channel. Therefore, we impose the constraint of an invariant incidence relation.

The physical constraint is that a room must be large enough to embed the associated module. This constraint can be variously interpreted according to the design style with respect to the module. The width and height of a module may be allowed to vary subject to the area or aspect-ratio, or may be defined by the designer. Typical examples are *discrete modules* such that a module is selected from several functionally equivalent candidates ([1]–[5] for slicing structures, [6]–[11] for hierarchical structures, or [12], [13] for general structures), *continuous modules* such that the width and height of a module are arbitrary subject to the area ([14], [15]), and *bounded continuous modules* such that the width and height of a module have their preassigned lower bounds ([16], [17]). In this paper, we focus on the continuous modules.

A basic but nontrivial question is whether or not there exists a layout the area of which is the sum of the areas of the modules. Such a layout is called the *zero-wasted-area layout* [14]. If the floorplan is a slicing structure, the answer is obviously yes. A zero-wasted-area layout is easily obtained by a finite sequence in which linear equations are solved one at a time.

Regarding to the general structures, the most important contribution has been by Wimer, Koren, and Cederbaum [14], who proved the existence of a zero-wasted-area layout through analysis of the solution

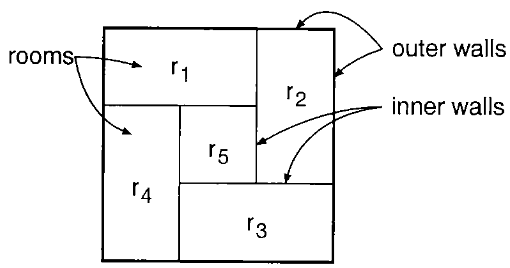

Fig. 1 Definitions of floor-rectangle, rooms, and walls.

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space. Several subsequent algorithm studies succeeded in realizing the zero-wasted-area layout. Wang and Chen [15], for example, proposed a network analogous approach.

However, their approaches are all global; that is, their solutions use the global property. As typically seen in Wang and Chen [15], [16] or in Moh, Chang, and Hakimi [17], the algorithms collect all the constraints in a list resulting in a huge system of equations. Thus, the global approach needs an enormous computational cost. It is strongly hoped that a local, or greedy, approach with some global optimality will be developed.

This paper proposes such an approach. We begin with a layout, which may not satisfy the area constraint, and simulate the air-pressure mechanics, iterating the movement of one wall at a time to the force-balancing position while maintaining the incidence relation. The distance of a movement is determined by simulated air-pressure of the rooms that are incident to the wall. By this movement, the pressures of these rooms are induced to change. Accordingly, the force of some walls may increase. Thus it appears that a layout may not be approaching a zero-wasted-area. But the idea of *energy* is introduced to observe the degree of resemblance of the current layout to the zero-wasted-area layout. It is proved that a wall-movement monotonically reduces the energy and that the energy is zero if and only if the zero-wasted-area layout is attained. An idea which arises from the phenomenon of air is also found in [18] where modules are iteratively expanded like "balloons." But the method has no such guaranty.

The algorithm is evolved to methods which move all the walls simultaneously, resulting in a further speed enhancement with a sacrifice of the above mentioned guarantee. The experimental results revealed that our algorithms are too fast to be measured by the instance in the literatures [14], [15], [17] that consists of only twenty modules. A high performance of the algorithm was shown by further experiments for artificially made, complex instances including hundreds of modules.

The rest of this paper is organized as follows. Section 2 is devoted to a sketch of the principle of the simulated air-pressure model. In Sect. 3, the basic algorithm is described. Section 4 discusses the relation among the pressure, force, and energy when the zero-wasted-area layout is attained. In Sect. 5, a theorem on the algorithm convergency is presented. The algorithm is enhanced in Sect. 6. The experiments in Sect. 7 show the efficiency of the proposed algorithms. Finally, Sect. 8 concludes this paper.

2. Definitions and Sketch of Principle

A floorplan has rooms $r_1, r_2, \ldots, r_n$. A continuous module the area of which is a_ℓ is associated to every room r_ℓ. The width and height of room r_ℓ of the layout are x_ℓ and y_ℓ, respectively. The area constraint is $x_\ell y_\ell \geqq a_\ell$ $(\ell = 1, \ldots, n)$. The width and height of the floor-rectangle are X and Y, respectively.

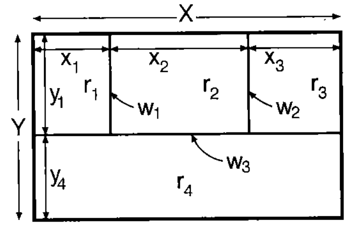

Fig. 2 A sample floorplan instance of a slicing structure.

