Emergent Engineering Design
Design Creativity and Optimality Inspired by Nature

Final Defense
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Outline

1. Introduction
2. Emergent Engineering Design
3. Research Validation
4. Dynamics of Design Processes
5. Contributions
6. Conclusions
7. Future Work
1. Introduction

- Motivation
- Problem Statement
- Research Questions and Hypotheses

2. Emergent Engineering Design

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1. Introduction

Motivation

- Growing complexity of artifacts (built engineering systems)
- Increased competition and globalization
  - Innovation = competitive advantage
  - Numerical optimization not sufficient
- A need for a coherent method addressing two objectives:
  - Development of novel designs
  - Optimization of engineering systems
Motivation

- Inspiration from Nature
- Complex systems as models of phenomena occurring in nature
  - Simplicity of mechanisms and potential richness of generated behaviors
- A fact that designers usually use only a small set of design/decision rules to develop design concepts
1. Introduction
   ✓ Motivation
   ➡ Problem Statement
   ▪ Research Questions and Hypotheses

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Problem Statement

- How to establish a design method based on models of complex systems that would satisfy two major engineering objectives:
  - Develop novel designs, and
  - Optimize engineering systems

- If proposed, developed, and implemented:
  - Enhances traditional engineering design process
  - Provides new understanding of engineering design
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1. Introduction

Research Questions and Hypotheses

**Fundamental Research Question**

How can one construct an effective method for designing engineering systems that would support development of novel designs and their efficient optimization?

**Fundamental Hypothesis**

Emergent Engineering Design, a design method in which all three major elements of engineering design (i.e. design representation, actual design process, and design evaluation) are modeled as complex systems, can effectively produce novel designs and efficiently optimize them.
1. Introduction

Research Questions and Hypotheses

Ultimate Dissertation Objective

Develop an engineering design method based on models of complex systems that provides a conceptually coherent framework for producing novel designs and their efficient optimization.

- Design novelty (representation space definition)
- Design decomposition
- Design generation and optimization
- Design evaluation
1. Introduction

Research Questions and Hypotheses

**Research Question 1 (Represent):**

Based on the existing knowledge on how to represent engineering systems; what mechanisms and models can be used to produce novel designs?

**Research Hypothesis 1:**

Evolutionary Design and Complex Systems provide a framework for defining generative representations, i.e. representations of engineering systems based on simple programs, which can successfully produce novel designs.

**Research Question 3 (Generate and Optimize):**

One of the major objectives of almost all engineering design processes is achieving optimality; what mechanisms should be used to efficiently optimize engineering designs?

**Research Hypothesis 3:**

Evolutionary Computation provides a framework for conducting engineering design processes and optimizing engineering designs.
2. Emergent Engineering Design

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   - Assumptions
   - Design Representations
   - Design Processes
   - Design Evaluation
   - Overview

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2. Emergent Engineering Design

Assumptions

Phases of a Conceptual Design Process

Core of the Design Method

- Representation Space Definition
- Generation and Optimization of Design Concepts
- Design Decomposition
- Design Evaluation
Assumptions

Generality of Structural Design Representations

- Atoms
- Single members
- Small sets of members
- Components (substructures)
- Entire structures
2. Emergent Engineering Design

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Design Representations

- Incorporate:
  - representation of an artifact being designed
  - representation of a design process

- Computational/abstract descriptions of engineering systems expressed in terms of attributes

- Choice of a particular representation is strongly influenced by a designer’s goal:
  - optimality, or
  - novelty
Design Representations

- **Parameterized** representations (optimality):
  - Focus restricted to a particular design concept or at most several concepts
  - Attributes encoded directly as genes

- **Generative** representations (novelty):
  - Design concepts generated by rules
    - Cellular Automata (Frazer 1995)
    - Embryogenies (Bentley and Kumar 1999)
    - L-systems (Hornby and Pollack 2002)
Design Representations

Size of the search space: $2.4\times10^{90}$

Exhaustive search requires $2.24\times10^{84}$ years of computing time (1 eval. = 30 s.)
2. Emergent Engineering Design

Design Representations

fitness = the total weight of the structural system
Can We Do Better?

