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E-BLOW: E-Beam Lithography Overlapping aware Stencil Planning for MCC System

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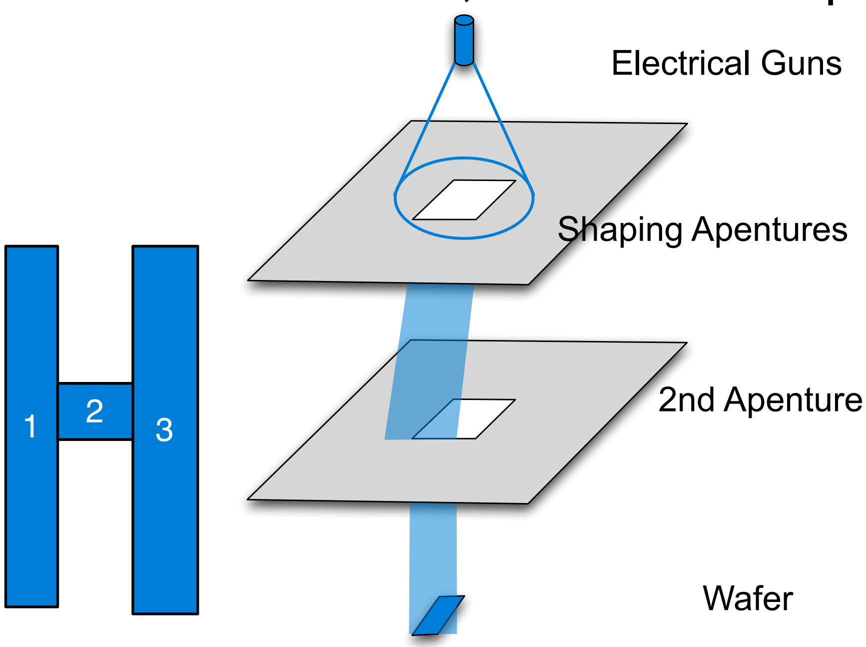
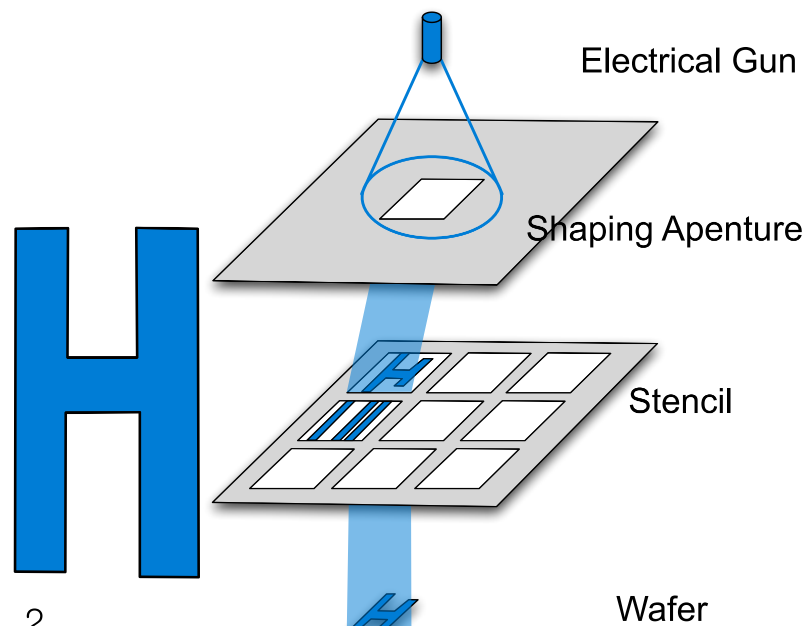
Introduction– E-Beam

- E-Beam lithography:
  - Several decades, for mask manufacturing
  - Candidate for next generation lithography, with MPL/EUV/DSA
- Conventional E-Beam system:
  - variable shaped beams (**VSB**): shaping aperture + second aperture
  - Character Projection (**CP**): a pattern (**character**) is pre-designed on the **stencil**, then it can be printed in one electronic shot;