Here, we present two examples of a global approach to contrast with our local approach.

Looking at the floorplan instance shown in Fig. 2, we first determine the positions of the three inner walls w_1, w_2, and w_3 when $XY = a_1 + a_2 + a_3 + a_4$ is satisfied. Accordingly, the width x_ℓ and height y_ℓ of each room r_ℓ are determined. Since the topology is a slicing structure, the solution is easily obtained:

$$x_1 = \frac{a_1}{a_1 + a_2 + a_3} X, \; y_1 = \frac{a_1 + a_2 + a_3}{a_1 + a_2 + a_3 + a_4} Y.$$

The formula is global in the sense that it cannot be calculated without knowing all the physical and topological constraints.

For a slightly more complex case, consider a "spiral" layout in Fig. 1 to be solved by a global approach. We have $x_1 + x_2 = X$, $x_4 + x_5 = x_1$, $x_2 + x_5 = x_3$, $y_1 + y_4 = Y$, $y_3 + y_5 = y_4$, $y_1 + y_5 = y_2$, and $x_i y_i = a_i$ for $1 \leqq i \leqq 5$. Assuming without loss of generality that $X = Y = 1$, for example, x_1 is a positive solution of the second order equation: $(1 - a_3 - a_4)x_1^2 + (a_1 a_3 - a_2 a_4 + a_1 - a_2 - a_3 + a_4 - 1)x_1 + (-a_3 - a_4 - 1)a_1 = 0$. A more complex floorplan will provide higher order equations. For example, for a floorplan instance with 14 rooms, there are two equations of two variables on a maximum 20th order.

In contrast, our approach uses a single formula at a time in terms of local values. It starts with an initial layout such that X and Y are arbitrary subject to $XY = \sum_{\ell=1}^{n} a_\ell$ and improves the layout at each step. Topological constraint is maintained in the process, but physical constraint may be violated.

We simulate the natural phenomenon of air-pressure inflicting a force to the walls according to Pascal's principle, each wall thus moving toward the force-balancing position. Area a_ℓ represents the quantity of air sealed in room r_ℓ of volume $x_\ell y_\ell$. The *pressure* of room r_ℓ is given by

$$P_\ell = \frac{a_\ell}{x_\ell y_\ell}.$$

The force from the room r_ℓ to the wall w_i is proportional to the length of the part of w_i shared with r_ℓ. Take a vertical wall w_i, which will receive force from the rooms that are incident to w_i from the right or left.

Algorithm SAPS {
    Set initial positions of walls subject to the topological constraint and $XY = \sum a_\ell$.
    Calculate pressures, forces and energy.
    Until E becomes small enough {
        Select an unbalanced wall w.
        Apply force-balancing to w.
        Update pressures, forces and energy.
    }
    Output the layout.
}

Fig. 3 The basic algorithm: SAPS.

The algebraic sum rightwards is the force that tends to move w_i to the right. Let R_i^- and R_i^+ be a set of rooms adjacent from the left and right of w_i, respectively. The *force* F_i of w_i is defined by

$$F_i = \sum_{r_\ell \in R_i^-} P_\ell y_\ell - \sum_{r_\ell \in R_i^+} P_\ell y_\ell .$$

The force to a horizontal wall is defined similarly.

The operation called the *force-balancing* for an inner wall w moves w to the position where the force is zero while maintaining the position of the other walls. The algorithm repeats the force-balancing as long as there exists any unbalanced wall and time allows. In the process, an operation to a wall may increase the forces of other walls. But the layout monotonically approaches a zero-wasted-area layout if we measure it by a global function called *energy*,

$$E = \sum_{\ell=1}^{n} a_\ell \log \frac{a_\ell}{x_\ell y_\ell}.$$

This is verified in Sect. 4.

3. Basic Algorithm

The basic version of our algorithm *Simulated-Air-Pressure-Single (SAPS)* is described in Fig. 3.

Let us apply Algorithm SAPS to the example in Fig. 2. It is trivial that the position of w_3 is determined by one time application of the force-balancing. Therefore, we have only to consider to determine x_1, x_2, and x_3. Let $\vec{x}^{(k)} = (x_1^{(k)}, x_2^{(k)}, x_3^{(k)})^T$ be the column vector of the widths after the force-balancing for w_1 and w_2 was applied k times. Since this is a very simple case, the force-balancing operations of w_1 and w_2 are linear transformations given by

$$M_1 = \frac{1}{a_1 + a_2} \begin{pmatrix} a_1 & a_1 & 0 \\ a_2 & a_2 & 0 \\ 0 & 0 & a_1 + a_2 \end{pmatrix} \quad \text{and}$$

