Soft Computing: Industrial Applications

Andrew Kusiak
Intelligent Systems Laboratory
2139 Seamans Center
The University of Iowa
Iowa City, IA 52242 – 1527
andrew-kusiak@uiowa.edu
http://www.icaen.uiowa.edu/~ankusiak

Based on material provided by P. P. Bonissone

Outline

- Overview of soft computing
  - Introduction and SC components
- Hybrid soft computing
- Modeling with FL and EA
- Applications of Hybrid SC
- Conclusions

Soft Computing

- Soft computing includes:
  - Approximate reasoning:
    » Probabilistic reasoning, fuzzy logic
  - Search and optimization:
    » Neural networks, evolutionary algorithms

Soft Computing: Illustrative Applications

SC Technologies
- Neural nets (NN)
- Fuzzy logic (FL)
- Probabilistic reasoning (PR)
- Genetic algorithms (GA)
- Hybrid systems

Related Technologies
- Statistics (Stat.)
- Artificial intelligence (AI):
  - Case-based reasoning (CBR)
  - Rule-based expert systems (RBR)
- Machine learning (ML)
- Bayesian belief networks (BBN)

Applications
- Classification
  - Monitoring/Anomaly detection
  - Diagnostics
  - Prognostics
  - Configuration/Initialization
- Prediction
  - Quality assessment
  - Equipment life estimation
- Scheduling
  - Time/Resource assignments
- Control
  - Machine/Process control
  - Process initialization
  - Supervisory control
- DSS/Auto-decision making
  - Cost/Risk analysis
  - Revenue optimization

Problem Solving Technologies

HARD COMPUTING

- Precise Models
  - Symbolic logic reasoning
  - Traditional numerical modeling and search

SOFT COMPUTING

- Approximate Models
  - Approximate reasoning
  - Functional approximation and randomized search

Soft computing (SC): The symbiotic use of emerging problem-solving tools.

According to L. Zadeh:
"...in contrast to traditional hard computing, soft computing exploits the tolerance for imprecision, uncertainty, and partial truth to achieve tractability, robustness, low solution cost, and better rapport with reality"
Hybrid Soft Computing

• Overview of soft computing
  - Introduction and SC components
• Hybrid soft computing
  • Modeling with fuzzy logic and evolutionary algorithms
  • Applications of Hybrid SC
• Conclusions
Synergy in Soft Computing

- **Loose Hybridization (Model Fusion)**
  - Combines methodologies *outputs, not features*
  - Outputs are compared and aggregated, to *increase reliability*

- **Hybrid Search Methods**
  - Intertwining *local* search within *global* search
  - Embedding knowledge in operators for global search

**Hybrid SC Applications**

- **Soft computing overview**
  - Introduction and SC Components

- **Hybrid soft computing**
  - **Modeling with FL and EA**
  - Applications of Hybrid SC
  - Conclusions
Modeling

• Model = Structure + Parameters + Search Method

• Classical control theory:
  - Structure: order of the differential equations
  - Parameters: coefficients of differential equations.
  - Search method: gradient.

Example (MISO): Max-min Composition with Centroid Defuzzification

- If X is SMALL and Y is SMALL then Z is NEG. LARGE
- If X is SMALL and Y is LARGE then Z is NEG. SMALL
- If X is LARGE and Y is SMALL then Z is POS. SMALL
- If X is LARGE and Y is LARGE then Z is POS. LARGE

Response surface

Example (MISO): Max-min Composition

Soft Computing: Evolutionary Algorithms

- Most evolutionary algorithms (EAs) can be described by:
  \[ x[t+1] = s(v(x(t))) \]
  - \( x[t+1] \): the population at time \( t \)
  - \( v(x) \): the variation operator(s)
  - \( s(x) \): the selection operator

Evolutionary Computation: Scalar-Valued Fitness Function

- Example: Find the maximum of the function \( z(x,y) \)

  \[ z = f(x, y) = 3*(1-x)^2*exp(-(x^2) - (y+1)^2) - 10*(x/5 - x^3 - y^5)*exp(-x^2-y^2) \]

  Example: Find the maximum of the function \( z(x,y) \)

  - \( x, y \): the population providing a random sample of solution space
  - \( z \): the fitness function

  Generation 0
  - Initial population
  - Genetic algorithm

  Evolutionary programs

  Generation 10
  - By evolving the individuals, we create a bias in the sampling and over-sample the best region(s) getting "close" to the optimal point(s)
Modeling Using Evolutionary Algorithms

• Evolutionary Algorithm:
  - The structure of the model is the representation of an individual in the population (e.g., binary string, vector, parse tree, finite state machine).
  - The parameters of the model are the population size, mutation probability, recombination probability, etc.
  - The search method is a global search based on maximization of the fitness function.