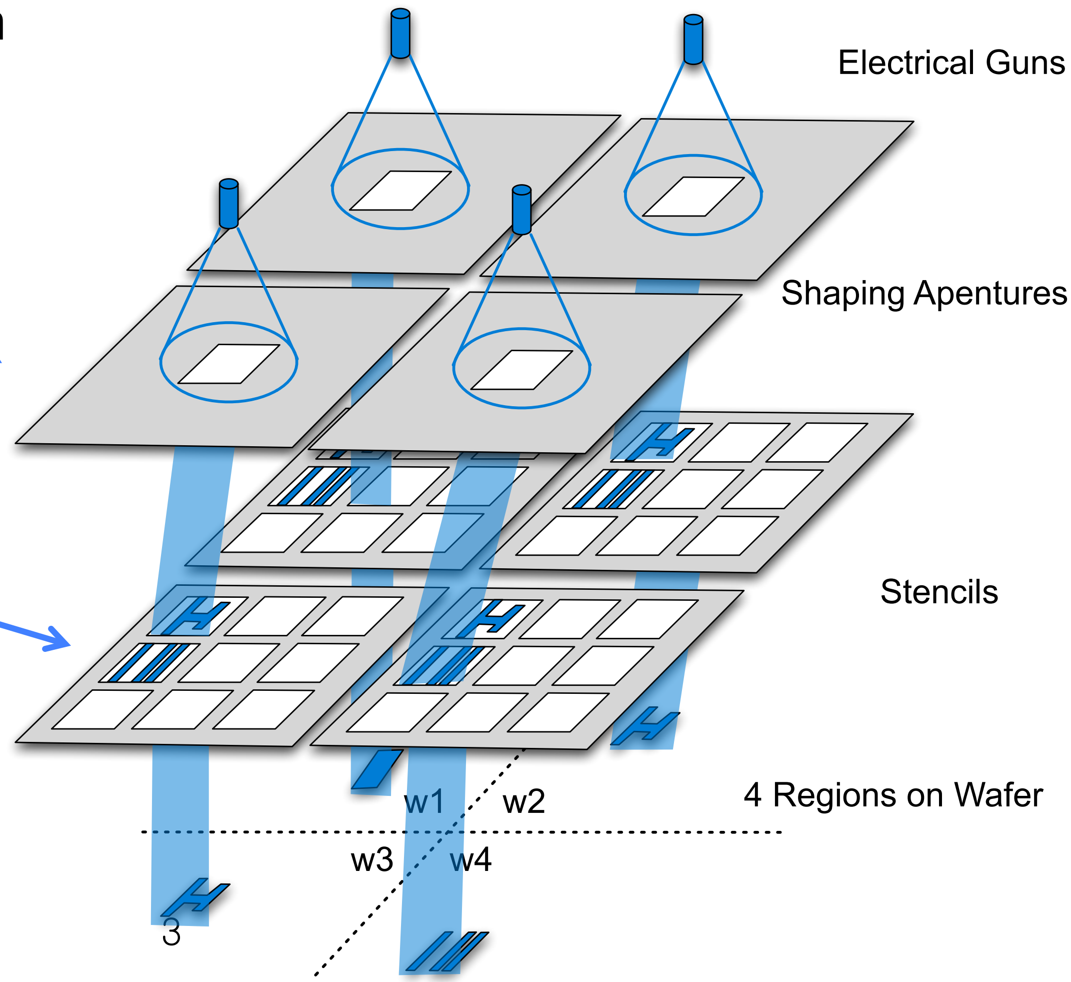


Introduction– MCC system

- Multi-Column Cell (MCC) system
  - Several independent character projections (CP) to speed-up
  - Each CP is applied on one section of wafer.
  - Share one stencil design

MCC system with 4 CPs

4 stencils share 1 design



Introduction– MCC system Shot#

- MCC system with:
  - ***P*** CPs, wafer is divided into *P* regions
  - ***n*** character candidates (patterns) $\{c_1, \ldots, c_n\}$
  - For c_i, its VSB shot# is n_i; repeat t_{ic} on region w_c
  - a_i: indicate whether c_i is selected on stencil
- Total shot# for region w_c:

$$T_c = \boxed{\sum_{i=1}^{n} a_i \cdot (t_{ic} \cdot 1)} + \boxed{\sum_{i=1}^{n} (1 - a_i) \cdot (t_{ic} \cdot n_i)}$$

