There is a unique map from a design to a fabrication plan.
Fabrication-Oriented Design

Design Space

Fabrication Space
From A Design to Multiple Fabrication Plans

A design

Least Fab Time

Jigsaw

Chopsaw

A

C
From a Design to Multiple Fabrication Plans

A design Pareto-optimal frontier
Design and Fabrication Plans as Programs

A sequence of geometric construction operations (Code)

A sequence of physical instructions (Code)

compiler

Wu, Chenming, Haisen Zhao, Chandrakana Nandi, Jeffrey I. Lipton, Zachary Tatlock, and Adriana Schulz. "Carpentry compiler." ACM Transactions on Graphics (TOG) 38, no. 6 (2019): 1-14.
What if you want to optimize the design itself?
Considering Design Variations

| Fab. Time | Material Cost | Input design |
|-----------|---------------|--------------|
| 80%       | 15%           |              |

$10.0
6.67 min

$12.0
1.37 min

$8.5
2.98 min

5%
Co-optimization of Design and Fabrication Plans

Multiple design variations, Pareto-optimal fabrication plans.
Search Challenges: Multilevel

Search over designs $\mathcal{D}$

Search over plans $\mathcal{F}$

Space of Fabrication Plans

Given $d \in \mathcal{D}$, search over fab. plans $\mathcal{F}$

$\exists J = \mathbb{R}^d \oplus \mathbb{R}^f$

The constraint region of the upper-level problem is implicitly determined by the lower-level optimization problem.
Search Challenges: Multi-level

Fabrication Time (min)

Material Cost (dollar)

8-10

For instance, in 66438 design variations, more than 10000 hours...
Approach

Search Algorithm

Data Structure

Expansion

Contraction

Pareto Front

Extraction

Pareto fronts

Initialization
Key Insight: Equivalent Substructures!
E-graphs for design and fabrication
Defining equivalence
Bag-of-Parts (BOP) E-graph

Atomic node
Union node
E-class
BOP of E-class
Approach

Search Algorithm
Typical E-Graph Search

\[
\begin{align*}
E & \quad + \\
   & \quad + \quad * \\
3 & \quad 2 \\
   & \quad + \quad 4 \\
   & \quad + \\
   & \quad 3 \\
   & \quad 2 \\
E & \quad + \\
   & \quad + \quad * \\
3 & \quad 2 \\
   & \quad + \quad 4 \\
   & \quad + \\
   & \quad 3 \\
   & \quad 2
\end{align*}
\]
Iterative Contraction and Expansion on E-graphs
ICEE Overview

Feasible design space $\mathcal{D}$

...
Preparing to Contract and Expand

A1

A2

A3

A4

A5

A6

A7

A8

A9

A10

A11

E1: [x, y, y, z]
E2: [y, z, w, w]
E3: [x, y]
E4: [
E5: [w, w]
E6: [x]
E7: [y]
E8: [z]
E9: [w]
E10: [w]

0.85
0.95
0.25
0.45
0.65
0.65
0.15
0.85
0.25
0.35

Exploration
Impact

25
Contraction

Expansion

Pareto Front

Extraction

Pareto fronts

Initialization

A

A

A

A

E1: { x y z }

E4: { y z }

E3: { x y }

E7: { y }

E8: { z }

E6: { x }

E5: { w w }

E9: { w }

U1

U4

A

A

A

A

A

A

A

A

A

A

0.45

0.85

0.65

0.65

0.25

0.15

0.85

0.95

0.35

0.15
Terminal Conditions

Expansion

Contraction

Pareto Front

Extraction

Pareto fronts

Initialization

Material cost

Fab. time

A_{11}

A_{12}

A_{13}

A_{14}

A_{15}

A_{16}

E_{1}:

E_{2}:

E_{3}:

E_{4}:

E_{5}:

E_{6}:

E_{7}:

E_{8}:

E_{9}:

E_{10}:

E_{11}:

E_{12}:

E_{13}:

E_{14}:

U_{1}

U_{2}

U_{3}

U_{4}

U_{5}

U_{6}

U_{7}

U_{8}

U_{9}

0.45

0.65

0.85

0.95

0.65

0.85

0.45
Approach

Iterative Contraction and Expansion on E-graphs

Bag-of-Part (BOP) E-graphs

Expansion

Contraction

Pareto Front Extraction

Pareto fronts

Initialization
Benefits of Design Exploration

20-30%

30-35%

50-60%

[$82.0, 0.81 inches, 36.]

[$79.5, 0.14 inch]
Benefits of Design Exploration:

- 7%
- 7%
- 15%
Benefits of Design Exploration

62%  

79%  

74%  

82%
Benefits of Design Exploration

From initial design
From design exploration

Fab. Time vs Material

Fab. Time vs Material

Fab. Time vs Material
Comparison with Experts

Expert design (gray) vs Design exploration

Expert plan (green) vs Design variant plan

Fab. Time vs Material

E...
## Comparison with Baseline Method

| Model        | $|D|$ | #EDV | Time (min)       |
|--------------|-----|------|------------------|
|              |     |      | Ours       | Baseline   |
| Frame        | 13  | 8    | 2.8          | 6.5        |
| Jungle Gym   | 54  | 18   | 109.0     | 761.2      |
| Long frame   | 65  | 19   | 8.2       | 59.7       |
| Table        | 1140| 59   | 40.8      | 612.8      |
| Window       | 10463| 116 | 131.7     | 2050.0     |
Extensions

- Spruce plywood
- Fiberboard sheet
- Aluminum sheet

Max U: 0.202

Max U: 0.564

Max U: 0.591

Max U: 0.202

Max U: 0.102
Future Work

• Continuous design variations

• Application of the ICEE strategy

• Objective extension: appearance, ease of assembly…

• Learning-based method to speedup the Pareto front extraction phase
  • Predict the objective metrics of an arrangement
Designs and fabrication plans are programs!