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Pavement LCA 2017

Applications of LCA for Network-Level Pavement Management

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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

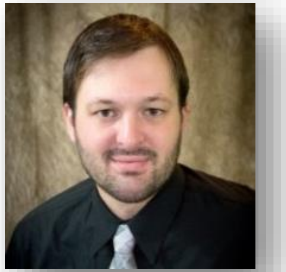
– ***Joao Santos***

– *Adelino Ferreira*

National Sustainable Pavement Consortium

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

– *James Bryce*



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- ✓ Example Applications
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Background

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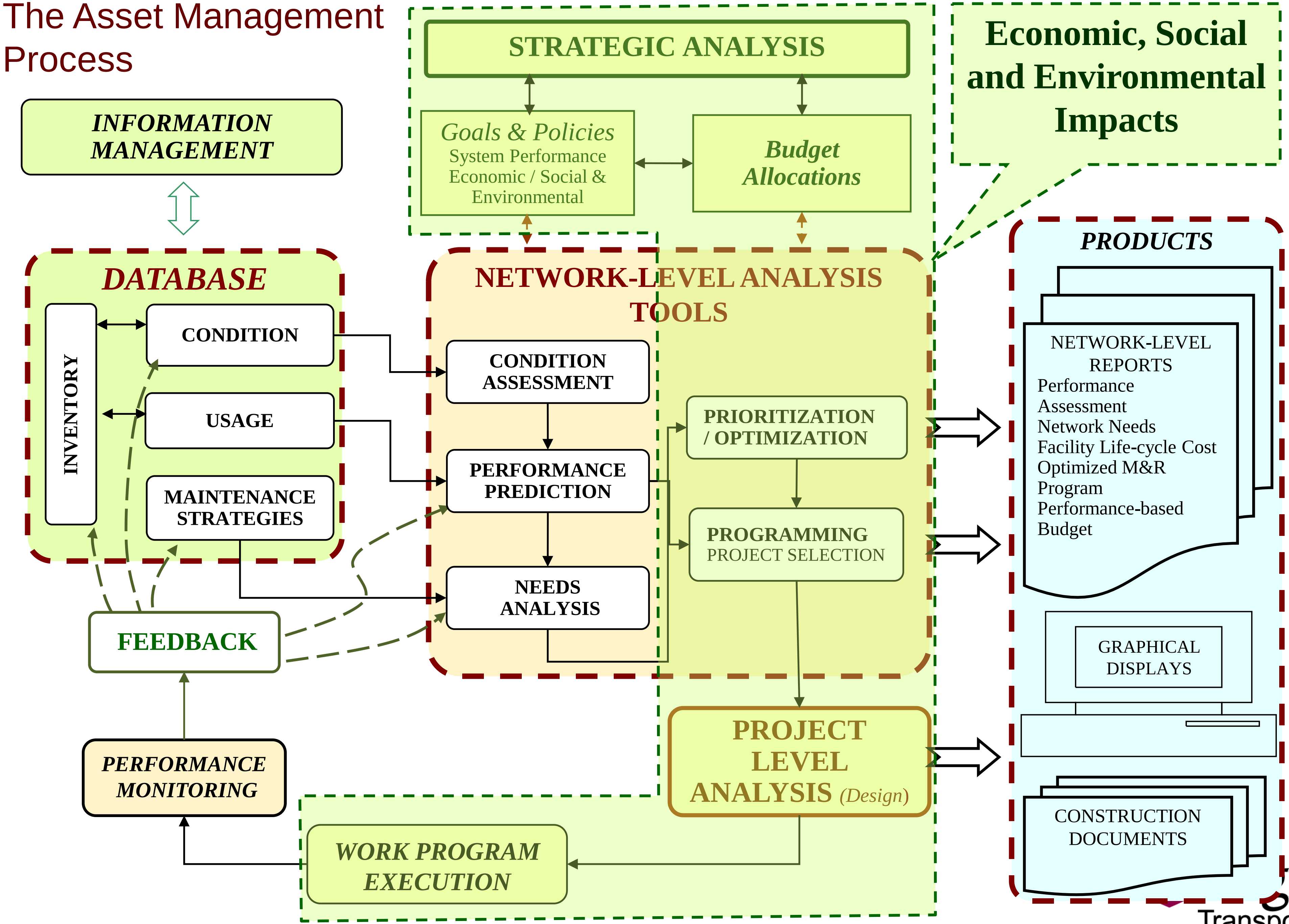
The Asset Management Process