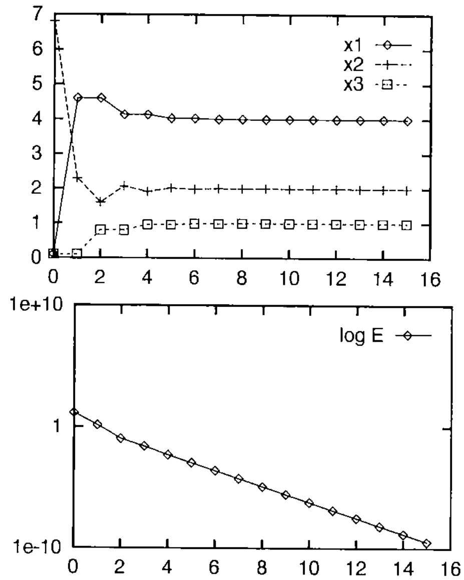

Fig. 4 Transitions of widths (above) and energy (below) by force-balancing for $(a_1, a_2, a_3) = (4, 2, 1)$ and $(x_1^{(0)}, x_2^{(0)}, x_3^{(0)}) = (0.1, 6.8, 0.1)$.

$$M_2 = \frac{1}{a_2 + a_3} \begin{pmatrix} a_2 + a_3 & 0 & 0 \\ 0 & a_2 & a_2 \\ 0 & a_3 & a_3 \end{pmatrix},$$

respectively. We have

$$\begin{aligned} \vec{x}^{(k)} &= M_2 M_1 \vec{x}^{(k-1)} \\ &= \frac{X}{C} \begin{pmatrix} a_1 \\ a_2 \\ a_3 \end{pmatrix} + \frac{\alpha^k}{C} \begin{pmatrix} B & B & -\frac{AB}{a_3} \\ -a_2 & -a_2 & \frac{a_2 A}{a_3} \\ -a_3 & -a_3 & A \end{pmatrix} \vec{x}^{(0)}, \end{aligned}$$

where $A = a_1 + a_2$, $B = a_2 + a_3$, $C = a_1 + a_2 + a_3$. $X = x_1^{(0)} + x_2^{(0)} + x_3^{(0)}$, and $\alpha = \frac{a_1 a_3}{AB}$. Since $0 < \alpha < 1$, $\vec{x}^{(k)}$ converges to the correct value. The convergence of x_1, x_2 and x_3 to the correct values is not monotonical as observed in Fig. 4 (above). However from the energy point of view, the convergence to the correct solution is monotonical as shown in Fig. 4 (below). Note that the analysis as mentioned above may not be applicable for general layouts.

4. Conditions for Zero-Wasted-Area Layout

The zero-wasted-area layout is characterized by the condition:

[**Pressure-Balance**] $P_\ell = 1$ for every room r_ℓ.

On the other hand, operation force-balancing is targeting the layout satisfying the condition:

[**Force-Balance**] $F_i = 0$ for every wall w_i.

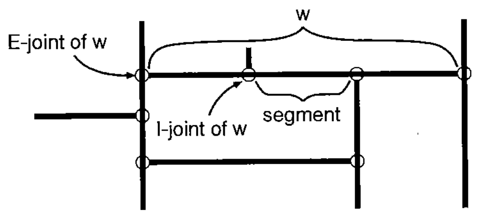

Fig. 5 Joints of a wall and a segment.

Therefore we want to know if **Force-Balance** implies **Pressure-Balance**. Moreover, we want to know if repetition of operations makes a layout converge to a layout that satisfies **Pressure-Balance**. We show this using the energy. First, we show a relation between **Pressure-Balance** and

[**Energy-Zero**] $E = 0$.

Lemma 1: The energy is non-negative and **Energy-Zero** implies **Pressure-Balance**.

Proof: For any real number $z > 0$, it holds $\log z \geqq 1 - 1/z$. Then,

$$E \geqq \sum_{\ell=1}^{n} a_\ell \left(1 - \frac{x_\ell y_\ell}{a_\ell}\right) = \sum_{\ell=1}^{n} a_\ell - \sum_{\ell=1}^{n} x_\ell y_\ell = 0.$$

Equality holds if and only if $\log \frac{a_\ell}{x_\ell y_\ell} = 1 - \frac{x_\ell y_\ell}{a_\ell}$ for every room r_ℓ. This implies that $\frac{a_\ell}{x_\ell y_\ell} = 1$. □

By Lemma 1, the energy can be used to measure how close the current layout is to zero-wasted-area layout.

