11th National Conference on Transportation Asset Management

July 10–12, 2016

Minneapolis Marriott City Center, Minneapolis, Minnesota

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

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Center for Sustainable Transportation Infrastructure

Contents

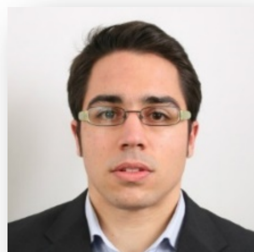
Acknowledgements

University of Coimbra & Portuguese Foundation for Science and Technology (Grant SFRH/BD/79982/2011)

MODAT – Multi-Objective Decision-Aid Tool for Highway Asset Management

EMSURE – Energy and Mobility for Sustainable Regions

- ✓ ***Joao Santos***



- ✓ *Adelino Ferreira*

National Sustainable Pavement Consortium

Mississippi, Pennsylvania, Wisconsin and Virginia DOT, FHWA, and Virginia Tech

- ✓ *James Bryce*

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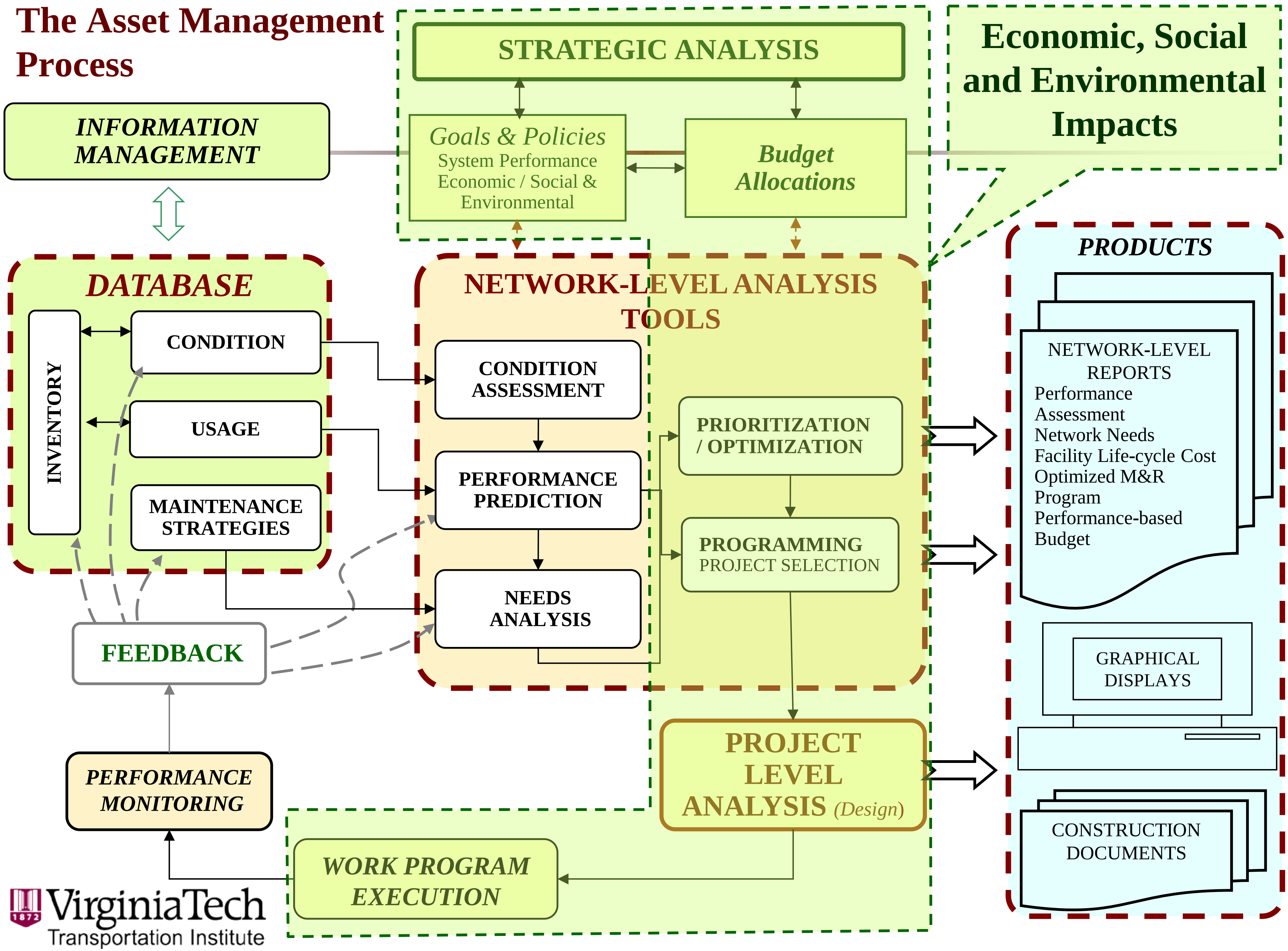
Background



The Asset Management Process
STRATEGIC ANALYSIS
Economic, Social and Environmental Impacts
INFORMATION MANAGEMENT
Goals & Policies
System Performance
Economic / Social & Environmental
Budget Allocations
DATABASE
INVENTORY
CONDITION
USAGE
MAINTENANCE STRATEGIES
NETWORK-LEVEL ANALYSIS TOOLS
CONDITION ASSESSMENT
PERFORMANCE PREDICTION
NEEDS ANALYSIS
PRIORITIZATION / OPTIMIZATION
PROGRAMMING
PROJECT SELECTION
PRODUCTS
NETWORK-LEVEL REPORTS
Performance Assessment
Network Needs
Facility Life-cycle Cost
Optimized M&R Program
Performance-based Budget
GRAPHICAL DISPLAYS
CONSTRUCTION DOCUMENTS
FEEDBACK
PERFORMANCE MONITORING
PROJECT LEVEL ANALYSIS (Design)
WORK PROGRAM EXECUTION
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Objective

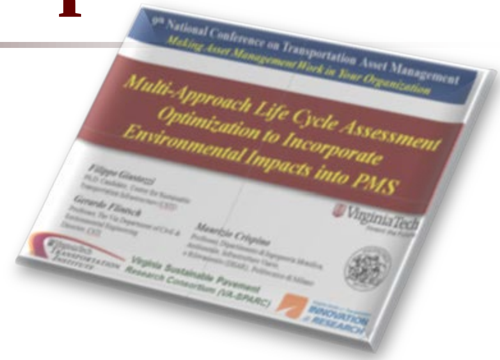
- To develop a multi-objective optimization framework that hosts a comprehensive and integrated pavement life cycle cost and life cycle assessment model that covers the whole pavement's life cycle (cradle to grave)
- To apply the model to improve the management of our pavement assets

Why Multi-objective Optimization?