Sure, we can....

But how...???

“You have to graduate... Students don’t get tenure.”
How about going a step further in imitating the nature?

- **Morphogenesis** – a process of development of a structure of an organism or a part.
Morphogenic Design
Why Cellular Automata?

- One of the simplest mathematical representations of complex systems
- Models for complex systems and processes consisting of a large number of identical, simple, locally interacting components
- Discrete dynamical system simulators used to study pattern formation and self-organization processes
Generative Representations

Consist 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
Generative Representations

Design embryo:

- an ordered set of cell values
- represents an initial configuration (usually one-, or two-dimensional) of structural members (e.g. types of wind bracing, beams, columns)
- forms a seed from which a design concept is developed
Generative Representations

Design rule:

- A formal description of a transformation that changes the current configuration of structural members into a new configuration.
- This transformation defines a unit time step.
Generative representation of a wind bracing system

Developmental process of constructing a wind bracing system from its generative representation (time trajectory of a cellular automaton)
1. Introduction

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   ✓ Assumptions
   ✓ Design Representations
   - Design Processes
   □ Design Evaluation
   □ Overview

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Design Processes

- Categories of models of engineering design processes:
  - Formal models
  - Heuristic models
  - Agent-based models

- Emergent Engineering Design can be classified as a heuristic (generate-and-test) model of a design process
Design Processes

- Mechanisms of generation of design concepts:
  - Generative representations (cellular automata)
  - Evolutionary algorithms

- Generative representations component constitutes the creative part of Emergent Engineering Design

- Evolutionary computation component provides the optimization mechanisms
2. Emergent Engineering Design

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Design Evaluation

- Provides measure of quality/fitness of generated design concepts
- Enables comparisons among generated design concepts and selection of the best ones
- Usually conducted by specialized structural analysis packages, e.g. SODA combined with evaluation models
2. Emergent Engineering Design

Design Evaluation: Multi-stage Process

- Generative representation
- Design concept
- Application of loads
- Detailed design
- Structural analysis and sizing optimization
- Total weight
- Assign fitness

SODA
2. Emergent Engineering Design

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Overview

Emergent Engineering Design

- Design Representation
- Design Decomposition
- Design Generation and Optimization
- Design Evaluation

Synthesis

- Computer Science
- Biology
- Engineering
- Mathematics
3. Research Validation

1. Introduction
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3. Research Validation
   - Validation Methodology
   - Empirical Performance Validation
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Validation Methodology

- Validation of the design method conducted using the Validation Square methodology (Pedersen et al. 2000):
  - Qualitative validation:
    - Theoretical Structural Validity (TSV)
    - Empirical Structural Validity (ESV)
  - Quantitative validation:
    - Empirical Performance Validity (EPV)
    - Theoretical Performance Validity (TPV)
3. Research Validation

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  - Validation Methodology
  - Empirical Performance Validation
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The proposed design method was implemented in a computer system called *Emergent Designer*.
Emergent Designer

- Integrated research and design support tool:

<table>
<thead>
<tr>
<th>Unified Evolutionary Computation Engine (De Jong)</th>
<th>Cellular automata computation using <em>Mathematica</em> (Wolfram Research)</th>
<th>Design evaluation conducted by SODA (Grierson)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical and dynamical Systems analysis (JSML)</td>
<td>Automatic report generation using <em>OpenOffice.org</em></td>
<td>Visualization (Mathematica &amp; PtPlot)</td>
</tr>
</tbody>
</table>
3. Research Validation

Design Experiments

- Extensive empirical studies conducted:
  - Investigation of the usefulness of the individual components:
  - Empirical studies of the integrated components:

  **Phase I**
  - Generative representations (novelty)

  **Phase II**
  - Evolutionary computation (optimization)

  **Phase III**
  - Generative representations evolved by evolutionary algorithms (novelty + optimization)
Design Experiments

- Two conceptual design problems considered:
  
  Design of a wind bracing system
  
  2 types of wind bracings:
  - simple X bracings
  - K bracings
  7 types of wind bracings

  Design of the entire steel structural system in a tall building
Generative Representations