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National Sustainable Pavement Consortium

- ✓ **Objective:** To establish a research consortium focused on enhancing pavement sustainability
  - ✓ Identification and evaluation of novel products, practices, and pavement systems
  - ✓ Best practices for sustainable pavement management
  - ✓ Climatic changes adaptation

Scope:

Research

- ✓ Applied – Shorter term quick gains
- ✓ Basic – Answer fundamental questions

Education

- ✓ Materials to support short courses
- ✓ Materials to help develop academic classes

Outreach

- ✓ Short courses, seminars, webinars and workshops

U.S. Department of Transportation Federal Highway Administration

VDOT Virginia Department of Transportation

PENNDOT

Wisconsin Department of Transportation

MDOT

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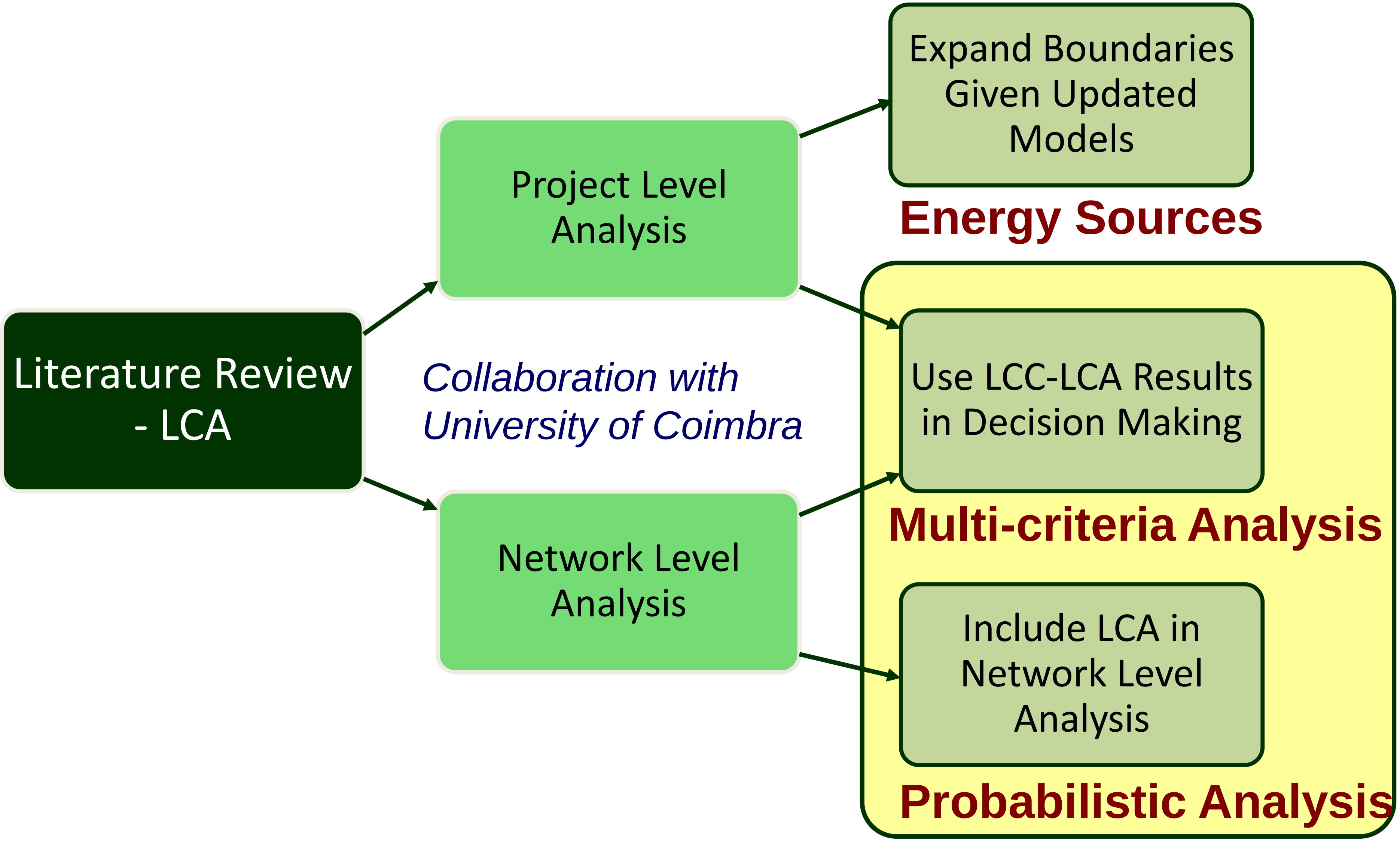
LCA for Pavements Projects