- Sustainable transportation systems requires decisions in a context of
  - ✓ **Economic development**
  - ✓ **Ecological sustainability**
  - ✓ **Social desirability**

  } **High-level Performance Indicators**
- 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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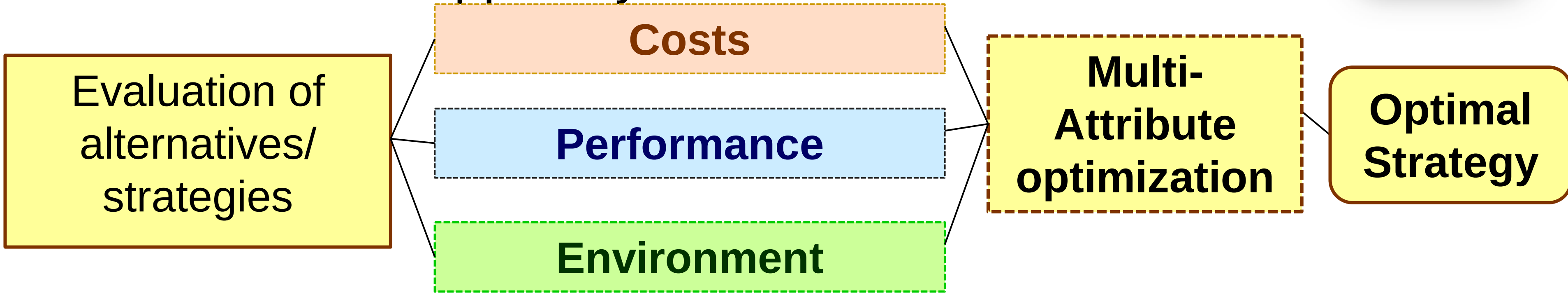
Making Asset Management Work in Your Organization

Multi-Approach Life Cycle Assessment Optimization to Incorporate Environmental Impacts into PMS

Filippo Giustozzi
Gerardo Flintsch
Maurizio Crispino

- 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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Giustozzi, Crispino, & Flintsch, "Multi-Attribute Life Cycle Assessment of Preventive Maintenance Treatments on Road Pavements for Achieving Environmental Sustainability," The *International Journal of Life Cycle Assessment*, 2012.

Incorporating the Use-phase into LCA for Pavements - Approach

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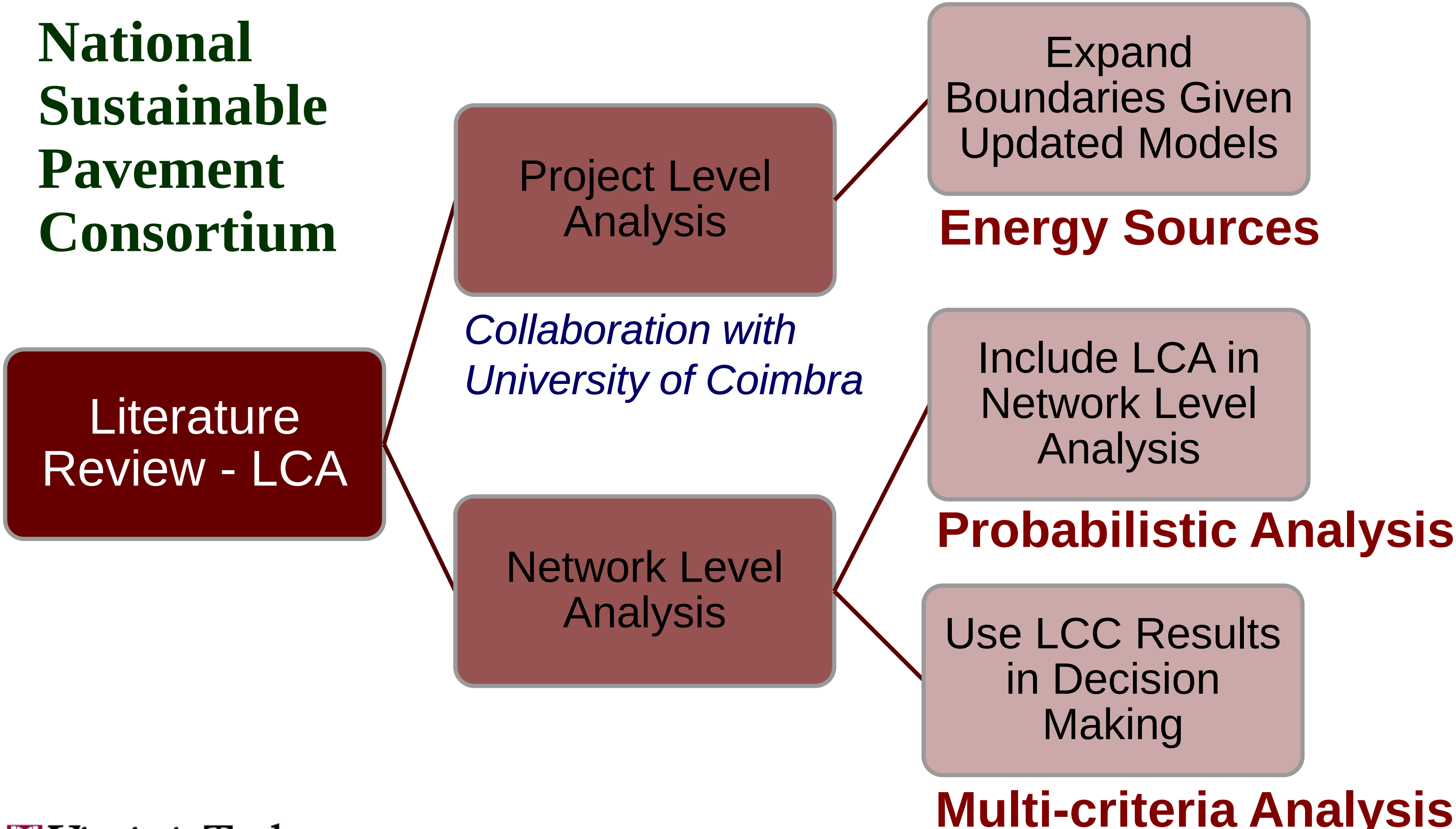

