Multi-objective Optimization Approach for Sustainable Pavement Maintenance and Rehabilitation Programming

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Acknowledgements

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MODAT – Multi-Objective Decision-Aid Tool for Highway Asset Management
EMSURE – Energy and Mobility for Sustainable Regions

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✓ Adelino Ferreira

National Sustainable Pavement Consortium
Mississippi, Pennsylvania, Wisconsin and Virginia DOT, FHWA, and Virginia Tech

✓ James Bryce
The Asset Management Process

- **DATABASE**
  - Inventory
    - Condition
    - Usage
    - Maintenance Strategies

- **INFORMATION MANAGEMENT**

- **CONDITION ASSESSMENT**
  - Performance Prediction
  - Needs Analysis

- **NETWORK-LEVEL ANALYSIS TOOLS**
  - Condition Assessment
  - Prioritization / Optimization
  - Programming

- **PROJECT LEVEL ANALYSIS (Design)**

- **WORK PROGRAM EXECUTION**

- **FEEDBACK**

- **STRATEGIC ANALYSIS**
  - Goals & Policies
    - System Performance
    - Economic / Social & Environmental
  - Budget Allocations

- **PRODUCTS**
  - Network-Level Reports
    - Performance Assessment
    - Network Needs
    - Facility Life-cycle Cost
    - Optimized M&R Program
    - Performance-based Budget

- **ECONOMIC, SOCIAL AND ENVIRONMENTAL IMPACTS**

- **PROJECT SELECTION**
  - Programming

- **PERFORMANCE PREDICTION**
  - Needs Analysis

- **PERFORMANCE MONITORING**

- **GRAPHICAL DISPLAYS**

- **CONSTRUCTION DOCUMENTS**

- **Goals & Policies**
  - Economic / Social & Environmental

- **Network Needs**

- **Facility Life-cycle Cost**

- **Optimized M&R Program**

- **Performance-based Budget**

- **Virginia Tech Transportation Institute**
Objective

- To develop a multi-objective optimization framework that hosts a comprehensive and integrated pavement life cycle cost and life cycle assessment model that covers the whole pavement’s life cycle (cradle to grave)

- To apply the model to improve the management of our pavement assets
Why Multi-objective Optimization?

- Sustainable transportation systems require decisions in a context of:
  - Economic development
  - Ecological sustainability
  - Social desirability

- All resource allocation involve some kind of tradeoff.

- Multi-objective optimization finds a set of decision variables (Pareto set of solutions):
  - Satisfies constraints
  - "Balances" various objective functions (performance criteria)
Antecedent: Adding a 3rd Objective: Minimizing the Life Cycle Environmental Impact

- Objectives:
  - Assess the environmental impacts of road-related practices, strategies, and materials
  - Implement a procedure to include these eco-efficiency values into a more comprehensive decision support system

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Incorporating the Use-phase into LCA for Pavements - Approach

National Sustainable Pavement Consortium

Literature Review - LCA

Project Level Analysis

Collaboration with University of Coimbra

Network Level Analysis

Expand Boundaries Given Updated Models

Energy Sources

Include LCA in Network Level Analysis

Probabilistic Analysis

Use LCC Results in Decision Making

Multi-criteria Analysis

Virginia Tech Transportation Institute
Framework
LCCA
Optimization of Transportation Costs
What factors are important?
How Important?

How we account for them?

- Climate Change (CC)
- Acidification (AC)
- Eutrofization (EU)
- Pollution that affect Human Health (HH)
- Consumption of Energetic Resources (ADR ER)
- Consumption of Mineral Resources (ADR MR)
- Photchemical Smog (PS)

LCA Framework

- Following
  - UCPRC Pavement LCA (Harvey et al., 2010)
Pavement Phases Considered in the LCCA/LCA

Materials Extraction and Production

Construction and M&R

Usage

Congestion

End-of-Life
Multi-Objective Optimization-Based Decision Support System for Sustainable Pavement Management

MOO Module
- Model Formulation
  - Decision Variables
  - Objective Functions
  - Constraints
- Solution Approach
  - Augmented Weighted Tchebycheff
- Solution Algorithm
  - AHGA