With stencil, CP shot# Without stencil, VSB Shot#

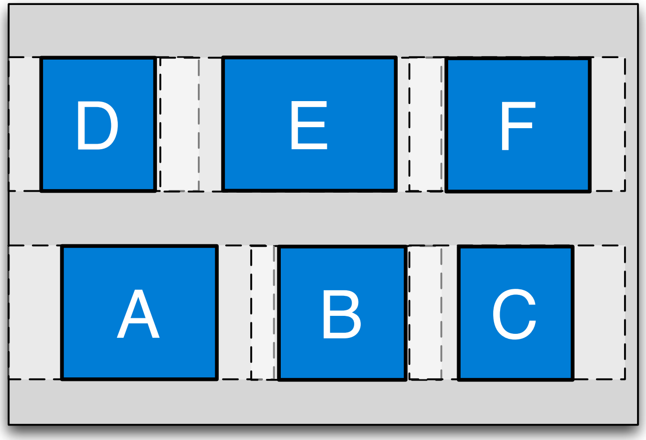
- MCC system writing time: $T_{total} = \max\{T_c\}$

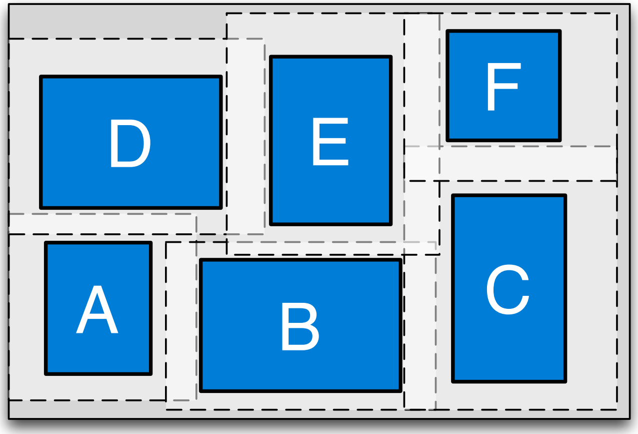
Problem Formulation

Overlapping aware Stencil Planning (OSP) Problem:

- **Input:** set of characters; MCC system info
- **Output:** selected characters, pack them on stencil
- **Objective:** minimize MCC system writing time

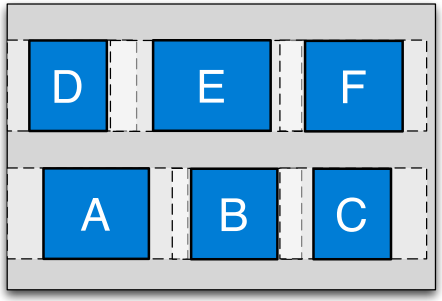
- 1D-OSP and 2D-OSP problems:



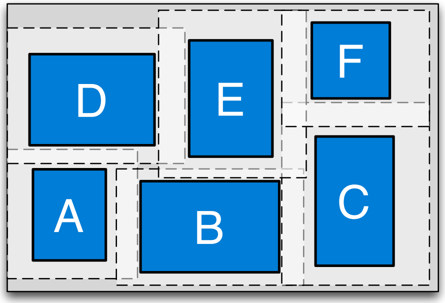


Problem Formulation-- Complexity

- ***Lemma 1***: 1D-OSP is NP-hard
  - Reduced from Multiple-Knapsack problem



- ***Lemma 2***: 2D-OSP is NP-hard
  - Reduced from Strip Packing problem



- New challenges for MCC system:
  1. New total shot# functions
  2. More character number (more than 4000)

E-BLOW

E-BLOW for 1D-OSP

- ILP formulation

$$\min \quad T_{total} \qquad (2)$$

$$\text{s.t} \quad T_{total} \geq T_c^{VSB} - \sum_{i=1}^{n}(\sum_{k=1}^{M} R_{ic} \cdot a_{ik}), \ \forall c \in P \qquad (2a)$$

$$x_i + w_i \leq W, \qquad \forall i \in N \qquad (2b)$$

$$\sum_{k}^{m} a_{ik} \leq 1, \qquad \forall k \in M \qquad (2c)$$

$$x_i + w_{ij} - x_j \leq W(2 + p_{ij} - a_{ik} - a_{jk}) \qquad (2d)$$

$$x_j + w_{ji} - x_i \leq W(3 - p_{ij} - a_{ik} - a_{jk}) \qquad (2e)$$

a_{ik}, a_{jk}, p_{ij} : ~~0-1 variable~~ (2f)

  - NP-hard to solve ILP, runtime penalty.
  - LP relaxation cannot be applied here. Why? ($a_{ik} = a_{jk} = 0.5$)

E-BLOW for 1D-OSP (cont.)