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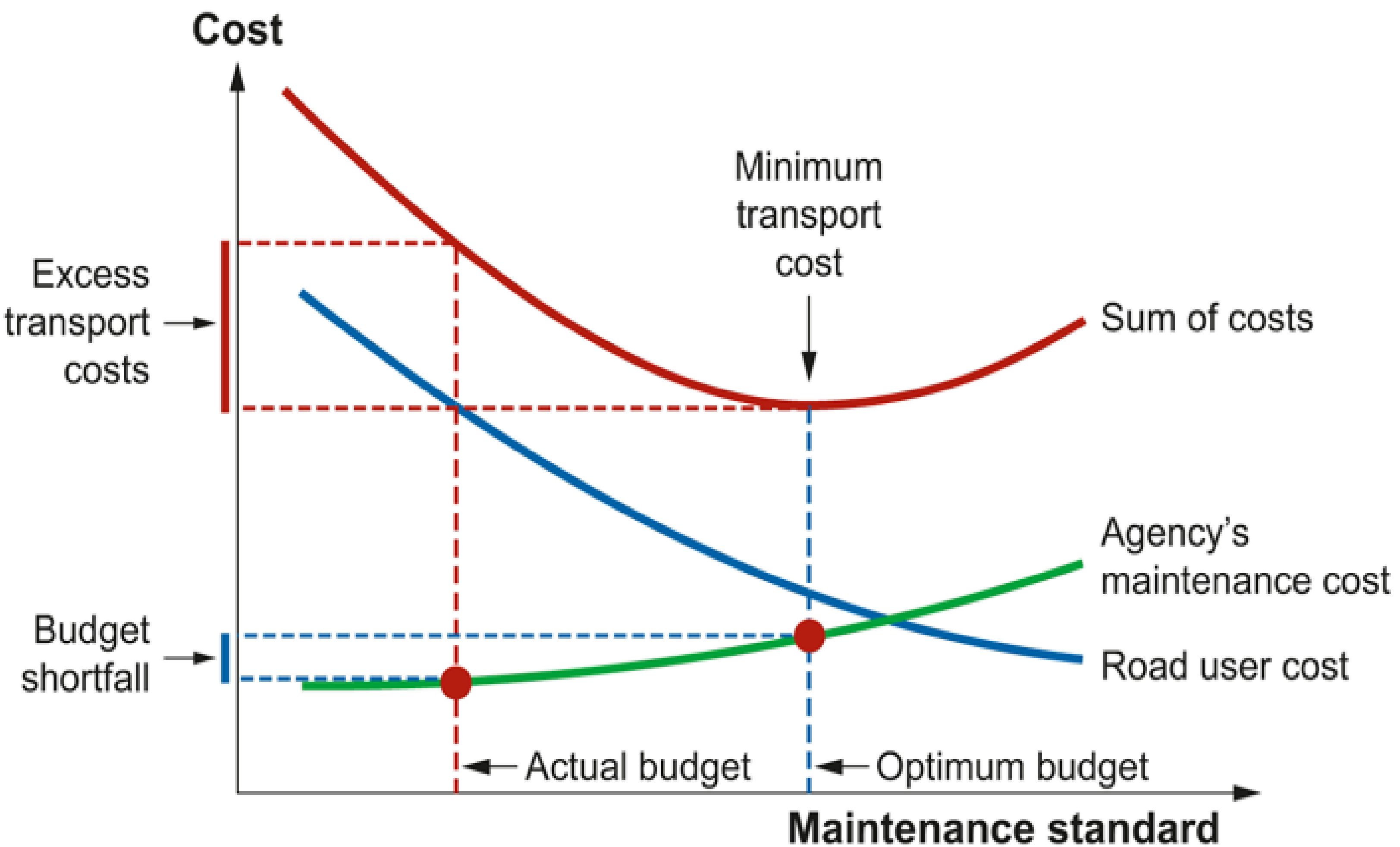
Framework

LCCA
Optimization of Transportation Costs



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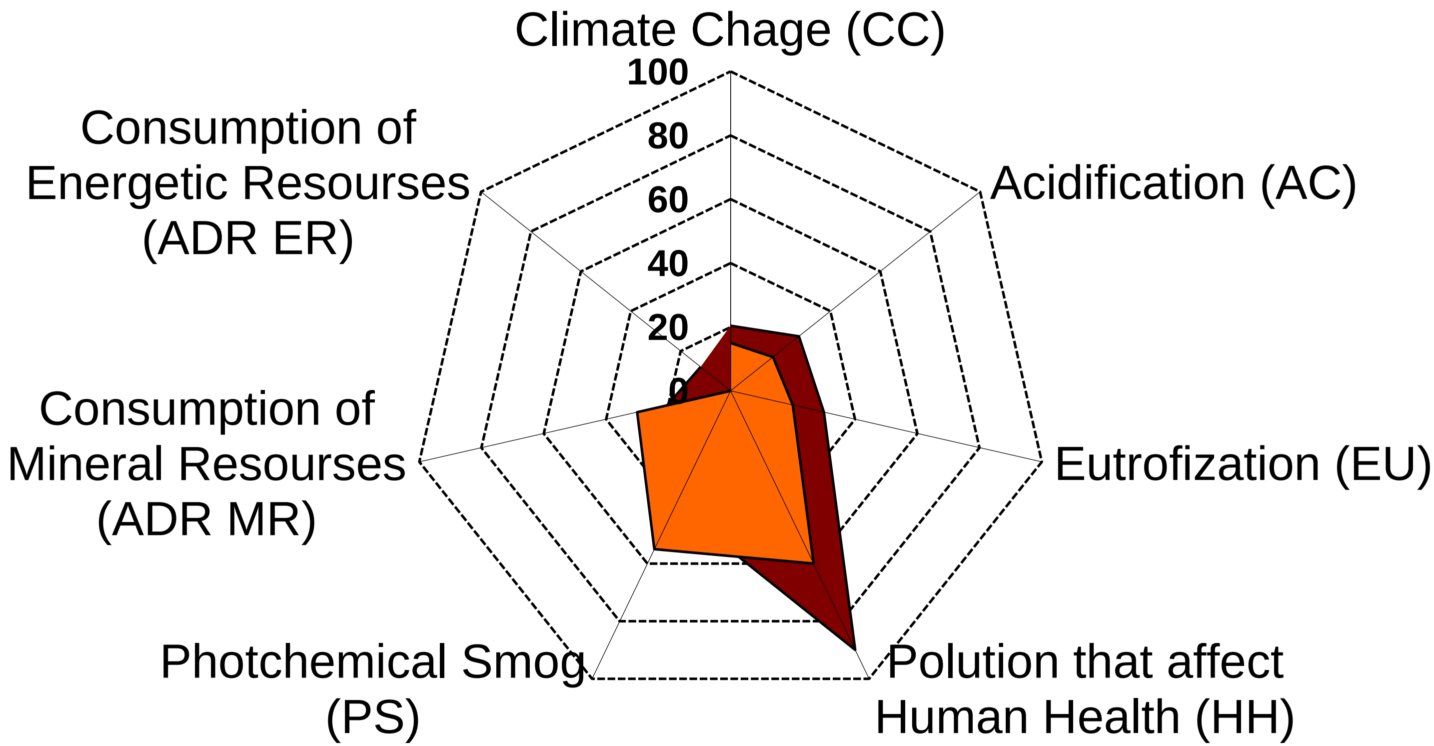
World Road Association Mondiale de la Route

Life Cycle Assessment

What factors are important?