Next, we focus on the relation between force and pressure. A point on a wall where another wall is incident is called a *joint*. A joint is called an *E-joint* of a wall w if it is on the end of w, an *I-joint* of w otherwise. A *segment* is a part of a wall between two adjacent joints. See Fig. 5 for example.

The *segment balance graph* G_{SB} is defined as follows. The vertices represent rooms including the outer room. For convenience, they are referred to by the names of corresponding rooms. For each segment shared by two rooms r_ℓ and r_m such that $P_\ell \geqq P_m$, there is an undirected edge between corresponding vertices r_ℓ and r_m if $P_\ell = P_m$, or a directed edge from r_ℓ to r_m if $P_\ell > P_m$. An example is shown in Fig. 6. An edge of G_{SB} is said to *cross* the wall w if the segment corresponding to the edge is a part of w. For example, edges (r_1, r_2) and (r_2, r_5) cross w in Fig. 6.

A directed cut is a minimal set of directed edges such that the deletion of them separates the graph into two connected components and the directions of its edges are confluent. We have two lemmas on cuts.

Lemma 2: If G_{SB} has a directed edge, G_{SB} has a directed cut of G_{SB} including the edge.

Proof: Let G'_{PB} be a graph obtained from G_{SB} by identifying every pair of vertices connected by an undirected edge. Since the direction of edge corresponds to the difference of the pressures, G'_{PB} has no directed cycle. It is a fundamental fact that any edge in a directed graph without directed cycles (directed acyclic graph, DAG) is included in a directed cut. The directed cut of G'_{PB} corresponds to that of G_{SB}. □

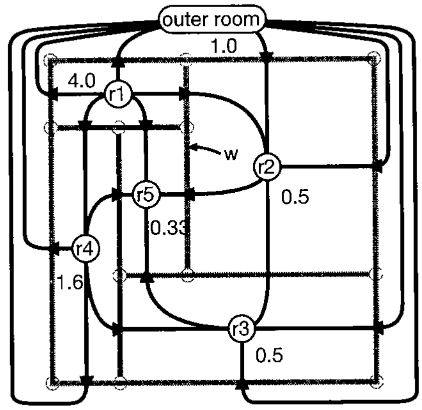

Fig. 6 A layout (shaded lines) and its segment balance graph (solid lines). Vertices represent rooms $r_1, \ldots, r_5$ and the outer room. The numbers denote current pressures of the rooms.

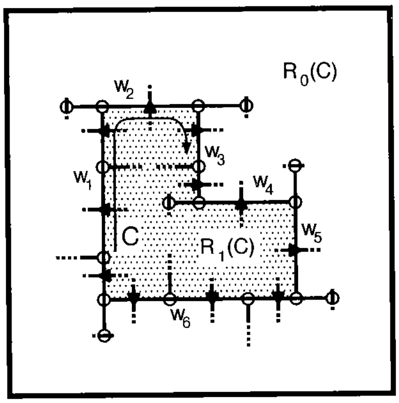

Fig. 7 Partition of rooms by directed cut.

A directed cut C of G_{SB} classifies the set of rooms into two each of which corresponds to the connected component of the graph. We denote the set of rooms including the outer room as $R_0(C)$ and the other $R_1(C)$. In Fig. 7, an example of cut C, $R_0(C)$ and $R_1(C)$ is shown.

By tracing clockwise the boundary of the region consisting of rooms of $R_1(C)$, a cyclic sequence of walls can be extracted. For example, the sequence $(w_1, w_2, w_3, w_4, w_5, w_6)$ is extracted from the layout shown in Fig. 7. A wall w in the sequence is labeled either 'EE,' 'EI,' 'IE,' or 'II.' The former letter in each label corresponds to the type of the joint J_p where w meets with the previous wall in the sequence, as E-joint or I-joint of w. Similarly, the latter letter corresponds to the type of the joint J_n with the next wall. Those definitions will be clearly understood by Fig. 8.

Note that for two walls that touch at a joint, at

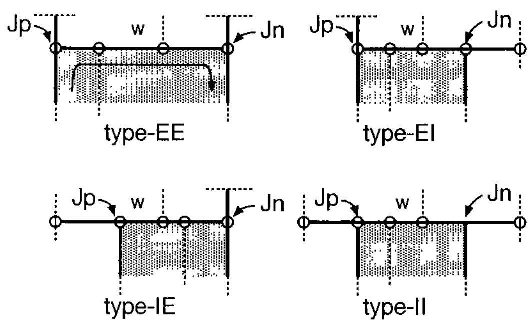

Fig. 8 Types of a wall in the sequence.

