Optimization of Design and Fabrication Plans for Carpentry

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

$$\mathbb{R}^D \rightarrow \mathbb{R}^F$$

Design Space

Fabrication Space
From Design to Multiple Fabrication Plans

A design Pareto-optimal frontier

Material cost vs. fabrication time
Design and Fabrication Plans as Programs

A sequence of geometric construction operations (Code)

A sequence of physical instructions (Code)

What if you want to optimize the design itself?
Considering Design Variations

- Design Variations
- Material Cost: 15%
- Fab. Time: 80%

$10.0  
6.67 min

$12.0  
1.37 min

$8.5  
2.98 min

$8.5  
5%
Co-optimization of Design and Fabrication Plans

Multiple design variations

Pareto-optimal fabrication plans

Material cost

Fabrication time
Search Challenges: Multilevel

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

$J = \mathbb{R}^D \oplus \mathbb{R}^F$

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

More than 10000 hours

For in 66438 design variations
Approach

Search Algorithm

Data Structure

Expansion

Contraction

Pareto Front

Extraction

Pareto fronts

Initialization
Key Insight: Equivalent Substructures!

Within a single design variation

Across different design variations

[Diagram showing equivalent substructures across different designs]
Equivalence graphs (E-graphs)

E-graphs for design and fabrication

Atomic e-nodes

Union e-nodes

Bag of parts A

Bag of parts B

E-class for BOP A

E-class for BOP B

A

B

E
Defining equivalence:

\[ \square \square \square = \square \square \square \]

\[ \square \square \square = \square \square \square \]

\[ \square \square \square = \square \square \square \]

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Approach

Search Algorithm

Bag-of-Part (BOP) E-graph

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Initialization
Typical E-Graph Search
Iterative Contraction and Expansion on E-graphs
ICEE Overview

Input design

Feasible design space $\mathcal{D}$
Terminal Conditions

Expansion

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Iterative Contraction and Expansion on E-graphs

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Pareto fronts

Initialization
Benefits of Design Exploration

- 20-30%
- 30-35%
- 50-60%

36.48 minutes
15.42 minutes!
Benefits of Design Exploration

7%

7%

15%

2.34 inches, 59.50 mins]
Benefits of Design Exploration

- 62% error reduction
- 74% error reduction
- 79% error reduction
- 82% error reduction
Benefits of Design Exploration
Comparison with Experts

Expert design (gray) vs Design exploration

Expert plan (green) vs Design variant plan

Material

Fab. Time

Material

Fab. Time
| 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!