How Important?

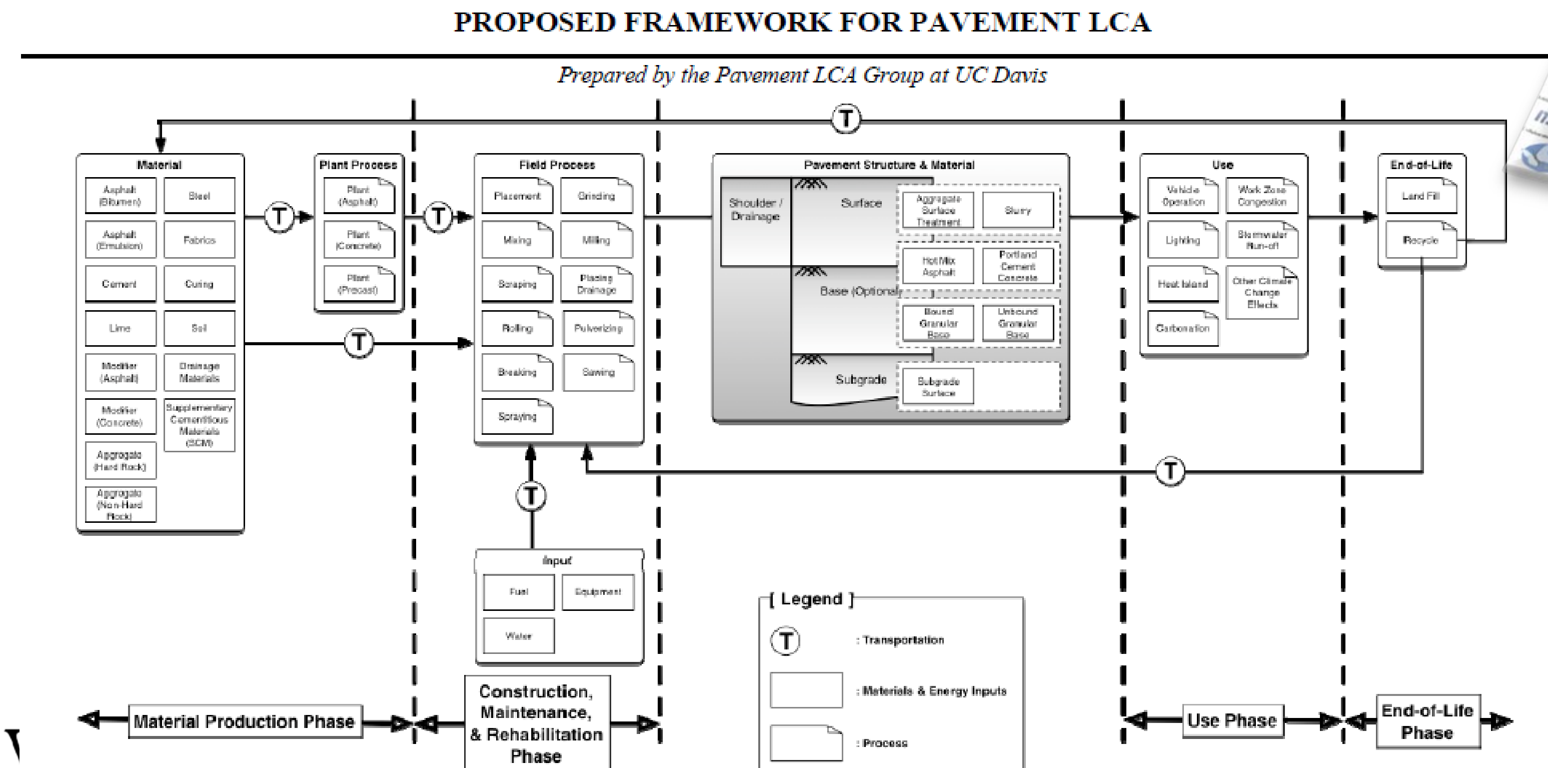
How we account for them?



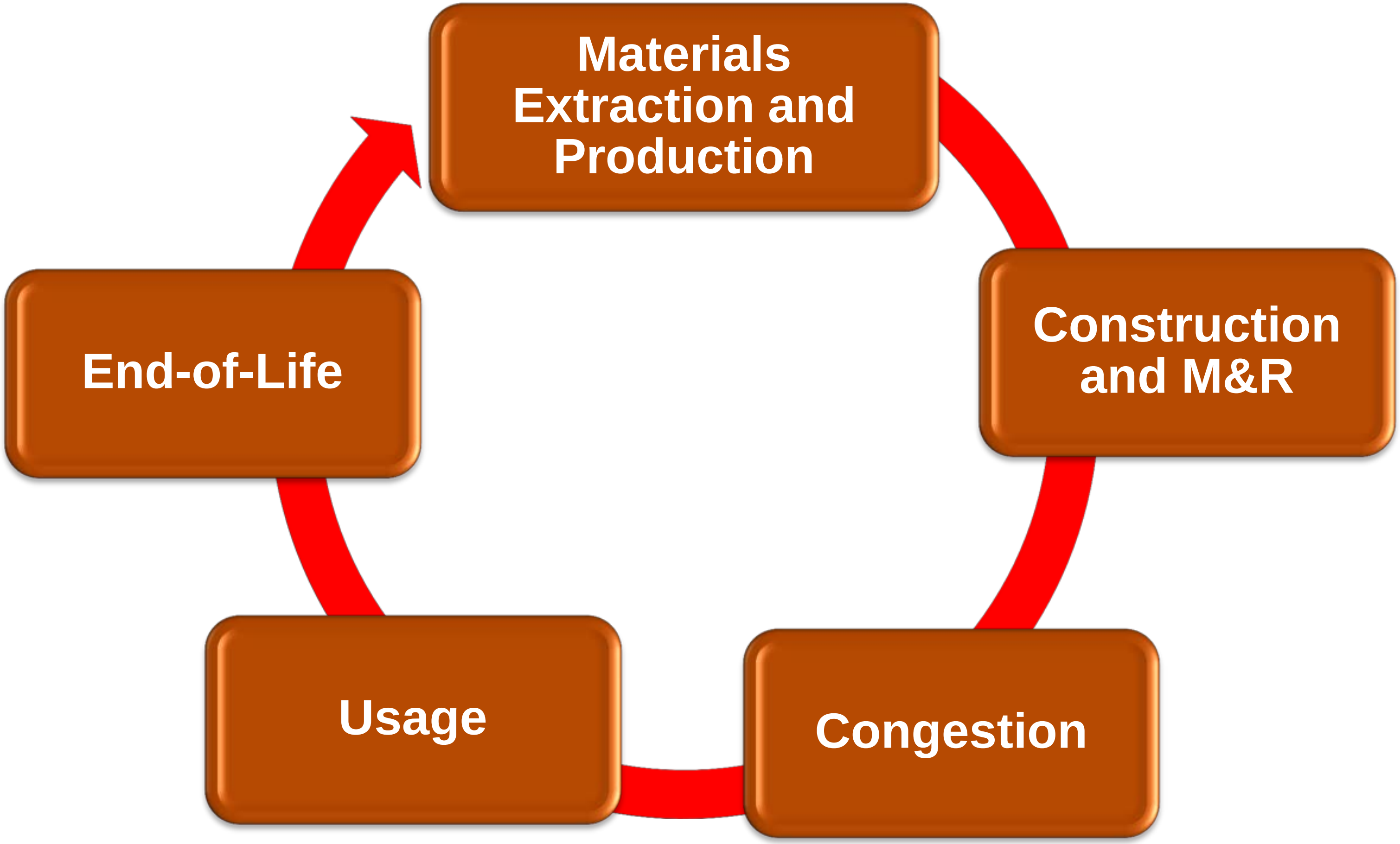
Santos, J., Ferreira, A., and Flintsch, G.W., “A life cycle assessment model for pavement management: methodology and computational framework,” International Journal of Pavement Engineering, 2014, pp. 1-20