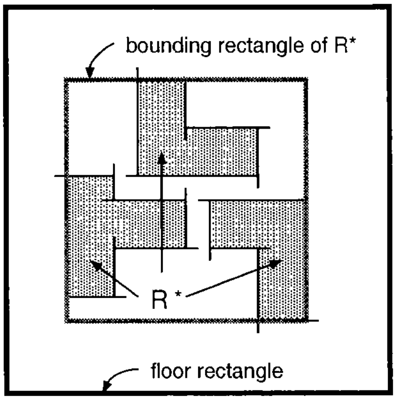

Fig. 9 The bounding rectangle of R^*.

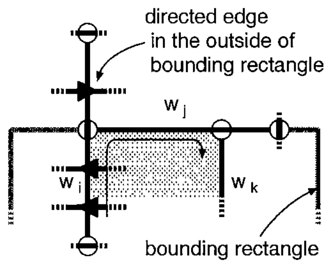

Fig. 10 A wall jutting out from the bounding rectangle.

least one wall ends there. Thus if the latter letter of the label of w is 'I' then the former letter of the label of the next wall should be 'E.' Also, if the latter letter of the label of w is 'E' then the former letter of the label of the next wall should be 'I' unless w is the outer wall.

Lemma 3: Let **Force-Balance** be satisfied. A cyclic sequence of walls extracted from a directed cut C of G_{SB} consists either only of type-EI inner walls or only of type-IE inner walls.

Proof: Suppose that there is a wall w of type-EE in the sequence. All edges of G_{SB} which cross w are directed and have the same direction. Then w is not balanced, a contradiction. Therefore, no type-EE wall is contained in the sequence.

Trivially the number of the letter 'E' appearing in the sequence is not less than that of 'I.' The existence of a type-II wall implies the existence of a type-EE wall. Therefore, no type-II wall is contained.

Suppose that there is an inner wall w such that the previous wall is outer. The type of w is type-EI. The type of all walls that follow must be type-EI since there is no type-EE wall. However this contradicts the fact that the type of an inner wall whose next wall is outer is type-IE. Therefore, no outer wall is contained.

If there exists a type-EI (type-IE) wall, the next wall must be type-EI (type-IE, respectively). Thus, all the walls are uniquely either type-EI or type-IE. □

Lemma 4: The condition **Force-Balance** implies the condition **Pressure-Balance**.

Proof: Assume that **Force-Balance** is satisfied but **Pressure-Balance** is not. There exists a directed edge in G_{SB} and a directed cut. Let R^* be a set of rooms which is the union of $R_1(C)$ over all directed cuts C in G_{SB}. The *bounding rectangle* of R^* is the minimum rectangle including R^*. An illustrative example of R^* and its bounding rectangle is shown in Fig. 9. Let w_j be a wall where R^* touches the bounding rectangle (See Fig. 10). Let w_i and w_k be the previous and next walls of w_j, respectively, in the sequence of some cut including w_j. By Lemma 3, either w_i or w_k juts out from the bounding rectangle as shown in Fig. 10. Let w_i be such a wall. To balance the force on w_i, there is a directed edge that crosses w_i in the outside of the bounding rectangle. There exists a cut C' including the edge by Lemma 2. The room corresponding to a vertex incident to the edge is in $R_1(C')$ and in the outside of the rectangle. This is a contradiction to the definition of the bounding rectangle. □

Theorem 1: Three conditions **Pressure-Balance**, **Force-Balance** and **Energy-Zero** are equivalent.

Proof: Obviously, **Pressure-Balance** implies **Force-Balance** and **Energy-Zero**. Lemmas 1 and 4 lead the theorem. □

5. Convergency

The key issues of the force-balancing operation are in (1) existence of a force-balancing position preserving the topology, and (2) convergency to the zero-wasted-area layout.

Lemma 5: For any wall, there is a unique force-balancing position preserving the topology.

Proof: Let w be a vertical wall. Let $F(t)$ be the force inflicted to w when it is moved from the current position by distance t. We have

$$F(t) = \sum_{r_\ell \in R^-} \frac{a_\ell}{x_\ell + t} - \sum_{r_\ell \in R^+} \frac{a_\ell}{x_\ell - t},$$

and

$$\frac{d}{dt}F(t) = -\sum_{r_\ell \in R^-} \frac{a_\ell}{(x_\ell + t)^2} - \sum_{r_\ell \in R^+} \frac{a_\ell}{(x_\ell - t)^2} < 0.$$

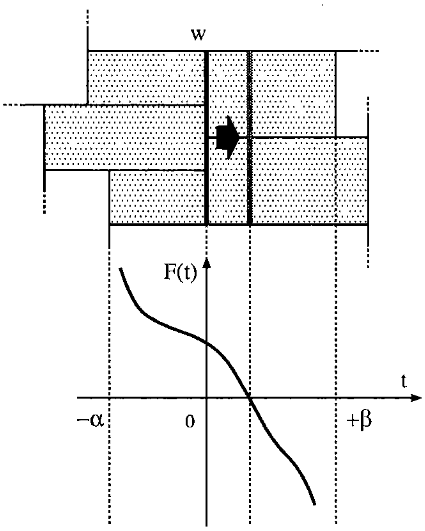

Fig. 11 Force inflicted to w with respect to the position.