- Simplified ILP formulation

$$\max \sum_i \sum_j a_{ij} \cdot profit_i \tag{3}$$

$$\text{s.t.} \quad \sum_i (w_i - s_i) \cdot a_{ij} \leq W - B_j, \forall j \tag{3a}$$

$$B_j \geq s_i \cdot a_{ij}, \forall i \tag{3b}$$

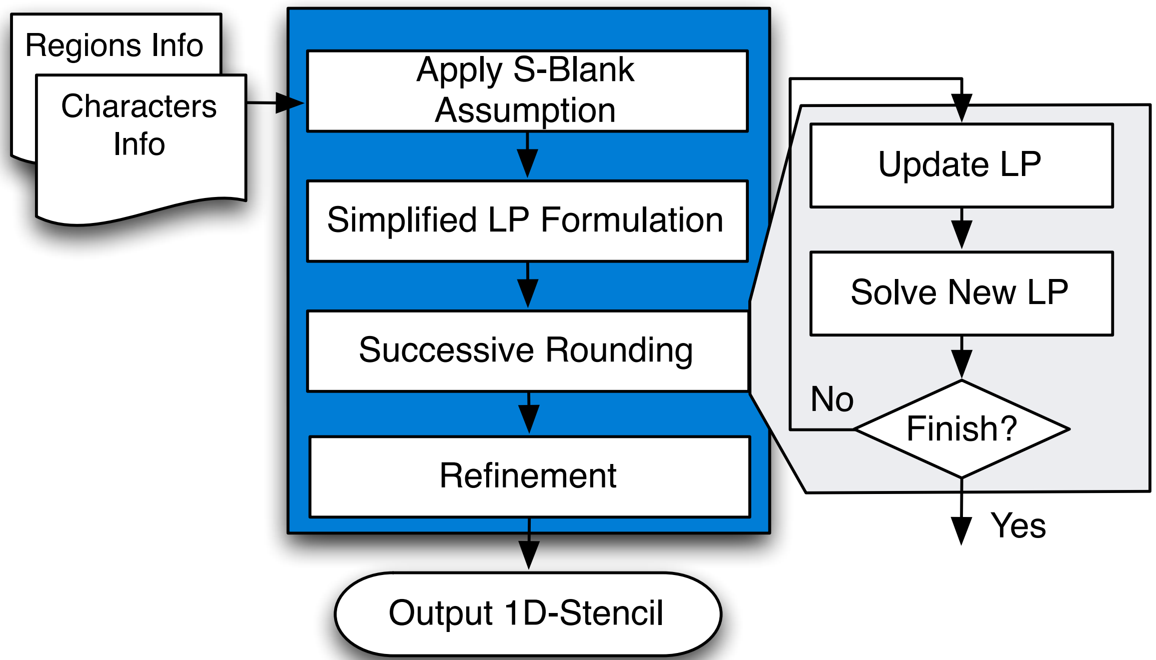
$$\sum_j a_{ij} \leq 1, \quad \forall c_i \in C^C \tag{3c}$$

$$a_{ij} = 0 \quad \text{or} \quad 1 \tag{3d}$$

- **Theorem**: The LP Rounding solution of (3) can be a **0.5/α – approximation** to program (3'), where (3') is a similar multiple knapsack problem.

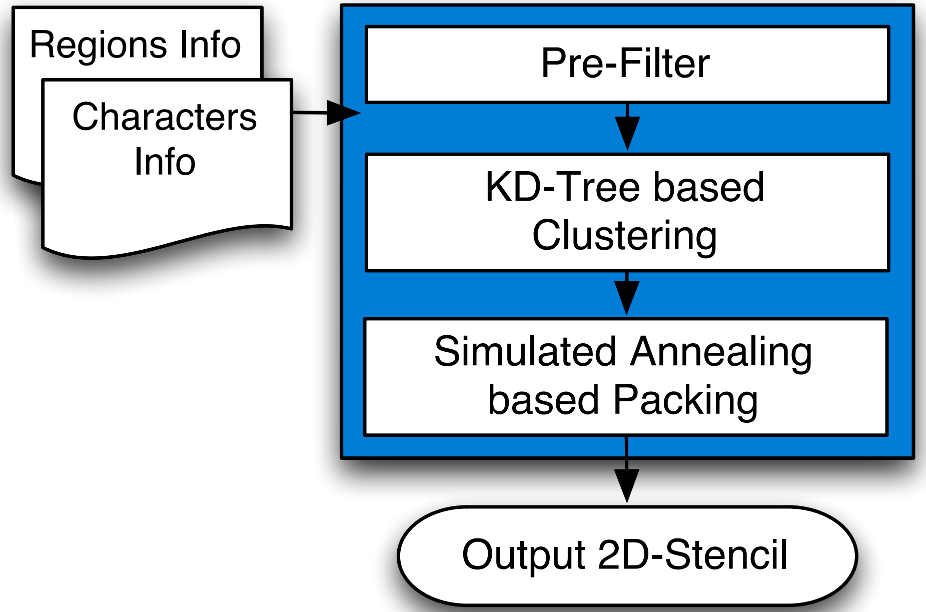
E-BLOW for 1D-OSP (cont.)