LCA Framework

- Following
  - ✓ International Standard Organization (ISO, 2006)
  - ✓ UCPRC Pavement LCA (Harvey et al., 2010)



Pavement Phases Considered in the LCCA/LCA



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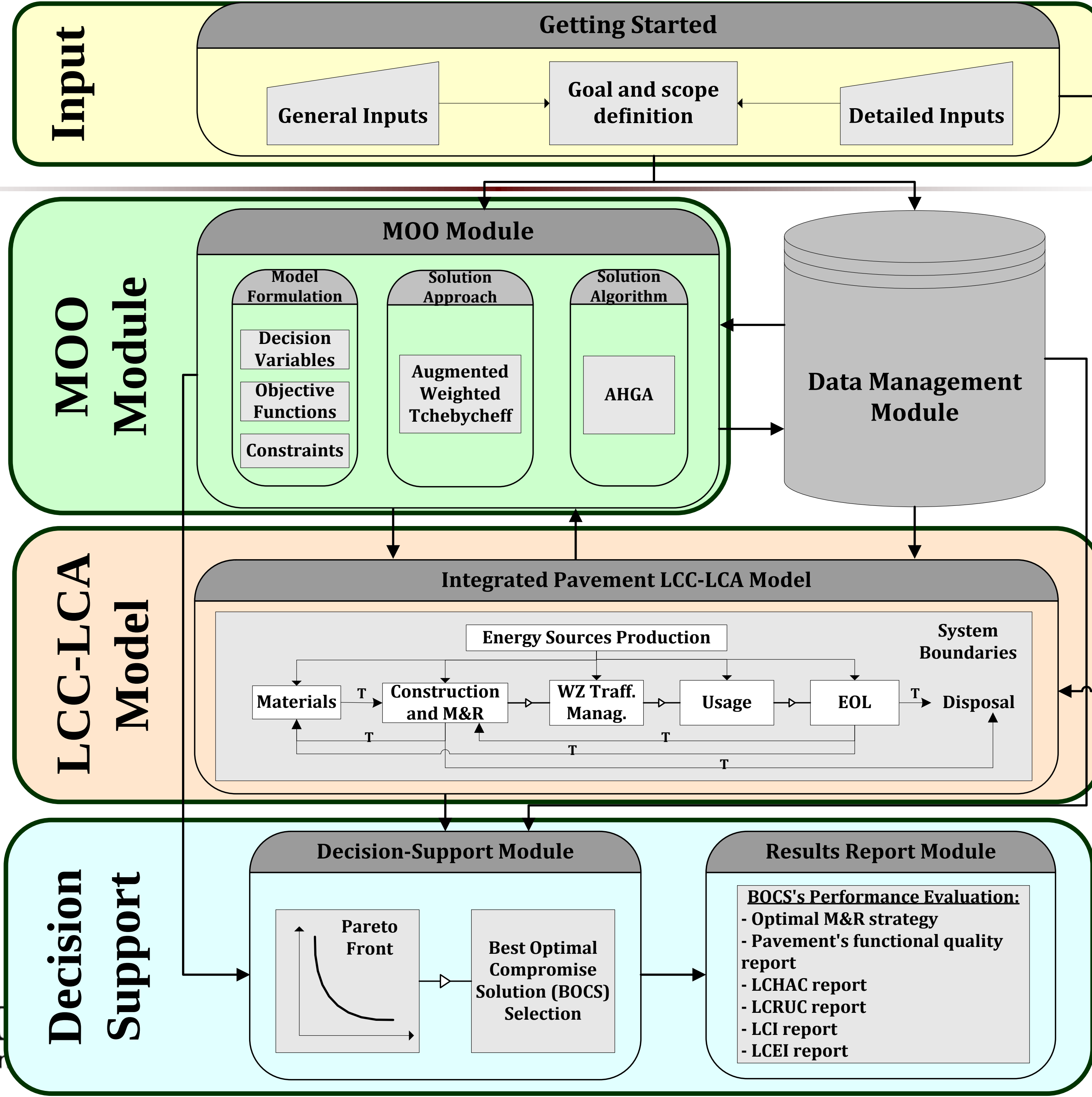
Multi-Objective Optimization-Based Decision Support System for Sustainable Pavement Management



DEC-UC

Multi-Objective Optimization Model Formulation

Objective functions

Agency Cost

$$Minimize \;\; OF_1 = \sum_{t=1}^{50} \frac{1}{(1+d)^t} \times \sum_{r=1}^{6} \left(C_{rt}^{MatExt\,Prod} + C_{rt}^{C.M\&R} + C_{rt}^{TM} \right) \times X_{rt} \qquad (1)$$