Since $F(t)$ is continuous, monotonically decreasing, and that $F(t) \to +\infty$ as $t \to -\alpha$ and $F(t) \to -\infty$ as $t \to +\beta$, where α is the minimum width among the rooms of R^- incident left to w and β is the minimum width among the rooms of R^+ incident right to w. $F(t)$ is a function as depicted in Fig. 11. Thus there exists the unique t such that $F(t) = 0$ within the range $(-\alpha, +\beta)$. Therefore the topology of the layout is preserved. The same discussion for a horizontal wall holds. □

By Lemma 5 and the feature of the function $F(t)$ in the proof, the force-balancing position can be found efficiently, for example, by binary search.

An operation balances a selected wall, but it may cause other force-balanced walls to be unbalance. Therefore from the point of force-balancing, the convergency will not be clearly observed. However we can show that each force-balancing operation certainly improves the layout from the point of energy.

Lemma 6: The operation of force-balancing for any force unbalancing wall reduces the energy.

Proof: Let w be an unbalanced wall. Let $F(t)$ and $E(t)$ be the force inflicted to w and the energy when w is moved from the current position by distance t. Extracting only terms including t for simplicity, we have

$$E(t) = \sum_{r_\ell \in R^-} a_\ell \log \frac{a_\ell}{(x_\ell + t)y_\ell} + \sum_{r_\ell \in R^+} a_\ell \log \frac{a_\ell}{(x_\ell - t)y_\ell}$$

and

$$\frac{d}{dt}E(t) = -\sum_{r_\ell \in R^-} \frac{a_\ell}{x_\ell + t} + \sum_{r_\ell \in R^+} \frac{a_\ell}{x_\ell - t} = -F(t).$$

Since $E(t)$ is minimum when $-F(t) = 0$, the force-balancing reduces the energy by greater than zero. □

Lemma 5 and 6 lead the following theorem.

Theorem 2: The algorithm SAPS improves the floorplan at each step under the energy.

```
Algorithm SAPA {
  Set initial positions of walls subject to the topo-
  logical constraint and XY = Σ a_ℓ.
  Set initial values of "activities".
  Calculate pressures, forces and energy.
  Until E becomes small enough {
    Change "activities" δ_i for every inner wall w_i.
    Move w_i by δ_i F_i for every inner wall w_i.
    Update pressures, forces and energy.
  }
  Output the layout.
}
```

Fig. 12 The enhanced algorithm: SAPA.

Note that Theorem 2 does not guarantee that the iteration of force-balancing makes the layout converge to zero-wasted-area floorplan. But, many circumstantial evidences allow us to be optimistic: every example we experimented showed rapid convergency to the zero-wasted-area layout.

6. Enhanced Algorithms

In SAPS, a single wall is selected and moved to force-balancing position at a time. We enhance the algorithm aiming to accelerate the computation by moving all the walls to some appropriate positions simultaneously. This enhanced algorithm is rather considered to simulate more faithfully the natural phenomenon than SAPS. We call it Simulated-Air-Pressure-All (SAPA) which is described in Fig. 12. This change may lose the guarantee by Theorem 2. A parameter "activity" included in the algorithm will be effective to recover this drawback.

At every step, every wall moves by $\delta_i F_i$. We call the coefficient δ_i the *activity* of w_i. If δ_i is too large, the wall will jump over the unknown correct position, and then reciprocate. What is worse, the topology will be violated. If δ_i is too small, the wall moves by a very small distance each time and it takes long time to converge. Intuitively, it is a good strategy that activities are large enough in early stage and decrease as steps proceed. Several ideas for this dynamic activity control are described in the following.

(1) Limit

We introduce the limit on the distance of a movement to avoid radical movement of a wall. By a movement of a vertical wall w with $F > 0$, rooms on the left are expanded and rooms on the right are compressed. Let α and β as defined before be the minimum width among the rooms to be expanded and that to be compressed, respectively.