Data Management Module

Integrated Pavement LCC-LCA Model
- Energy Sources Production
- Materials
  - Construction and M&R
  - WZ Traff. Manag.
  - Usage
  - EOL
- Disposal
- System Boundaries

Decision-Support Module
- Pareto Front
- Best Optimal Compromise Solution (BOCS) Selection

Results Report Module
- BOCS's Performance Evaluation:
  - Optimal M&R strategy
  - Pavement’s functional quality report
  - LCHAC report
  - LCRUC report
  - LCI report
  - LCEI report

Getting Started
- General Inputs
- Goal and scope definition
- Detailed Inputs
Multi-Objective Optimization Model Formulation

**Objective functions**

Minimize \( OF_1 = \sum_{t=1}^{50} \frac{1}{(1 + d)^t} \times \sum_{r=1}^{50} \left(C_{rt}^{\text{MatExt Pr od}} + C_{rt}^{C.M \& R} + C_{rt}^{TM}\right) \times X_{rt} \) \hspace{1cm} (1)

**Agency Cost**

Minimize \( OF_2 = \sum_{t=1}^{50} \frac{1}{(1 + d)^t} \times \left\{ \sum_{r=1}^{6} \left(VehOperC_{rt}^{WZTM} + TDC_{rt}^{WZTM}\right) \times X_{rt} \right\} + VehOperC_t^{\text{Usage}} \) \hspace{1cm} (2)

**User Costs**

Minimize \( OF_3 = \sum_{i=1}^{3} CF_i^{CC} \times \left\{ \sum_{t=1}^{50} \left[ \sum_{r=1}^{6} \left(LCI_{irt}^{\text{MatExt Pr od}} + LCI_{irt}^{C.M \& R} + LCI_{irt}^{TM} + LCI_{irt}^{WZTM}\right) \times X_{rt} \right] \right\} \) \hspace{1cm} (3)

**Env. Impacts**

\( CCI_t = \Phi \left( CCI_0, X_{11}, ..., X_{1t}, ..., X_{r1}, ..., X_{rt}\right), \quad r = 1, ..., 6; \quad t = 1, ..., 50 \)

\( X_{rs} \in \Omega \left( CCI_t \right), \quad r = 1, ..., 6; \quad t = 1, ..., 50 \)

\( CCI_t \geq CCI_{\text{min}}, \quad t = 1, ..., 50 \)

\( \sum_{r=1}^{6} X_{rt} = 1, \quad t = 1, ..., 50 \)

\( \ldots \)
Multi-Objective Optimization Model
Solution Approach

Define a combined Objective Function

\[
\max_{i=1,\ldots,3} \left[ w_i \times \frac{f_i(\bar{X}) - f_i^{\min}}{f_i^{\max} - f_i^{\min}} \right] + \rho \times \sum_{i=1}^{N_{obj}} \frac{f_i(\bar{X}) - f_i^{\min}}{f_i^{\max} - f_i^{\min}},
\]

Subject to:

\[
w_i \geq 0, \quad i = 1,\ldots,N_{obj}, \quad \sum_{i=1}^{N_{obj}} w_i = 1, \quad \rho \in \mathbb{R}
\]

\[
w_i + \rho > 0, \quad i = 1,\ldots,N_{obj}
\]

Solve using and Adaptive Hybrid Genetic Algorithm
Decision Support Model

- Choose the solution in the Pareto front furthest from the most inferior solution, according to the membership function concept in the fuzzy set theory.
- The solution with the maximum value of $\beta_j$ is considered as the best optimal compromise solution (BOCS).

\[
u_i^j = \frac{f_i^\text{max} - f_i^j}{f_i^\text{max} - f_i^\text{min}}
\]

Where $\beta_j$ is the fuzzy cardinal priority ranking of each non-dominated solution.
Example Applications
Example I – LCCA/LCA Model only Life-Cycle Assessment of I-81 Recycling Project in Virginia, USA

Functional unit: Section of Interstate 81:
✓ 5.89 km long
✓ 2 lanes
✓ Directional AADT in 2011: 25000 (28% trucks)
✓ Annual traffic growth rate: 3%
✓ Project analysis period: 50 years