User Costs

$$Minimize \;\; OF_2 = \sum_{t=1}^{50} \frac{1}{(1+d)^t} \times \left\{ \left[\sum_{r=1}^{6} \left(VehOperC_{rt}^{WZTM} + TDC_{rt}^{WZTM} \right) \times X_{rt} \right] + VehOperC_t^{Usage} \right\} \qquad (2)$$

Env. Impacts

$$Minimize \;\; OF_3 = \sum_{i=1}^{3} CF_i^{CC} \times \left\{ \sum_{t=1}^{50} \left[\sum_{r=1}^{6} \left(LCI_{irt}^{MatExt\,Prod} + LCI_{irt}^{C.M\&R} + LCI_{irt}^{TM} + LCI_{irt}^{WZTM} \right) \times X_{rt} \right] + LCI_{it}^{Usage} \right\} \qquad (3)$$

Constraints

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

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

$$CCI_t \geq CCI_{min}, \qquad t = 1,\ldots,50$$

$$\sum_{r=1}^{6} X_{rt} = 1, \quad t = 1,\ldots,50$$

…

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Multi-Objective Optimization Model Solution Approach

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

Define a combined Objective Function

Subject to:

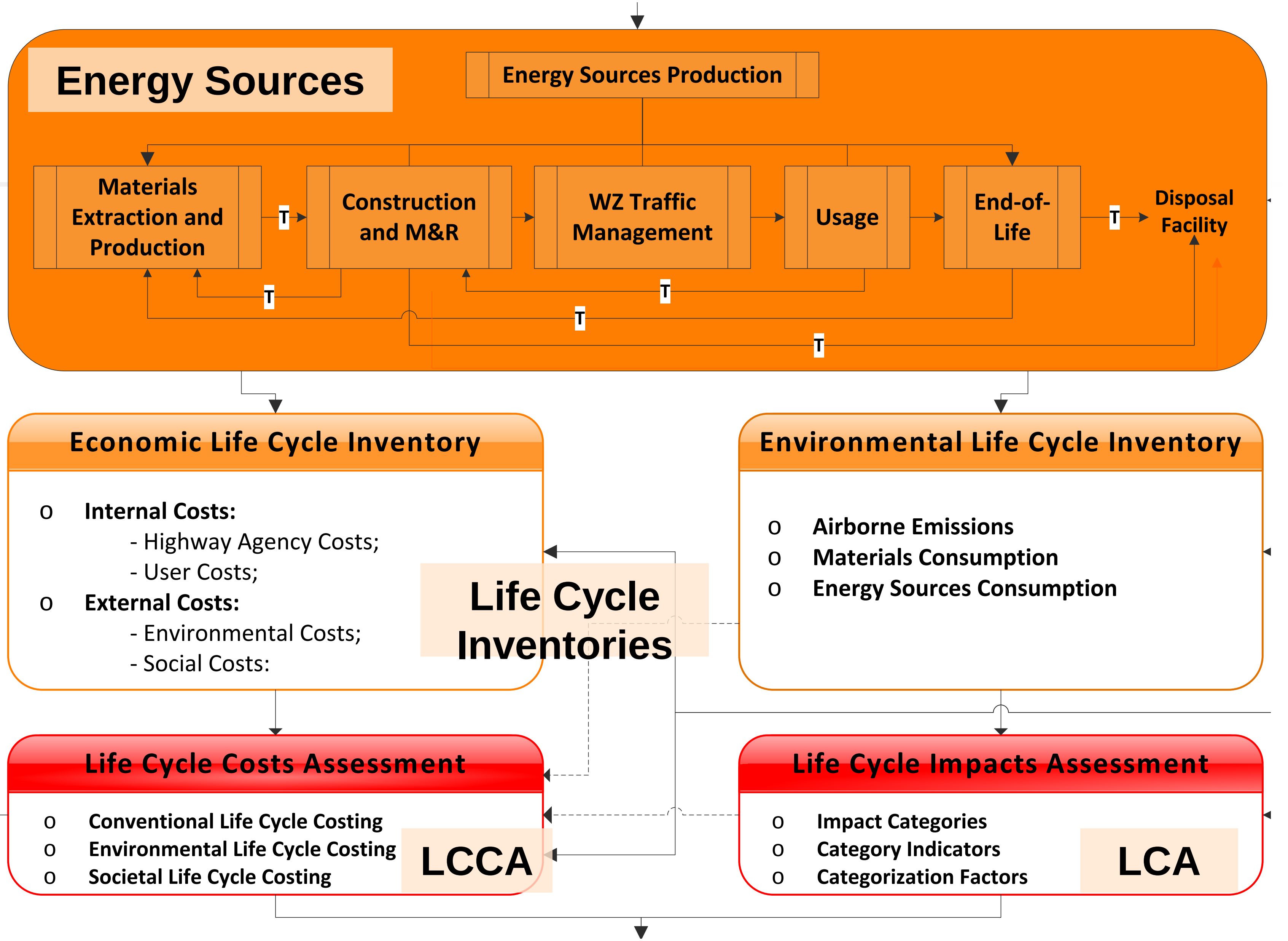
$$w_i \geq 0, \quad i = 1,\ldots,N_{obj}, \quad \sum_{i=1}^{Nobj} w_i = 1, \quad \rho \in \Re$$

with constraints

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

Solve using and Adaptive Hybrid Genetic Algorithm

LCCA-LCA Model



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Santos, J., Ferreira, A. and Flintsch, G. (2016). An adaptive hybrid genetic algorithm for pavement management. *5th International Conference on Theory and Practice in Modern Computing*, 2-4 July, Funchal, Madeira, Portugal.

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 β_j is considered as the best optimal compromise solution (BOCS)

$$u_i^j = \frac{f_i^{max} - f_i^j}{f_i^{max} - f_i^{min}}$$

$$\beta_j = \frac{\sum_{i=1}^{N_{obj}} u_i^j}{\sum_{i=1}^{N_{obj}} \sum_{j=1}^{M} u_i^j}$$

Where β_j is the fuzzy cardinal priority ranking of each non-dominated solution

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Example Applications

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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

Recycling-based

- Initial Intervention: I*n-Place* recycling;
- M&R plan: VDOT's maintenance actions performed in years 12, 22, 32 and 44