- Novel iterative solving framework to near-optimal solution
- LP relaxation with lower bound theoretically
- Successive rounding
- Dynamic programming based refinement



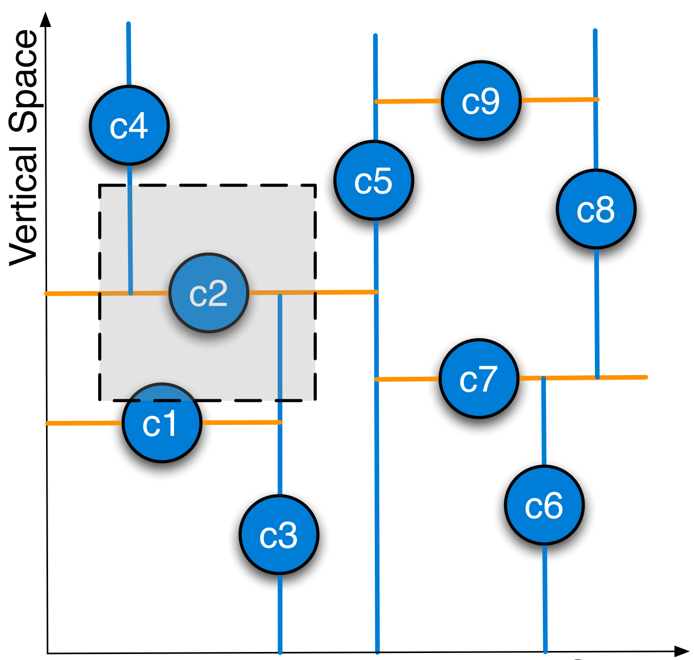
E-BLOW for 2D-OSP

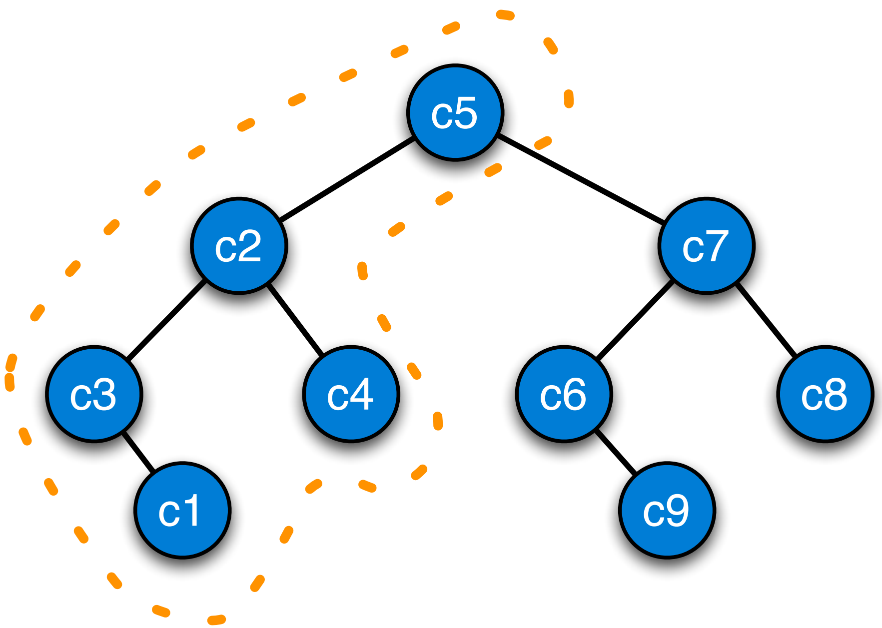
- Simulated annealing based framework.
- Sequence Pair as topology representation.
- Pre-filter process to remove bad characters.
- Clustering is applied to achieve speedup.



