Outline

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Introduction: Why Evolutionary Developmental Design?

- Growing complexity of engineering designs and manufacturing problems:
  - Need more compact ways of representing engineering design problems
  - Need more efficient ways of searching through such representation spaces
- Interest in designs/solutions exhibiting patterns or some form of structure
  - Need representations facilitating emergence of patterns/structures
  - Need representations which can include design knowledge
Introduction: Why Use Only Simplified Models?

- We cannot model all biological details
  - Complexity issues
  - Still too many unknown factors
  - Do not have yet sufficient computational power
- We don’t even need to create faithful models
  - Simple models can be more tractable
  - They can be better suited if we want to understand the impact of relevant factors of the problem
Steel Structural Systems in Tall Buildings: Design Problem

- Design an “optimal” steel structural system in a tall building
- Find “novel” design concepts
Steel Structural Systems in Tall Buildings: Model and Assumptions

- Simplified 2D model of a 3D structure
- Topological optimum design problem, i.e., optimal configuration of design members sought
- Types of members:
  - 7 types of bracings
  - 5 types of beams
  - 5 types of columns
  - 4 types of supports
Steel Structural Systems in Tall Buildings: Direct Representation

Symbolic attributes are combined together and form a linear genome

- Non-homogeneous genome
- Genome length is equal to 135 genes:
  50 columns + 40 beams + 40 wind bracings + 5 supports
Steel Structural Systems in Tall Buildings: Direct Representation

• Only wind bracing subsystem represented:
  – 7 possible types of wind bracings (0-6)
  – Beams, columns, and supports kept fixed

• Three types of design problems considered:
  – Problem 1 – No bracing and Simple X bracings
  – Problem 2 – No bracing and K bracings
  – Problem 3 – all 7 types of bracings
Steel Structural Systems in Tall Buildings: Design Evaluation

1. Translation
2. Application of loads
3. Structural analysis and calculation of the total weight
4. Assignment of fitness - total weight
Developmental Representations
Developmental representation consists of two parts:

– encoding of the ‘design embryo’
– encoding of a ‘design rule’ which is applied to the design embryo to develop a design concept from it
Developmental Representations

Design embryo:
- an ordered set of wind bracing types modeled as a group of “cells”
- represents an initial configuration of structural members
- forms an embryo from which a design concept is grown
Developmental Representations

Design rule:

– Encodes a set of instructions which transform the current configuration of structural members into a new configuration
– One such transformation defines a unit time step.
Developmental Representations

Example of a developed design to be evaluated

Developmental representation of a structural design

Developing Design

Development

Design embryo

Design rule
Developmental Representations: Cellular Automata

a) design embryo  design rule

b) 1D CA design rule

c) 6 bays

1D CA design rule
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1D CA design rule
1D CA design rule

story 16
story 15
story 14
story 13
story 12
story 11
story 10
story 9
story 8
story 7
story 6
story 5
story 4
story 3
story 2
story 1 = design embryo
Developmental Representations: Why CAs?

- Simplicity
- Direct relationship between discrete states and time steps and types of structural members in topological optimum design problems
- Capability to model local and spatial interactions
- Ability to generate emergent patterns
Developmental Representations: Why CAs?

• Compactness:
  – Direct representations – 150 genes
  – CA representations:
    • Problems 1 and 2: 13 genes
    • Problem 3: 348 genes but when totalistic CAs used only 24 genes

• Simplicity of enforcing symmetry constraint
  – Need symmetric design embryos
  – Need to constrain outcome values of a CA rule:
Design of Experiments: Research Questions

- What is the impact of the configuration of the design embryo (arbitrary configuration vs. randomly generated configuration) on the fitness of generated designs (Problems 1 and 2)?
- What is the impact of the symmetry constraint on the fitness of generated design (Problems 1 and 2)?
- What are the differences in evolvability between direct and developmental encodings in the context of structural design applications (all 3 problems)?
## Design of Experiments: Experimental Parameters