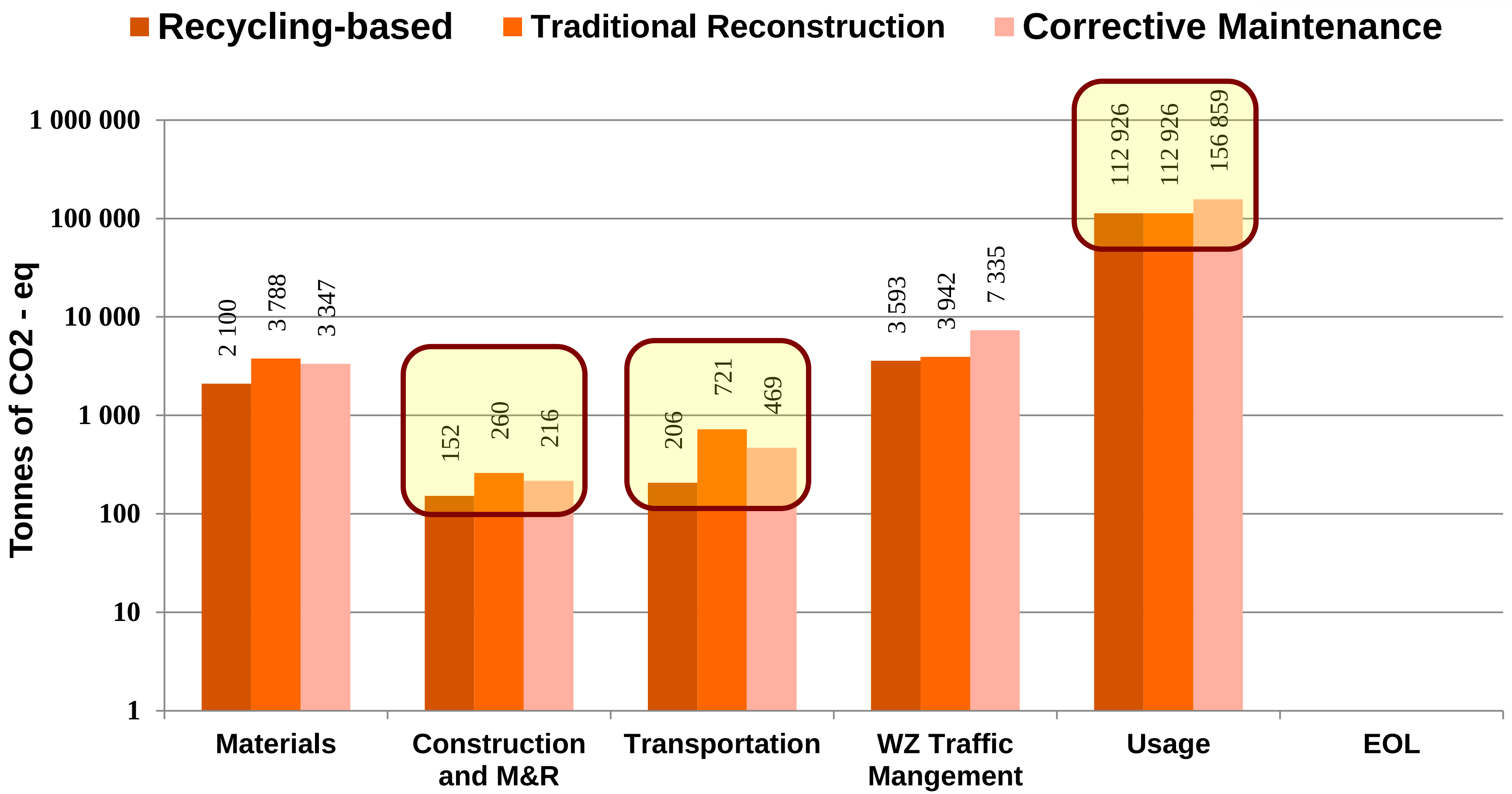
Traditional Reconstruction

- Initial Intervention: Traditional reconstruction
- M&R plan: VDOT's maintenance actions performed in years 12, 22, 32 and 44

Corrective Maintenance

- Initial Intervention: Corrective Maintenance
- M&R plan: VDOT's maintenance actions performed in years 4, 10, 14, 18, 24, 28, 34, 38, 44 and 48

Example of LCA Results
Impact on Climate Change



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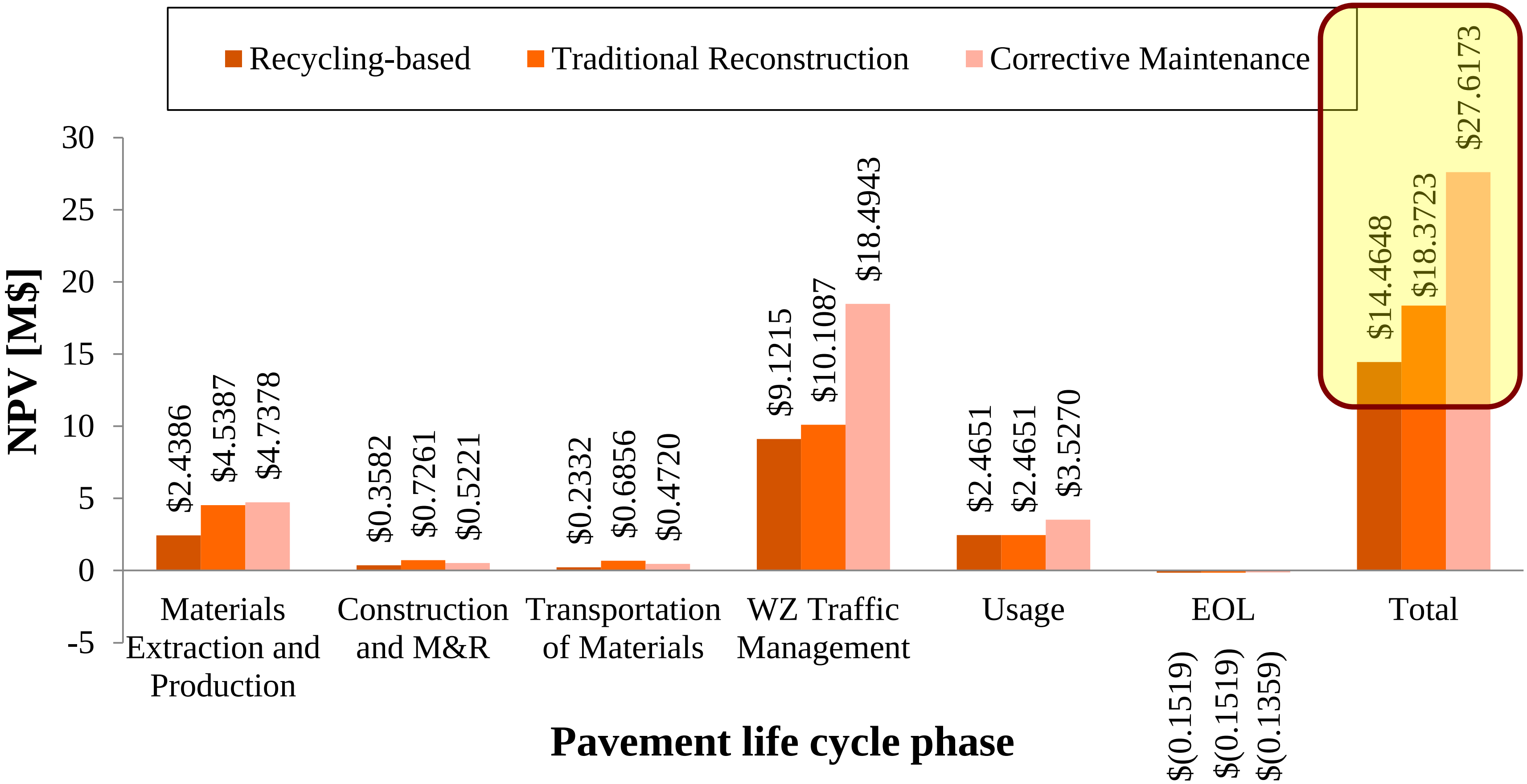
Santos, J., Bryce, J., Flintsch, G., Ferreira, A. and Diefenderfer, B. (2014). A life cycle assessment of in-place recycling and conventional pavement construction and maintenance practices. *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance*, 1-19.