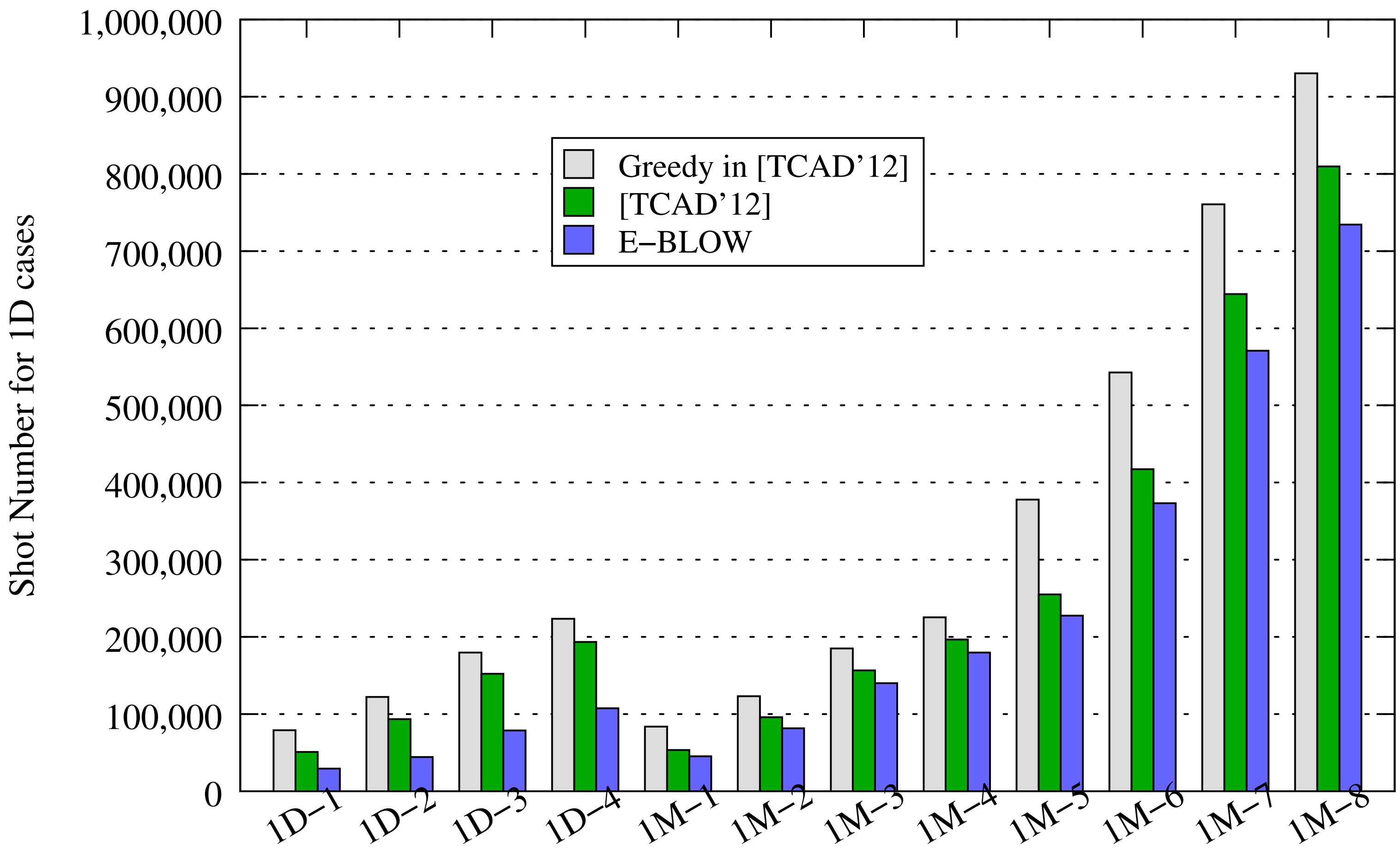
E-BLOW for 2D-OSP (cont.)