<table>
<thead>
<tr>
<th>Domain</th>
<th>Values</th>
<th>EA</th>
<th>Values</th>
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</thead>
<tbody>
<tr>
<td># of bays</td>
<td>5</td>
<td>Representation</td>
<td>CA or Direct</td>
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<tr>
<td># of stories</td>
<td>30</td>
<td>CA rule types</td>
<td>Standard or Totalistic, Radius 1 or 2</td>
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<td>Bay width</td>
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<td>EA type</td>
<td>Evolution Strategies</td>
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<td>Mutation rates</td>
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<td>Beams</td>
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<td>Crossover rates</td>
<td>0.0, 0.2, 0.5</td>
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<td>Columns</td>
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<td>Fitness</td>
<td>Total weight</td>
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<td>Supports</td>
<td>Fixed</td>
<td>Runs</td>
<td>5</td>
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<td>Types of wind bracings</td>
<td>7 types</td>
<td>Termination</td>
<td>1,000 (short-term), or 10,000 (long-term) evaluations</td>
</tr>
</tbody>
</table>
Experimental Results: Design Embryo Configuration

- Impact of arbitrarily selected design embryos vs. randomly generated design embryos tested

- Problems 1 and 2 only:
  - 256 possible CA rules – “CA contest”:
    - each CA rule was applied to the arbitrarily selected design embryos, and
    - each CA rule was applied to 5 randomly generated design embryos
Experimental Results: Design Embryo Configuration

- Best designs for **Problem 1** produced from the arbitrary design embryo:

  - Best design produced by rule 51 with the total weight of 560,646 lbs.
  - Configurations of wind bracings exhibit 3 different types of patterns
Experimental Results: Design Embryo Configuration

• Best designs for Problem 2 produced from the arbitrary design embryo:
  - Rule 151, 159, 183, 191, 215, 223, 247, 255
  - Rule 251
  - Rule 235
  - Rule 249
  - Rule 222, 254
  - Rule 19

• Best design produced by several CA rules with the total weight of 450,234 lbs.
• Configurations of wind bracings exhibit mostly fully-braced pattern
Experimental Results: Design Embryo Configuration

- Best designs for Problem 1 produced from the random design embryos:
  - Best design produced by rule 154 with the total weight of 550,366 lb (about 10,000 lbs. better than with the arbitrary embryo)
    - Thus, design embryo configuration has an impact on the design fitness
  - Configurations of wind bracings exhibit different types of patterns
Experimental Results: Symmetry Constraint

- Impact of the symmetry constraint on the fitness of design concepts
- Problems 1 and 2 only:
  - Only 64 symmetric CA rules:
    - each symmetric CA rule was applied to 8 symmetric design embryos:
Experimental Results: Symmetry Constraint

- Best symmetric designs for **Problem 1**

- Best design produced by rule 50 with the total weight equal to 556,177 lbs. (6,000 lbs. **worse** than design developed from random embryo)
  - Thus, design embryo configuration does not have a positive impact on improving design fitness

- Several distinct patterns found
Experimental Results: Evolvability

- All three problems considered in this group of experiments
- Genomes composed of design embryos and design rules (without symmetry constraint) were evolved by evolutionary algorithms
- Both standard and totalistic CA representations used and compared to direct representations
Experimental Results: Evolvability – Problem 2
Experimental Results: Evolvability – Problem 3
Experimental Results: Evolvability – Problem 1
Conclusions

- **Simple** evolutionary developmental system presented and tested on three structural design problems
- Cellular automata representations of wind bracing systems introduced
  - Composed of two parts: design embryo and design rule
  - Iteratively develop full design concepts from the design embryo
- Several key parameters of CA representations tested:
  - Configuration of design embryo – more complex configurations had positive impact on design fitness
  - Symmetry constraint - didn’t not have a positive impact on design fitness
Conclusions

• Compactness and Evolvability
  – CA encodings were usually more compact than direct representations (in cases when they were not, totalistic CAs could be used instead)
  – When evolved, they produced better results than direct representations in terms of fitness and ability to quickly locate optimal regions in the search space for 2 of out 3 considered structural design problems
  – CA representations bias the search toward solutions exhibiting patterns:
    • If such patterned solutions correspond to optimum regions of the search space then CA encodings should be superior
    • Otherwise, they may produce inferior results when compared to direct encodings
Questions