- Representations studied:
  - Elementary CA (two possible cell values)
  - 1D CA (7 possible cell values)
  - 2D CA

- Impact of various representation parameters:
  - Type of CA rules (standard vs. totalistic)
  - Type of design embryo (arbitrary vs. random)
  - Boundary conditions (periodic vs. non-periodic)
  - Location of the design embryo (top vs. bottom)
  - Symmetry constraint
### Generative Representations

- Remarkable structural shaping patterns discovered (elementary CA)
- Most important representation parameters identified:
  - Type of CA rules
  - Radius of the local neighborhood

#### Phase I
Generative representations (novelty)
Evolutionary Computation

- Parameterized representations only
- Two types of evolutionary algorithms studied:
  - Evolution Strategies
  - Genetic Algorithms
- Extensive sensitivity analyses conducted involving the following parameters:
  - Mutation rates
  - Crossover rates
  - Parent and offspring population sizes
  - Types of the generational model
3. Research Validation

Evolutionary Computation

Typical best-so-far curves:

fitness = the total weight of the structural system

Phase II
Evolutionary computation (optimization)
Evolutionary Computation

Typical average improvements:

- 5-8% in the short-term experiments (1,000 evals)
- 10-12% in the long-term experiments (10,000 evals)
Evolutionary Computation

Typical improvements between the best designs found in evolutionary optimization experiments and best designs found in a random search of CA rules

Short-term (1,000 evals)    Long-term (10,000 evals)

Phase II
Evolutionary computation (optimization)
Evolutionary Computation

- Comparison with the Known Design Concepts

**Phase II**

- **Evolutionary computation (optimization)**

**3. Research Validation**

**Populations 1 and 2** – poor quality parents
**Population 3** – ‘optimal’ parents
**Population 4** – medium quality parents
**Large population** – all above

![Graph showing improvement percentages for different populations.](image-url)
Evolutionary Computation

- Most important evolutionary computation parameters:
  - Type of evolutionary algorithm (ES better)
  - Population sizes (small sizes preferred)
  - Mutation rates (lowest preferred)
  - Initialization procedure (starting from known designs improves the final results)
Morphogenic Evolutionary Design

- Generative representations component integrated with the evolutionary computation component
- Several types of generative representations investigated:
  - Elementary CA
  - 1D CA
  - 2D CA
- Sensitivity analyses involving:

  Generative representation parameters:
  - Type of CA rules
  - Radius of the local neighborhood

  Evolutionary computation parameters:
  - Mutation and crossover rates
  - Population sizes

Phase III
Generative representations evolved by evolutionary algorithms (novelty + optimization)
Morphogenic Evolutionary Design

Typical average best-so-far curves (design of wind bracing system with 2 types of elements):

- **totalistic CA rules** outperformed parameterized representations
- also, …
- they found ‘optimal’ solution very fast (in less than 100 evaluations)
3. Research Validation

Morphogenic Evolutionary Design

Typical average best-so-far curves (design of the entire steel structural system):

Best results produced by **totalistic 1D CA** rules

also, …

**standard 1D CA rules** **outperformed** parameterized representations
### 3. Research Validation

**Morphogenic Evolutionary Design**

- Interesting structural shaping patterns found

- Morphogenic Optimization Only

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<table>
<thead>
<tr>
<th>Standard CA Radius = 1</th>
<th>Standard CA Radius = 2</th>
<th>Totalistic CA Radius = 1</th>
<th>Totalistic CA Radius = 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>547,428</td>
<td>548,283</td>
<td>559,982</td>
<td>563,865</td>
</tr>
<tr>
<td>5.4582</td>
<td>5.4386</td>
<td>4.8465</td>
<td>6.6902</td>
</tr>
</tbody>
</table>

**Phase III**

Generative representations evolved by evolutionary algorithms (novelty + optimization)
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   - 1D Cellular Automata
   - 2D Cellular Automata
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1D Cellular Automata

Even simplest CA rules produced diverse dynamical behavior and generated interesting structural shaping patterns.
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2D Cellular Automata

- More difficult to qualitatively study dynamical properties of design processes
  - High-dimensionality (150 variables)
2D Cellular Automata

but …

- Dynamics of 2D CA design concept generators can studied based on 1D time series
- Not 1-to-1 mapping but provides useful insights

Dynamics of Design Processes

![Graph showing transient and fixed-point behavior](image)
2D Cellular Automata

- Diverse dynamical behavior found:
  - Fixed-point
  - Periodic (of almost arbitrary period)
  - Chaotic

![Graph showing max. horizontal displacement over a range of values]
Why is Dynamics Important?