We introduce the parameters $\lambda_1 > 0$ and $0 < \lambda_2 < 0.5$ to limit the distance of the movement of w in order to avoid expanding over $\lambda_1\alpha$ and avoid compressing over $\lambda_2\beta$. The limit by λ_2 guarantees to maintain the incidence relation of the layout. Since the movement distance is δF, we should determine the activity δ to satisfy $|\delta F| \leq \min\{\lambda_1\alpha, \lambda_2\beta\}$. SAPA changes the activity δ to the value

$$\delta \leftarrow \min\left\{\delta, \frac{\min\{\lambda_1\alpha, \lambda_2\beta\}}{|F|}\right\}.$$

(2) Inertia
If the repetition of the movement of a wall w in the same direction is observed, the next movement of w will be increased by the inertia of the previous movement. By this idea, SAPA increases the activity δ to $\gamma_1\delta$ where $\gamma_1 > 1$. It may reduce the computation time since the final position of w is expected to be in the same direction. On the other hand, if alternating movements of w is observed, SAPA decreases the activity δ to $\gamma_2\delta$ where $0 < \gamma_2 < 1$.

(3) Temperature
If increase of the energy is observed, we guess that some walls move over some unknown correct position. Thus we should suppress the distance of movements. By this idea, SAPA decreases the activity δ of every wall to $\gamma_3\delta$ where $0 < \gamma_3 < 1$. This idea is understood to simulate a cooling the temperature.

7. Experiments

Our Simulated-Air-Pressure Algorithms were implemented in C language on a SUN SPARC-Station10 workstation. Algorithms tested are as follows.

SAPS (SEQ): Move all inner walls sequentially, in a fixed order.

SAPS (MAX): Select an inner wall with maximum force and move it.

SAPA (LT): $P = (0.50, 0.25, 1.00, 1.00, 0.80)$.
("Limit" and "Temperature")

SAPA (LI): $P = (0.50, 0.25, 1.05, 0.95, 1.00)$.
("Limit" and "Inertia")

SAPA (LIT): $P = (0.50, 0.25, 1.05, 0.95, 0.80)$.
("Limit," "Inertia" and "Temperature")

SAPA algorithms are characterized by parameter $P = (\lambda_1, \lambda_2, \gamma_1, \gamma_2, \gamma_3)$. Every SAPA algorithm is equipped with "Limit" or the incidence relation may be collapsed. We exclude SAPA algorithm only with "Limit" since it does not converge in most cases. Every algorithm stops when the normalized energy $E/\sum_{\ell=1}^{n} a_\ell$ becomes less than 1.0×10^{-5}. In SAPA algorithms, the energy is evaluated after every $n-1$ movements.

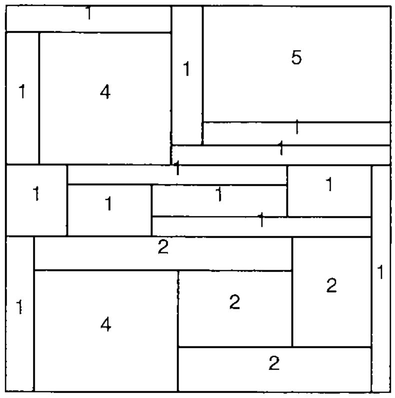

Fig. 13 The example in the literatures consisting of 20 modules. Numbers represent the areas of each module.

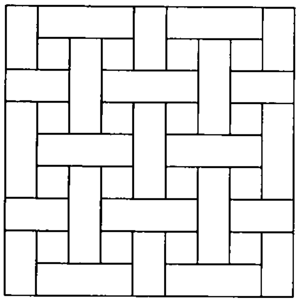

Fig. 14 Poly-spiral structure with 41 rooms.

The example named "F20" in the literatures [14], [15], [17] shown in Fig. 13 and complex but regular floorplans named "poly-spiral" structure were used for comparison. "Poly-spiral" structure is the extension of the spiral structure as shown in Fig. 14. The significant feature of poly-spiral structure is that it has no subfloorplan in it, making the problem difficult. Floorplans "Sn" of poly-spiral structure with n rooms were examined for $n = 13, 41, 85, 145, 221, 313$. For "F20," the algorithms start with 100 randomly generated initial layouts. For each "PSn," 100 sets of areas of rooms were generated where each area was randomly ranging from 10 to 100, and for each set the algorithms start with a randomly generated initial layout. Note that the initial layout affects slightly the time to converge but does not affect the level of quality of the final layout since the precision is the condition to end the process.

Results are summarized in Table 1. The column "Algorithm" lists the algorithms tested. The remaining columns give the average cpu-time (user time + system time) consumed for "F20" and the poly-spiral floorplans, respectively. We observe that every algorithm converges very quickly for each instance.

The effect of ideas is clearly demonstrated in Fig. 15 by which SAPA (LIT) is the best and comparable one is

Table 1 Average cpu-times (sec.) of our algorithms.