50 year time horizon
All phases except EOL
✓ Use phase evaluated using Chatti and Zaabar’s NCHRP models and MOVES
✓ Traffic congestion effects considered using MOVES
✓ Impact Assessment using TRACI

Each alternative had different rehab. schedules
Compared 3 Strategies

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Initial Intervention</th>
<th>M&amp;R Plan</th>
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</thead>
<tbody>
<tr>
<td>Recycling-based</td>
<td>In-Place recycling</td>
<td>VDOT’s maintenance actions performed in years 12, 22, 32 and 44</td>
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<tr>
<td>Traditional Reconstruction</td>
<td>Traditional reconstruction</td>
<td>VDOT’s maintenance actions performed in years 12, 22, 32 and 44</td>
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<tr>
<td>Corrective Maintenance</td>
<td>Corrective Maintenance</td>
<td>VDOT’s maintenance actions performed in years 4, 10, 14, 18, 24, 28, 34, 38, 44 and 48</td>
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</table>
Example of LCA Results
Impact on Climate Change

Example II – Multiobjective Optimization
Comparison of the Life Cycle Environmental and Economic Performance of pavement Construction and M&R Practices

Functional unit:
- 1 km-long 2-lanes asphalt section
- AADT: 20000
- Traffic Growth Rate: 3%
- PAP: 50 years

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<tr>
<th>Type of scenario</th>
<th>ID</th>
<th>Scenario name</th>
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<tbody>
<tr>
<td>Conventional VDOT</td>
<td>1</td>
<td>HMA - 0% RAP</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>HMA - 15% RAP</td>
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<td>Recycling-based VDOT</td>
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<td>Sasobit® WMA - 30% RAP</td>
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<tr>
<td>Preventive maintenance</td>
<td>13</td>
<td>Microsurfacing - 0% RAP</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>THMACO - 0% RAP</td>
</tr>
</tbody>
</table>
Example II – Multiobjective Optimization (cont.)

- Maintenance and rehabilitation plans

1. Conventional VDOT scenario
   - CM: 12 and 44
   - RM: 22
   - Conventional RC: 32

2. Recycling-based VDOT scenario
   - CM: 12 and 44
   - RM: 22
   - Recycling-based RC: 32

3. Preventive maintenance: Microsurfacing
   - Conventional RC: 32
   - Microsurf.: 7, 15, 23, 39 and 47

4. Preventive maintenance: THMACO
   - Conventional RC: 32
   - THMACO: 7, 16, 24, 39, 47

- Pavement Performance Prediction Models:
  - CM, RM and RC:
    \[
    CCI(t) = CCI_0 - e^{a + b \times c \ln \left( \frac{1}{t} \right)}
    \]

<table>
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<tr>
<th>M&amp;R activity category</th>
<th>$CCI_0$</th>
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<th>$b$</th>
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<tr>
<td>RC</td>
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<td>9.176</td>
<td>9.18</td>
<td>1.22777</td>
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</tbody>
</table>
Example II – Multiobjective Optimization (cont.)

Multi-criteria decision making approach:

- TOPSIS method;
- Combinatorial weight assignment method for the 3 main criteria: AC; RUC; Environmental Impacts
- Seven environmental sub-criteria weighted according to BEES software’s weights.

\[ W_{\text{HAC}} = 1 \]
\[ W_{\text{RUC}} = 1 \]
\[ W_{\text{Env}} = 1 \]

\[ W_{\text{HAC}} + W_{\text{RUC}} + W_{\text{Env}} = 1 \]

Conclusions
Conclusions

- Developed a customizable optimization-based pavement management DSS which includes:
  - An integrated pavement LCC-LCA model
  - An AHGA combing GA with an LS mechanism for tackling the pavement life cycle optimization problem
  - A MOO-based pavement life cycle optimization model
Conclusions (cont.)

- Real and Simulated Case studies
  - Demonstrated its applicability and practicality
  - Provided insights on the efficiency of new pavement engineering solutions in improving the environmental and economic dimensions of pavement infrastructure sustainability
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