- **Computation:**
  - May reduce computational efforts
    - Stop iteration when fixed-point behavior or periodic behavior reached

- **Novelty:**
  - Chaotic trajectories generate new design concepts at each iteration -> ‘trajectories of innovation’
5. Contributions

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5. Contributions
   - New Knowledge
   - Originality
   - Significance
   - Limitations

6. Conclusions

7. Future Work
5. Contributions

New Knowledge

- An integrated and conceptually coherent design method based on complex systems
- A consistent system of models and methods regarding engineering design with a strong emphasis on both novelty and optimization
- A class of representations of both engineering systems and design processes inspired by the processes occurring in nature
5. Contributions

New Knowledge

- A design support tool based on the models and methods proposed
- Experimental results which demonstrated the feasibility, novelty, and potential practical value of the proposed design method
5. Contributions

✓ 1. Introduction
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✓ 4. Dynamics of Design Processes
✓ 5. Contributions
  ✓ New Knowledge
    ➡ Originality
  □ Significance
  □ Limitations

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5. Contributions

Originality

- Novel, coherent, and relatively complete design method based on complex systems
- Novel generative representations of design concepts of engineering systems
- Novel designs of steel structural systems in tall buildings
5. Contributions

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5. Contributions
- New Knowledge
- Originality
- Significance

- Limitations

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5. Contributions

Significance

- Addresses two most important goals in engineering design: novelty and optimality
- Builds a bridge between design by nature and engineering design
- Potential applicability to a wide range of engineering design problems
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5. Contributions
   - New Knowledge
   - Originality
   - Significance
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Limitations

- Rapid growth of the CA rule spaces when the number of cell values increases
- Simple representations based on elementary CA may not be sufficient for some design problems
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Conclusions

- Emergent Engineering Design – a coherent design method based on complex systems
  - Ultimate Dissertation Objective achieved!
- Two important engineering objectives satisfied
  - Novel design concepts discovered
  - Efficient optimization of engineering systems performed
- A paradigm change from optimality only to novelty and optimality
- Nature Inspired Engineering Design - A promising direction of future research?
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Future Work

- Remaining two phases of the engineering design process:
  - Decomposition (co-evolutionary algorithms)
  - Evaluation (adaptive testing)

- Other types of generative representations:
  - More elaborate simple programs
    - non-uniform CA
    - mobile automata, …
  - L-systems
Future Work

- Other problem domains:
  - Discrete problems
    - space structures
    - bridges
    - …
  - Continuum problems
    - plates
    - shells (finite elements)
Acknowledgements

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Acknowledgements

- IT&E Computing Resources
- Wolfram Research
- Parents and Wife
Relevant Publications


Relevant Publications


Thank you!
Backup Slides
Qualitative Validation

■ Theoretical Structural Validity:
  □ Demonstration of validity of the components constituting Emergent Engineering Design (EED):
    ■ Based on the extensive literature review (chapter 2)
  □ Demonstration of internal consistency of the way the components were integrated:
    ■ Flow-chart representations focused on information flow (chapter 5)

■ Empirical Structural Validity:
  □ Demonstration of the appropriateness of the example problems used to test the proposed design method:
    ■ Documenting that the example problems represent the actual problems for which the EED is intended (chapters 2 and 4)
Quantitative Validation

- **Empirical Performance Validity:**
  - Demonstration that the outcome of the method is useful for the chosen example problems:
    - Generative representations component produces novel design concepts (chapter 6)
    - Evolutionary computation component optimizes engineering systems (chapter 7)
    - Integrated components produce novel design concepts and efficiently optimize them (chapter 8)