Soft Computing: Applications

• Overview of soft computing
  - Introduction and SC components
• Hybrid soft computing
  - Modeling with FL and EA
  - Applications of Hybrid SC
• Conclusions

Prediction of Paper Web Breakage

Example

- Developed a web breakage propensity indicator and a time-to-break predictor for the wet-end of a paper machine.

System Schematics

- Example system schematics

Summary of Selected Variables

<table>
<thead>
<tr>
<th>Sensor ID</th>
<th>Meaning</th>
<th>GE-17</th>
<th>Visualization</th>
<th>CART</th>
<th>Logistic Regression</th>
<th>Dropped</th>
<th>Reason To Drop</th>
</tr>
</thead>
<tbody>
<tr>
<td>s1</td>
<td>TMP feed, flow</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>s2</td>
<td>Chemical pulp feed</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>s3</td>
<td>Broke feed</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>s4</td>
<td>Filler to centrifugal cleaner pump</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>s5</td>
<td>Clay flow</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>s6</td>
<td>Broke to broke screen</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>s7</td>
<td>Broke percentage</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>s8</td>
<td>Bleached TMP percentage</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>s9</td>
<td>Total retention</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>s10</td>
<td>Ash retention</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>s11</td>
<td>Chemical pulp freeness</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>s12</td>
<td>Chemical pulp pH</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>s13</td>
<td>Chemical pulp conductivity</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>s14</td>
<td>TMP conductivity</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>s15</td>
<td>Broke conductivity</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>s16</td>
<td>Wire water pH</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>s17</td>
<td>Wire pit temperature</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>s18</td>
<td>Headbox conductivity</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>s19</td>
<td>Retention aid flow</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>s20</td>
<td>Retention aid/dilution tank</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>s21</td>
<td>Foam inhibitor flow to wire pits</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>s22</td>
<td>Slice lip position</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>s23</td>
<td>Wire section speed</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>s24</td>
<td>Ash content</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>s25</td>
<td>K-moisture</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>s26</td>
<td>White water pH</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>s27</td>
<td>White water tower temperature</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>s28</td>
<td>TMP proportioning chest</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>s29</td>
<td>Air content</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>s30</td>
<td>Headbox ash consistency</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>s31</td>
<td>Broke pH</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>s32</td>
<td>Chemical pulp percentage</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>s33</td>
<td>Chemical pulp feed, consistency</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>s34</td>
<td>Chemical pulp FEED, consistency</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>s35</td>
<td>Chemical pulp percentage</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>s36</td>
<td>Machine pulp</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>s37</td>
<td>TMP 1 tower pH</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>s38</td>
<td>TMP 2 tower pH</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>s39</td>
<td>Retention aid pipe pressure before screens</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>s40</td>
<td>Outer wire, wire water</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>s41</td>
<td>Draw difference 4th press - 1st drier-section</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>s42</td>
<td>Alkaline feed</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>s43</td>
<td>Draw difference 3rd - 4th press</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

Principal Components Analysis (PCA)