- KD-Tree based Clustering
  - Speed-up the process of finding available pair;
  - From *O(n)* to *O(logn);*
  - For *c2* to find another candidate with the similar space, only scan *c1 − c5.*



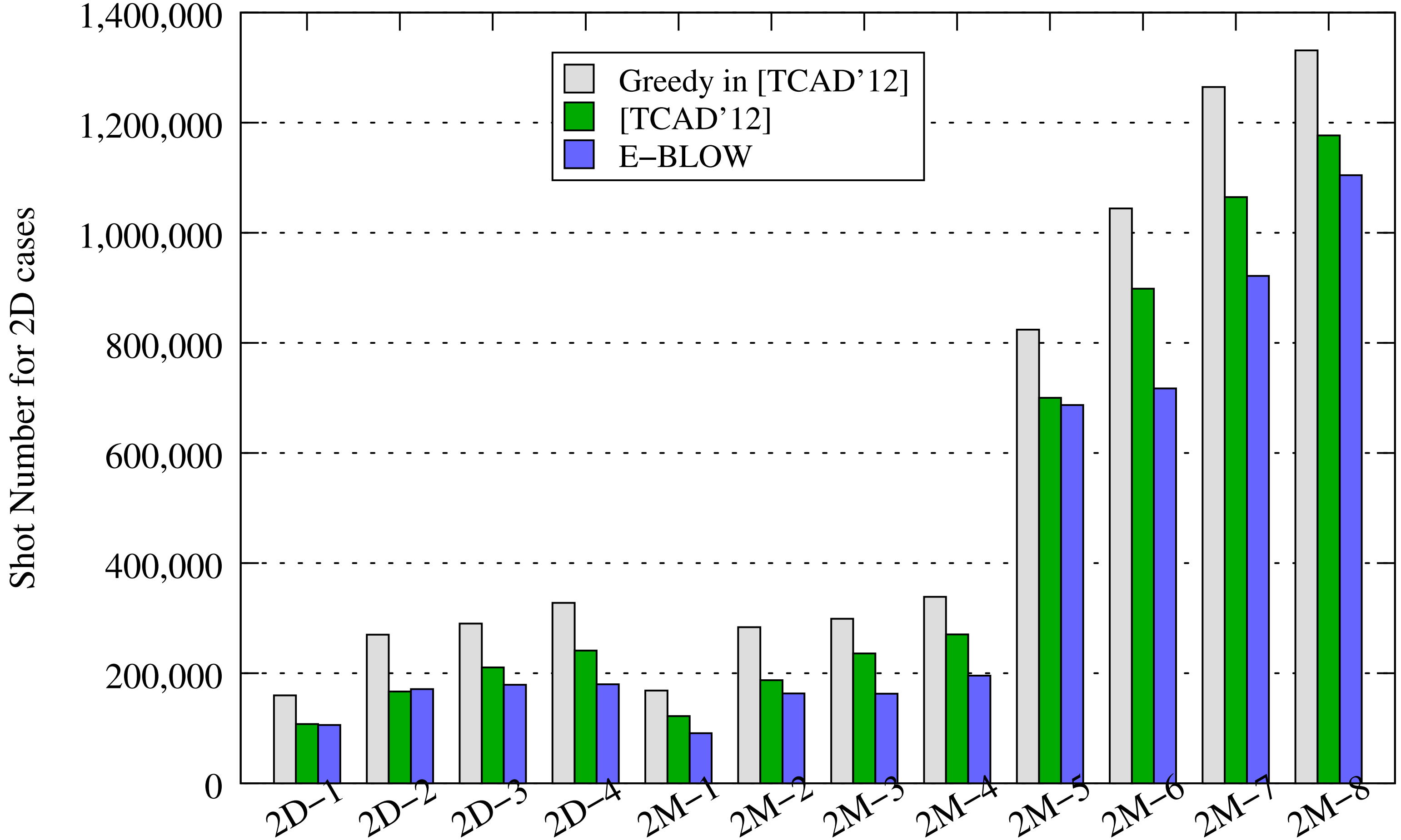


1D-OSP Writing Time Comparison



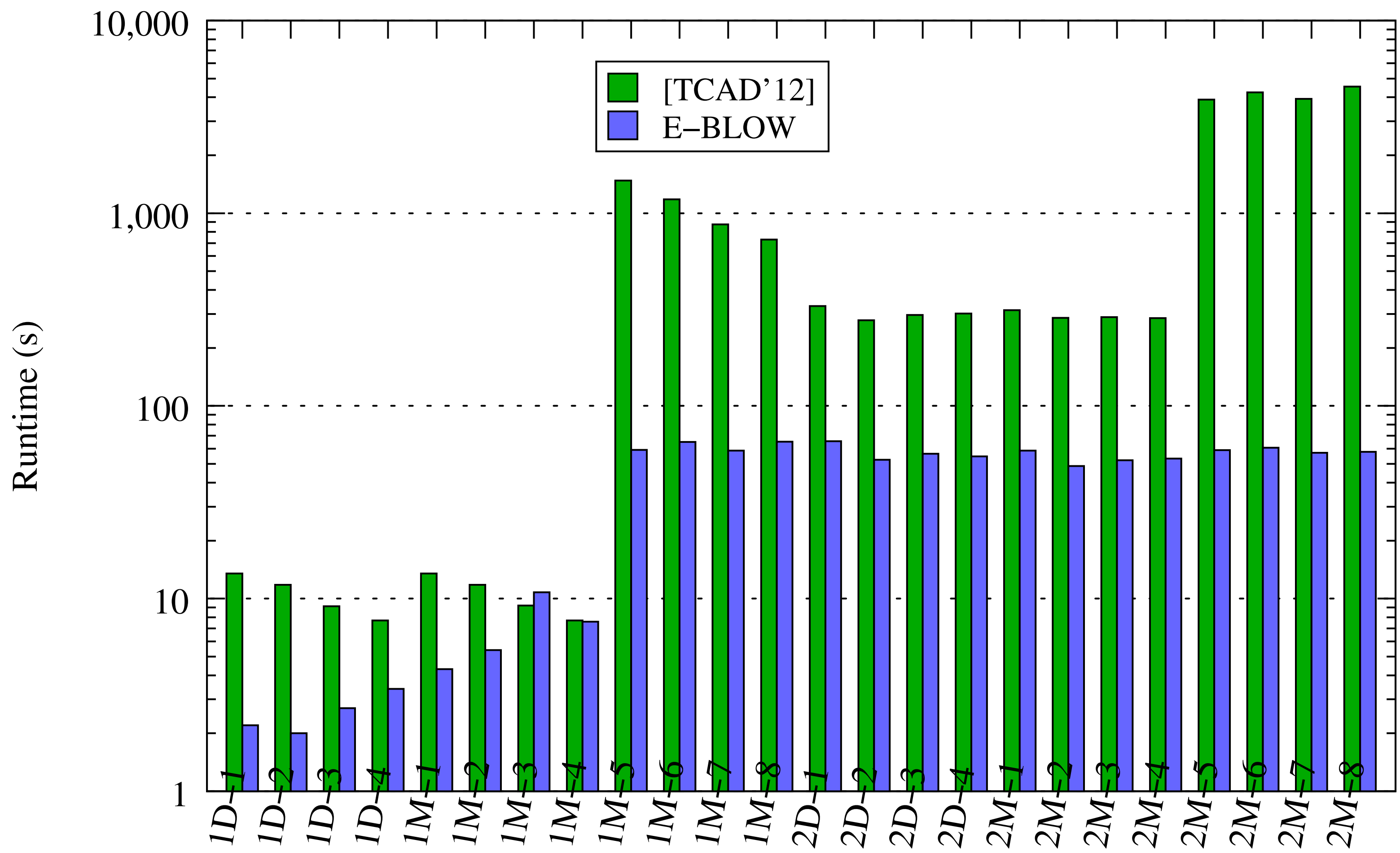
- For 1D cases, greedy algorithm introduces 47% more wafer writing time, and [TCAD'12] introduces 19% more wafer writing time.

2D-OSP Writing Time Comparison



- For 2D cases, greedy introduces 30% more wafer writing time, while [TCAD'12] introduces 14% more wafer writing time.

CPU Runtime Comparison



- Compared with [TCAD'12], E-BLOW can reduce 34.3% of runtime for 1D cases, while 2.8× speedup for 2D cases.

Conclusion

- E-BLOW, a tool to solve OSP problem in MCC system.
- E-BLOW can achieve better performance in terms of wafer writing time and CPU runtime, for both MCC system and traditional E-Beam system.

- E-Beam is under heavy R&D, including massive parallel writing.
  - More research to improve the throughput of E-Beam
  - More research on the E-Beam-aware design

♦ Thank You