- **Theoretical Performance Validity:**
  - Demonstration by induction that entails all previous validation steps (chapter 9)
  - Based on that the generality is claimed, understood here as the usefulness of the EED beyond the tested example problems (chapter 9)
Generative Representations 2D CA

2D Design Embryo

Design Rule - 2D CA Rule

Generative Representation

design embryo (linearized 2D array)  design rule (2D CA rule)
Generative Representations 2D CA

Shapes of the local neighborhood

radius = 1

radius = 1

radius = 1

radius = 1

radius = 1

radius = 2

radius = 2

radius = 2

radius = 2

radius = 2

Moore neighborhood

von Neumann neighborhood

Diagonal neighborhood

North-South neighborhood

East-West neighborhood
Generative Representations 2D CA

6 bays

30 stories

design rule (2D CA rule)

design embryo (2D array)

t = 0
t = 1
t = iteration_max

generated design concept
Developed Design Concepts

$t = 28$ \[\text{totalistic 2D CA rule}\] $t = 29$ \[\text{totalistic 2D CA rule}\] $t = 30$ \[\text{totalistic 2D CA rule}\] $t = 31$ \[\text{totalistic 2D CA rule}\] $t = 32$
Morphogenetic Evolutionary Design

Backup Slides
Morphogenic Evolutionary Design

![Graph showing evolutionary fitness over birth count for different CA rules and radii. The x-axis represents birth count, and the y-axis represents average best-so-far fitness. The graph includes data points for standard CA rule with radius 1, standard CA rule with radius 2, and totalistic CA rule with radius 1.]
Morphogenetic Evolutionary Design
Morphogenic Evolutionary Design
Novelty Criteria

“Creativity in design is not simply concerned with the introduction of something new into a design, although that appears to be a necessary condition for any process that claims to be labeled creative. Rather, the introduction of ‘something new’ should lead to a result that is unexpected (as well as being valuable).” (Gero 1996)

3 important aspects of a novel design concept:
- Something new (unknown design concept)
- Something unexpected (unexpected structural shaping pattern)
- Something valuable (measured by its performance and feasibility)
Cellular Automata: Mechanism

a) CA rule

b) 0 1 1 1 1 1 0 1 0 0 1 1 0 0 1 0 0 0

c) 0 1 1 1 1 1 0 1 0 0 1 1 0 0 1 0 0 0

d) t=0

t=1

t=2

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Formal Models

- Aim to establish engineering design science:
  - Systematic approach to engineering design (Pahl and Beitz 1984)
  - Axiomatic Design Theory (Suh 1990)
  - Formal grammars (both context-free and context-sensitive) (Mullins and Rinderle 1991)
  - Shape grammars (Stiny 1980)
  - TRIZ (Altshuller 1969)
Heuristic Models

- Based on the generate and test (trial-and-error) method:
  - Morphological analysis (Arciszewski 1977)
  - Protocol analysis (Stauffer et al. 1987)
  - Simulated annealing (Shea et al. 1997)
  - Evolutionary computation (Goldberg 1986, 1989)
  - Genetic Design (Roston 1994)
Agent-based Models

- Provide modular, distributed and knowledge-based approach to model design processes:
  - Multi-agent design systems (MADS) (Shen and Barthes 1995)
  - Agents with preferences (D’Ambrosio and Birmingham 1995)
  - Multi-agent systems for design space decomposition (Parmee 1996)
  - Agent-based conceptual design in dynamic environments (Campbell et al. 1999)
  - Function-behavior-structure framework for situated agents (Gero and Kannengiesser 2003)
Conceptual Design

Forms an initial stage of a design process

“Conceptual design is that part of the design process in which, by the identification of the essential problems through abstraction, by the establishment of function structures and by the search for appropriate working principles and their combination, the basic solution path is laid down through the elaboration of a solution principle. Conceptual design determines the principle of a solution.”

(Pahl and Beitz 1996)
2D Cellular Automata
Morphogenic Evolutionary Design

Evolutionary Optimization (left) vs. Morphogenic Evolutionary Design (right)

Short-term

Long-term
Evolutionary Optimization