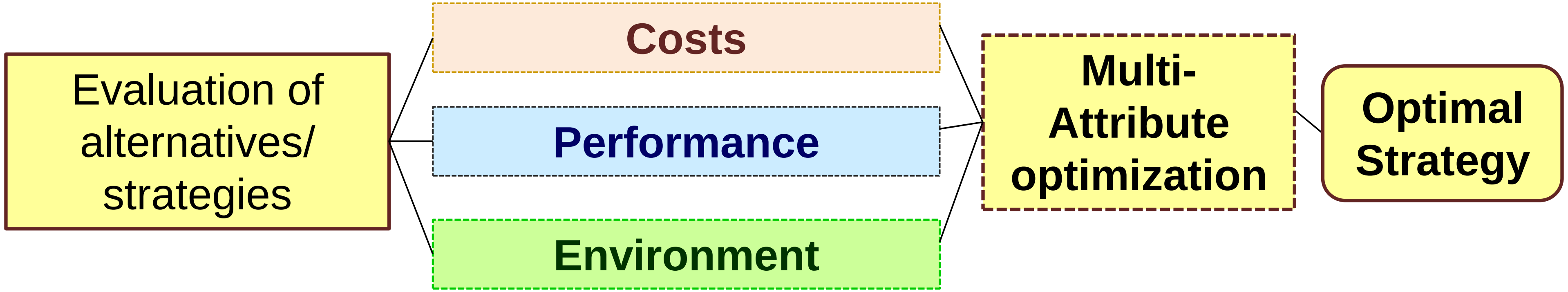


Objective

- ✓ To develop a comprehensive approach and supporting tools to calculate the life cycle impacts of pavement maintenance and rehabilitation projects and management approaches
  - Considers comprehensive and integrated pavement life cycle cost and (environmental) life cycle assessment models
  - Covers the whole pavement's life cycle (cradle to grave)
  - Balances performance, cost and environmental impacts
- ✓ To apply the model to improve the management of pavement assets

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



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.