<table>
<thead>
<tr>
<th>Principal Components</th>
<th>Eigenvalue</th>
<th>Proportion</th>
<th>Cumulative</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRINC1</td>
<td>14.42</td>
<td>90.14%</td>
<td>90.14%</td>
</tr>
<tr>
<td>PRINC2</td>
<td>0.45</td>
<td>3.02%</td>
<td>93.16%</td>
</tr>
<tr>
<td>PRINC3</td>
<td>0.25</td>
<td>1.62%</td>
<td>94.78%</td>
</tr>
<tr>
<td>PRINC4</td>
<td>0.11</td>
<td>0.72%</td>
<td>95.50%</td>
</tr>
<tr>
<td>PRINC5</td>
<td>0.05</td>
<td>0.35%</td>
<td>95.85%</td>
</tr>
<tr>
<td>PRINC6</td>
<td>0.02</td>
<td>0.14%</td>
<td>95.99%</td>
</tr>
<tr>
<td>PRINC7</td>
<td>0.00</td>
<td>0.00%</td>
<td>96.00%</td>
</tr>
<tr>
<td>PRINC8</td>
<td>0.00</td>
<td>0.00%</td>
<td>96.00%</td>
</tr>
<tr>
<td>PRINC9</td>
<td>0.00</td>
<td>0.00%</td>
<td>96.00%</td>
</tr>
<tr>
<td>PRINC10</td>
<td>0.00</td>
<td>0.00%</td>
<td>96.00%</td>
</tr>
<tr>
<td>PRINC11</td>
<td>0.00</td>
<td>0.00%</td>
<td>96.00%</td>
</tr>
<tr>
<td>PRINC12</td>
<td>0.00</td>
<td>0.00%</td>
<td>96.00%</td>
</tr>
<tr>
<td>PRINC13</td>
<td>0.00</td>
<td>0.00%</td>
<td>96.00%</td>
</tr>
<tr>
<td>PRINC14</td>
<td>0.00</td>
<td>0.00%</td>
<td>96.00%</td>
</tr>
<tr>
<td>PRINC15</td>
<td>0.00</td>
<td>0.00%</td>
<td>96.00%</td>
</tr>
<tr>
<td>PRINC16</td>
<td>0.00</td>
<td>0.00%</td>
<td>96.00%</td>
</tr>
</tbody>
</table>

Data size: 6,999 by 31
The First 3 Principal Components

- 1\(^{st}\) Principal Comp.
  - 1\(^{st}\) Derivative
  - 2\(^{nd}\) Derivative
  - Difference from steady state

Filtering First 3 Principal Components

Feature Extraction of First Three Principal Components

- 1\(^{st}\) Principal Comp.
- 2\(^{nd}\) Principal Comp.
- 3\(^{rd}\) Principal Comp.

Classification Tree Analysis for Web Breakage Propensity

<table>
<thead>
<tr>
<th>V14 Time since shift change in minutes</th>
<th>V5 PC1 deviation from steady state</th>
<th>V3 PC1 first derivative</th>
<th>BR/NB Break/No Break</th>
</tr>
</thead>
<tbody>
<tr>
<td>Last 1/3 = 1 hour: break indication</td>
<td>Previous 2/3 = no break indication</td>
<td>Misclassification: 10.6%FP; 14.8%FN</td>
<td></td>
</tr>
</tbody>
</table>

System Schematics

Adaptive Network-based Fuzzy Inference Systems (ANFIS)
### Trend Analysis: Time-to-Break Against Predictions

- Predicted time to break
- Actual time to break

### Prediction Error at time 60, i.e., E(60):

- **Limits for Useful Predictions and Results**
  - **Early Predictions:** (5) Premature warning may cause too many corrections
  - **No Predictions:** (14) $E(60)$
  - **Late Predictions:** (3) Not enough time to take corrective actions
  - **Useful Predictions:** (80) Enough time to take corrective actions

### Training and Testing Process

- **Data preparation**
  - Input data:
    - Scrubbing segmentation variable selection
    - PCA, filtering smoothing feature extraction, clustering normalization transformation shuffling

- **Scripts for training process**:
  - ANFIS Algorithms
  - Decision Trees

- **Run-time system**
  - Time-to-break prediction
  - Run time rule set

### Decision Engine Parameter Tuning/Optimization

- **Approach:** Iterative Process
  - Space of Decision Engine Design
  - Evolutionary Algorithm
  - Design Parameter Representation
  - Population of Trial Solutions

- **Evaluation Process**
  - Decision Engine Interface
  - Decision Engine Tuning/Optimization

- **Computation of Rate Class Decision Mismatch Penalties**
  - Decision Engine Design
  - Decision Mismatch Penalties
  - Validated Case Decision
  - Loop through all cases in Case Base