Algorithm	F20	S13	S41	S85	S145	S221	S313
SAPS (SEQ)	0.04	0.01	0.13	0.49	1.50	3.09	6.06
SAPS (MAX)	0.03	0.00	0.08	0.38	1.72	4.91	11.21
SAPA (LT)	0.04	0.01	0.13	0.45	1.46	3.22	6.24
SAPA (LI)	0.03	0.00	0.06	0.23	0.65	1.37	2.58
SAPA (LIT)	0.02	0.00	0.05	0.19	0.56	1.22	2.34

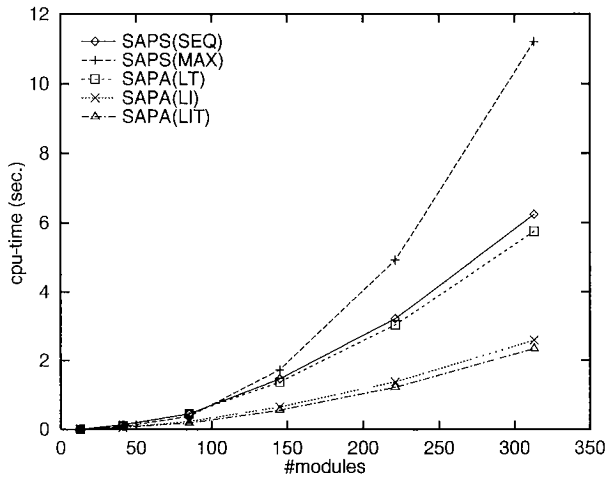

Fig. 15 The number of modules vs. average cpu-time.

SAPA (LI). The difference of these two is in "Temperature." "Temperature" is introduced to suppress violent movements of the walls when the energy increases. Since "Inertia" also has similar effect, "Temperature" gives a few effect in case that "Inertia" is equipped.

SAPA algorithms are faster than SAPS algorithms as expected. The reason may be as follows. In a force-balancing operation, the force is evaluated many times to search the force-balancing position. Thus it seems that the energy reduction per force evaluation in SAPS is less than that in SAPA in which the distance of movement is determined by evaluating the force once.

The worst is SAPS (MAX) though the idea of moving a maximally unbalanced wall looks very reasonable compared with SAPS (SEQ) which moves walls independent of the current layout. It may be by the reason that the operation of force-balancing is so fast that a thoughtless selection following the data order is better than spending time to search a wall with the maximum force. Note that SAPS (MAX) is equipped with linear search to find the wall in this implementation. It might be faster than SAPS (SEQ) if with a more efficient method to search.

8. Conclusion and Remarks

We proposed a new approach based on a simulated air-pressure model for the zero-wasted-area layout problem. The notion of energy was introduced to measure how close the current layout is to the zero-wasted-area layout. It is proved that the energy is reduced monotonically to zero each time the operation force-balancing is applied and that it is zero if and only if the zero-wasted-area layout is attained. It is a future work of theoretcial interest to give a proof to the complete form of Theorem 2 which is our conjecture: SAPS improves the floorplan at each step under the energy and converges it to the energy zero floorplan.

Further ideas obtained from the observation of natural phenomena were implemented. Experimental results showed that the proposed method is very promising in computation time and precision. It will be useful as an evaluation tool in such layout methodologies such as seen in a stochastic way in which cycles of generation and evaluation are repeated a huge number of times.

The air-pressure model and algorithms need to be enhanced to fit more realistic cases. For example, since the extremely thin module is hard to be implemented, the aspect-ratio constraint is imposed on each module in practice. An approach to handle such modules in the model is described in [19]. It is future work to answer requests arized from discrete modules (including shape-fixed modules), a module the area of which changes according to its aspect ratio, areas for routing, and so on.

There is yet another future work as follows: In practice, local changes of the topology of a floorplan are often acceptable expecting a better layout. Our proposed model will be appropriate for the purpose since the pressures and forces which reflect some local state will give us reasonable hints how to change the topology.

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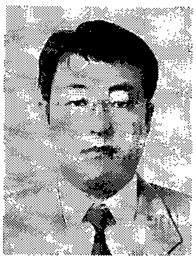

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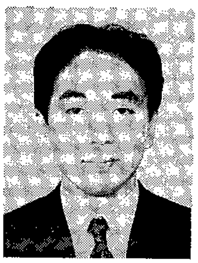

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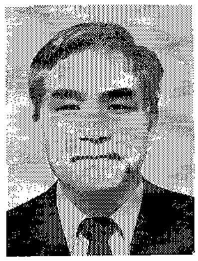

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