Framework

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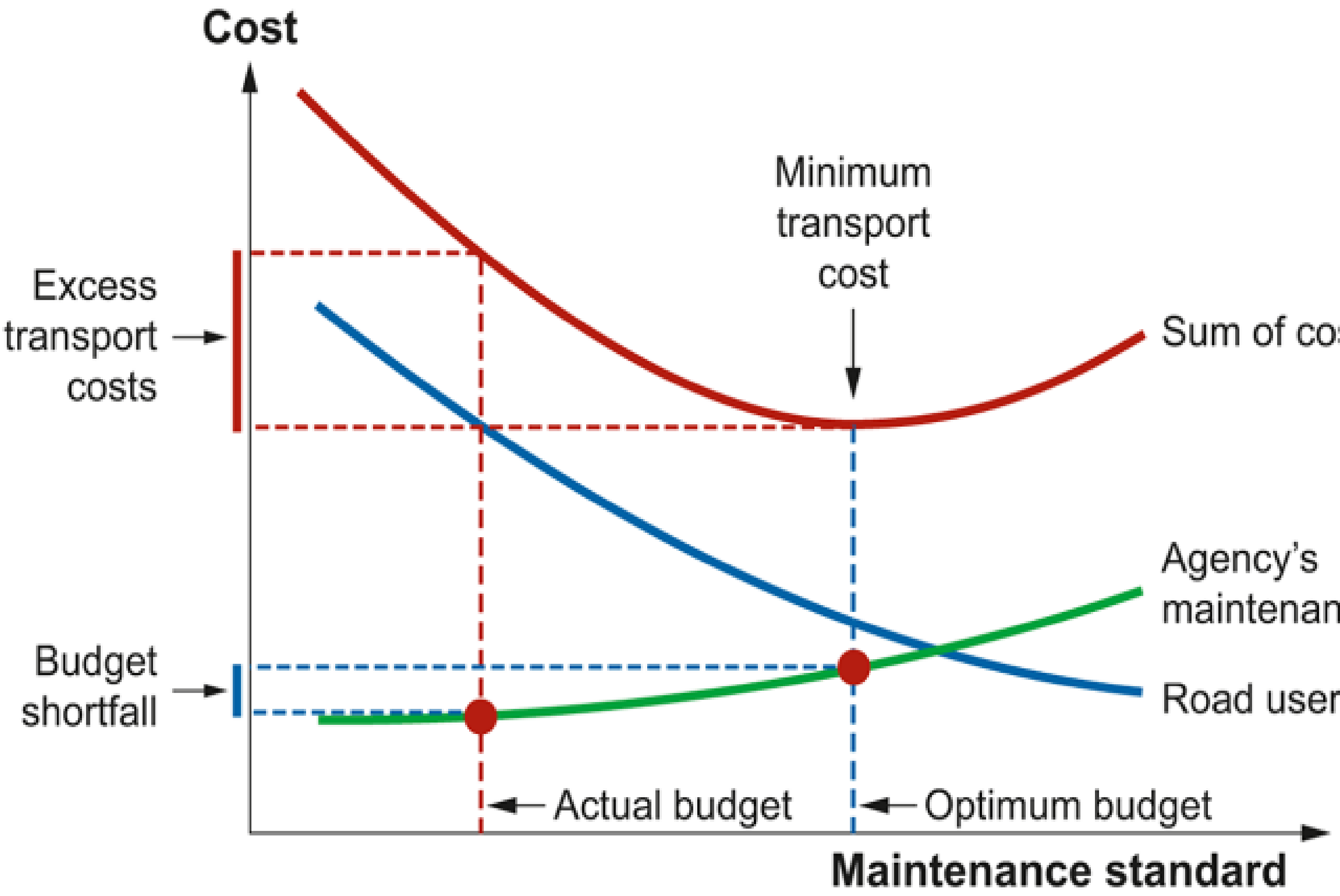
LCCA
Optimization of Transportation Costs