LCCA Comparison



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Santos, J., Bryce, J., Flintsch, G. and Ferreira, A. (2015). A comprehensive life cycle costs analysis of in-place recycling and conventional pavement construction and maintenance practices. *International Journal of Pavement Engineering* (online)

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

Type of scenario	ID	Scenario name
Conventional VDOT	1	HMA - 0% RAP
	2	HMA - 15% RAP
	3	HMA - 30% RAP
	4	Sasobit® WMA - 0% RAP
	5	Sasobit® WMA - 15% RAP
	6	Sasobit® WMA - 30% RAP
Recycling-based VDOT	7	HMA - 0% RAP
	8	HMA - 15% RAP
	9	HMA - 30% RAP
	10	Sasobit® WMA - 0% RAP
	11	Sasobit® WMA - 15% RAP
	12	Sasobit® WMA - 30% RAP
Preventive maintenance	13	Microsurfacing - 0% RAP
	14	THMACO - 0% RAP

Example II – Multiobjective Optimization (cont.)

- Maintenance and rehabilitation plans

1. Conventional VDOT scenario	2. Recycling-based VDOT scenario	3. Preventive maintenance: Microsurfacing	4. Preventive maintenance: THMACO
CM: 12 and 44 **RM:** 22 **Conventional RC:** 32	**CM:** 12 and 44 **RM:** 22 **Recycling-based RC:** 32	**Conventional RC:** 32 **Microsurf.:** 7, 15, 23, 39 and 47	**Conventional RC:** 32 **THMACO:** 7, 16, 24, 39, 47

- Pavement Performance Prediction Models:
  - ✓ CM, RM and RC:

$$CCI(t) = CCI_0 - e^{a + b \times c^{ln\left(\frac{1}{t}\right)}}$$

M&R activity category	CCI_0	a	b	c
CM	100	9.176	9.18	1.27295
RM	100	9.176	9.18	1.25062
RC	100	9.176	9.18	1.22777

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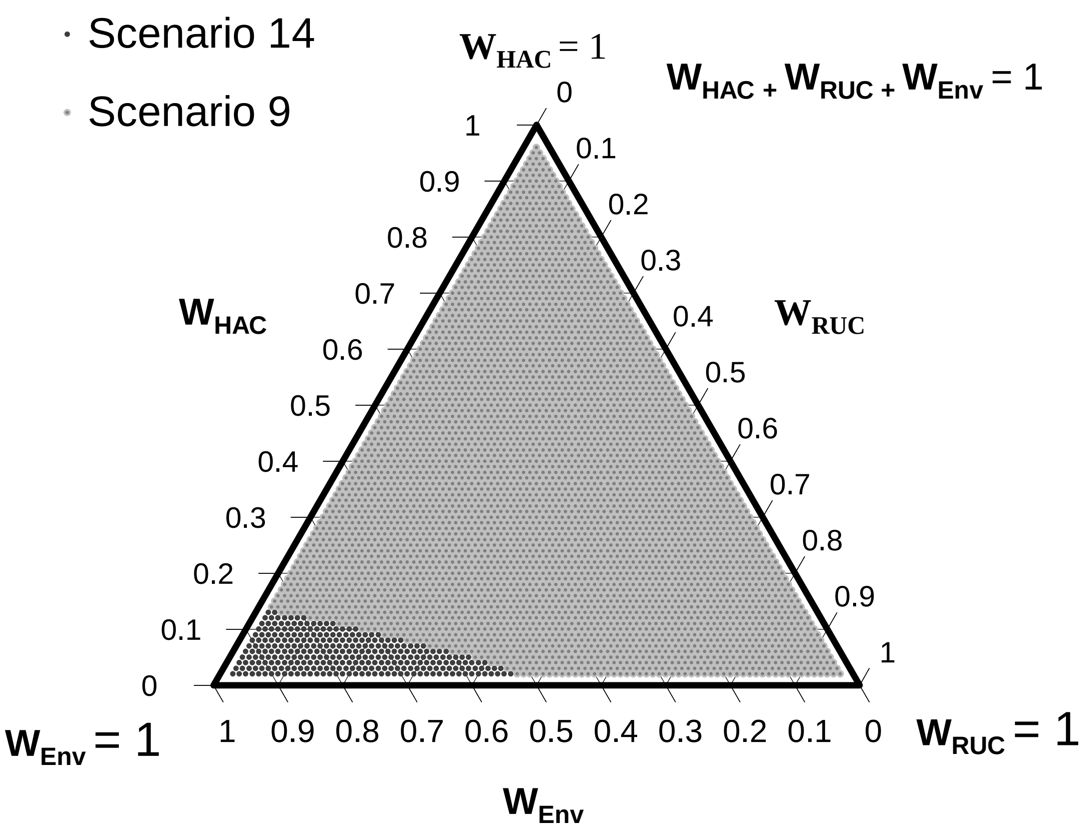
Example II – Multiobjective Optimization (cont.)

Multi-criteria decision making approach:

- ✓ TOPSIS method;
- ✓ Combinatorial weight assignment method fc the 3 main criteria:

  AC; RUC; Environme Impacts
- ✓ Seven environmental sub-criteria weighted according to BEES software's weights.



Santos, J., Flintsch, G. and Ferreira, A. (2016). Environmental and economic assessment of pavement construction and management practices for enhancing pavement sustainability. *Resources, Conservation & Recycling* (under review).

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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