- **Rule Based Decision Engine (RBDE) Parameter Tuning**

- **Problem Definition**
  - Space of a decision engine design
  - Space of positive real numbers
  - Decision mismatch penalty function

### Decision Mismatch Penalties

<table>
<thead>
<tr>
<th>Decision Engine Parameter</th>
<th>Tuning/Optimization</th>
<th>Evolutionary Algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Create initial population</td>
<td>${x_i}$</td>
<td>Population of trial solutions</td>
</tr>
<tr>
<td>Proportional selection</td>
<td>${x'_i} = S{x_i}$</td>
<td>(exploitation)</td>
</tr>
<tr>
<td>Intermediate population</td>
<td>${x'_i} = V{x'_i}$</td>
<td>(exploration)</td>
</tr>
<tr>
<td>New population</td>
<td>${x'_i}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Decision Engine Parameter Representation

- Population of Trial Solutions
  - Each individual in a given population represents a possible decision engine design parameter set

### Decision Engine Tuning/Optimization

- Population of Trial Solutions
- Evolutionary Algorithm
- Design Parameter Representation
- Population of Trial Solutions

### Decision Mismatch Penalties

- Decision Engine Parameter Tuning/Optimization
- Evolutionary Algorithm
- Decision Mismatch Penalties
- Validated Case Decision
- Loop through all cases in Case Base

### Decision Engine Parameter Tuning/Optimization

- Decision Engine Tuning/Optimization
- Evolutionary Algorithm
- Decision Mismatch Penalties
- Validated Case Decision
- Loop through all cases in Case Base

### Decision Mismatch Penalties

- Decision Engine Parameter Tuning/Optimization
- Evolutionary Algorithm
- Decision Mismatch Penalties
- Validated Case Decision
- Loop through all cases in Case Base
Conclusions: Soft Computing Applicability

- Applied soft computing to a broad range of applications, providing significant benefits in both cost and growth to many businesses.
  - Classification (Power gen., medical systems, aircraft engines, transportation)
  - Prediction (Industrial systems)
  - Scheduling
  - Control (Industrial systems, trading)
  - DSS (Autonomous decision making (Financial applications))
- Synergy in applications of hybrid soft computing:
  - Technology: Combination of knowledge and data used to derive initial structure and to refine parameters via local or global search
  - Application: Solution commonality

Business Impact

- Instantaneous decisions:
  - Faster to the customer
  - Enable creation of new products
  - Reduce percentage of not-taken policies
- Consistency with business rules (Lower UW variability):
  - Better pricing, higher margins
  - Possibly reduced reinsurance premium
  - Reduced risk (Improved reserve position)
- Instant response to change:
  - Lead the market
  - Intellectual property protection
- Process control:
  - Six sigma capability

Conclusions: SC New Directions

- Present -> Short term developments
  - SC technologies are (or will soon be) implemented on alternative, non-standard computing mechanisms
  - Evolvable Hardware (Field programmable gate arrays)
  - Bio-inspired systems: DNA and molecular computing
- Medium term developments
  - SC technologies are (or will soon be) implemented on alternative, non-standard computing mechanisms
  - Evolvable Hardware (Field programmable gate arrays)
  - Bio-inspired systems: DNA and molecular computing

Conclusions: SC Experiments

- Bio-inspired Systems: DNA and molecular computing (Examples)
  - Molecular genetic programming (Guerrieri & Manzoni, 2001)
  - Representations of GP graphs by DNA molecules, with crossover and mutation operators implemented using electric techniques in DNA computing
  - DNA-based fuzzy systems (Ishigami & Katagiri, 2000)
  - Encoding of fuzzy membership functions by DNA (hybridization processes), leading to the representation of initial rules sets (fuzzy-antecedent memory)
  - Fuzzy inference performed by annealing/hybridization processes
  - DNA neural network computation (no, exact, 2001)
  - DNA analog neural network in which atoms and ions are replaced by dihydro and molecular recognition of DNA
  - DNA evolutionary computation (Woodcock, 2000)
  - Binary-coded evolutionary algorithms, with primitive mutation and crossover, implemented on molecular computing, evaluating the “Pankov’s” function

*Annealing/Cool hybridization of a pair of complimentary DNA strands under provide a representation of highly parallel selective operations that is key for molecular computing (Adleman, 1994).