WORLD ROAD ASSOCIATION MONDIALE DE LA ROUTE
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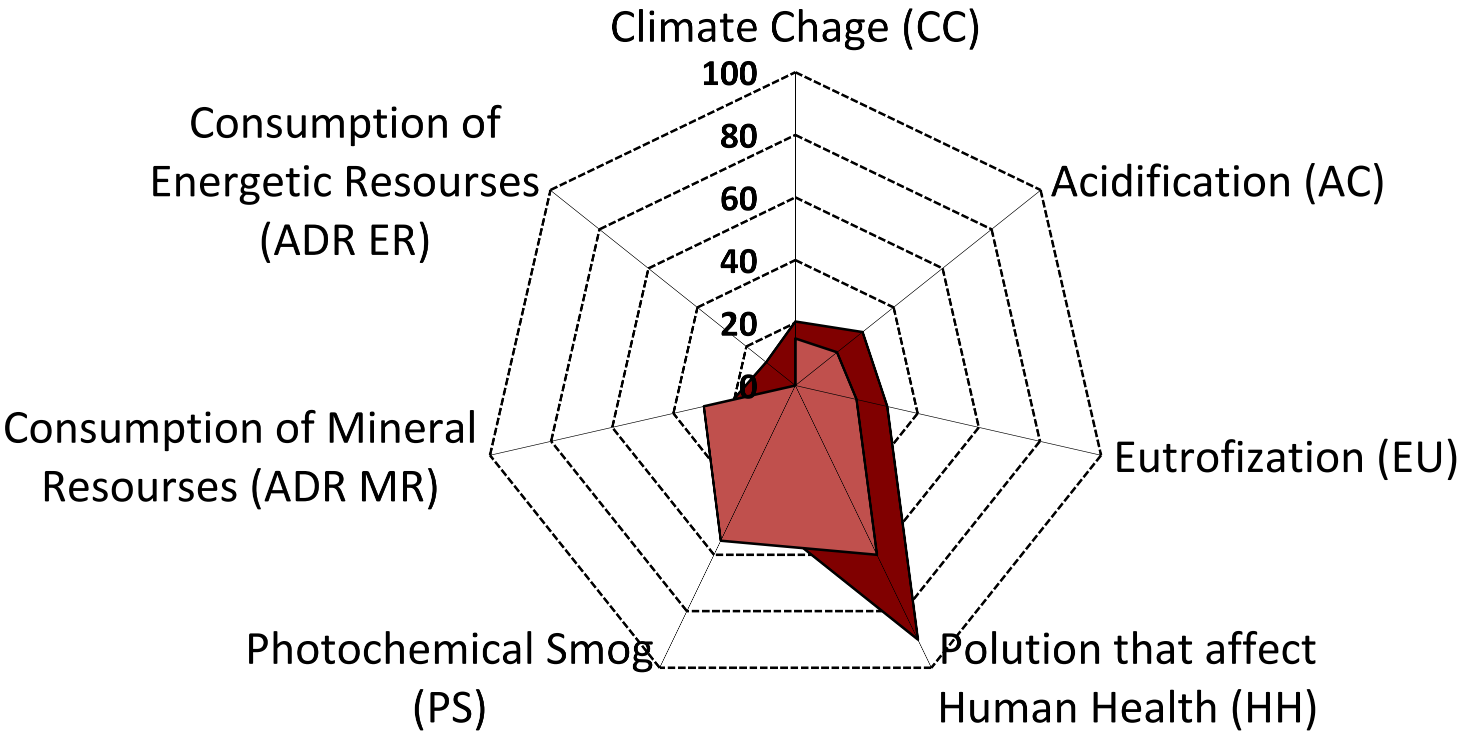
Life Cycle Assessment

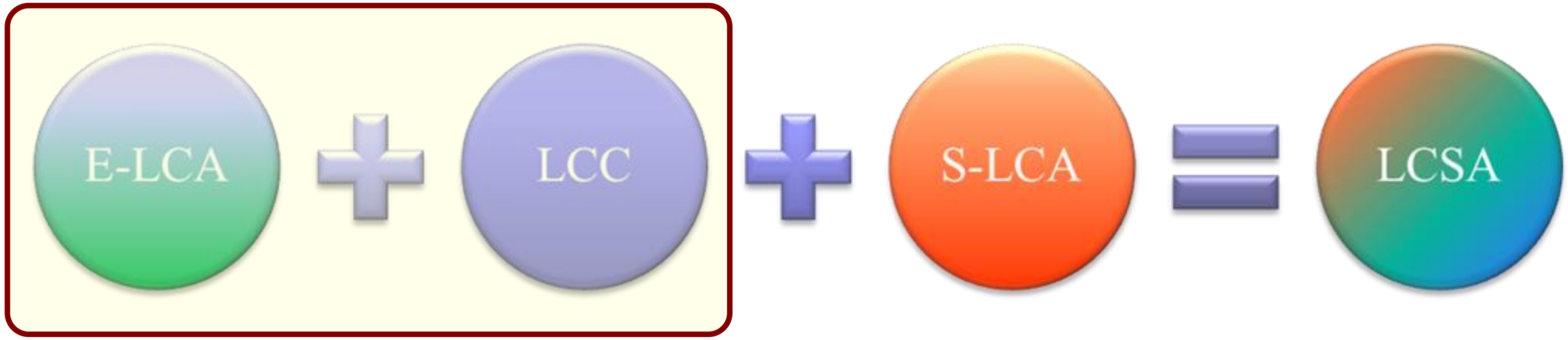


- ✓ What factors are important?
- ✓ How Important?
- ✓ How we account for them?

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

Life Cycle Sustainability Assessment (LCSA)

- ✓ The evaluation of all environmental, social and economic negative impacts and benefits in decision-making processes towards more sustainable products throughout their life cycle.



Source: UNEP (2012) Social Life Cycle Assessment and Life Cycle Sustainability Assessment

http://www.lifecycleinitiative.org/starting-life-cycle-thinking/life-cycle-approaches/life-cycle-sustainability-assessment/

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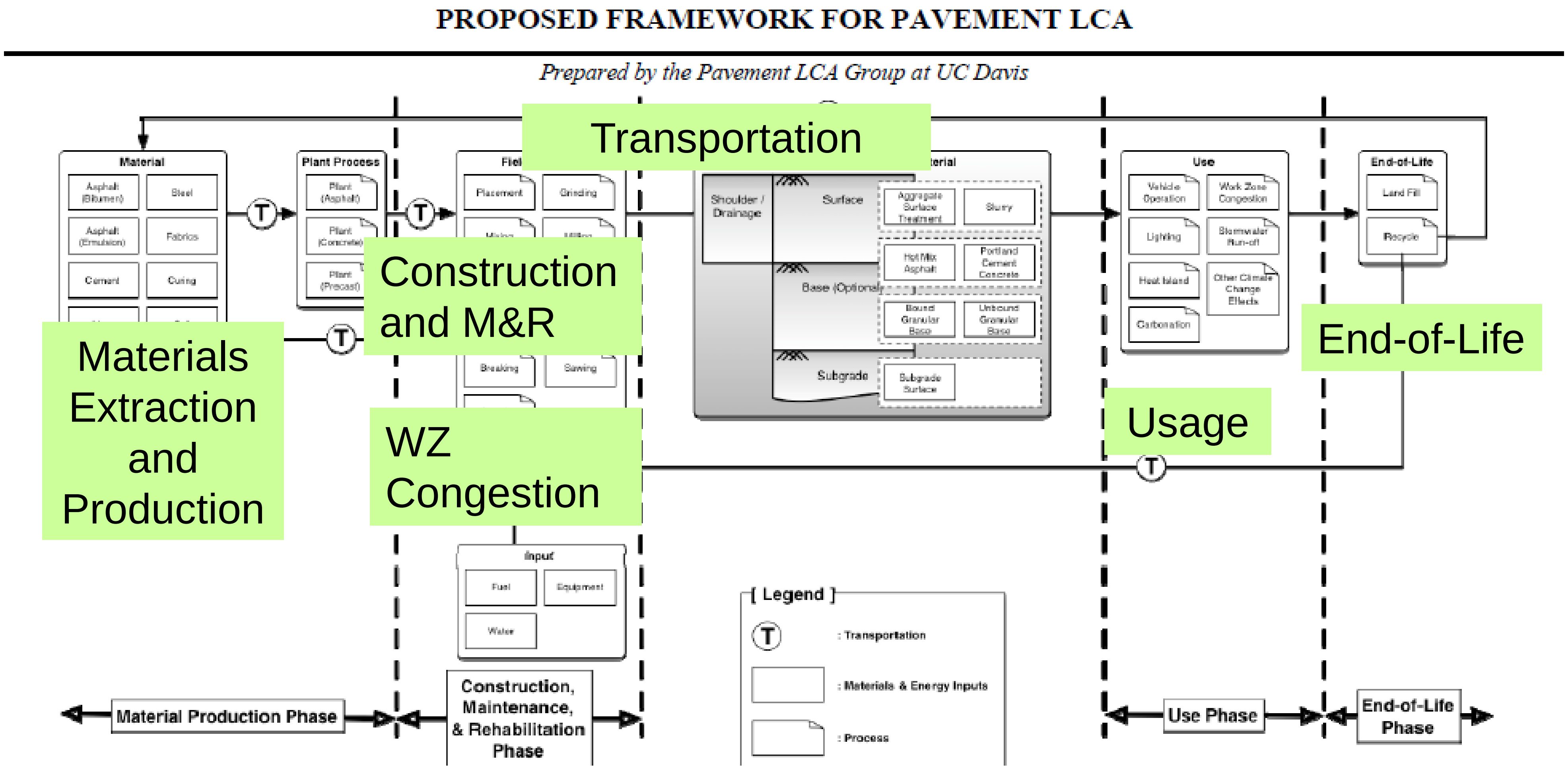
Pavement Phases Considered in the LCCA/LCA

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



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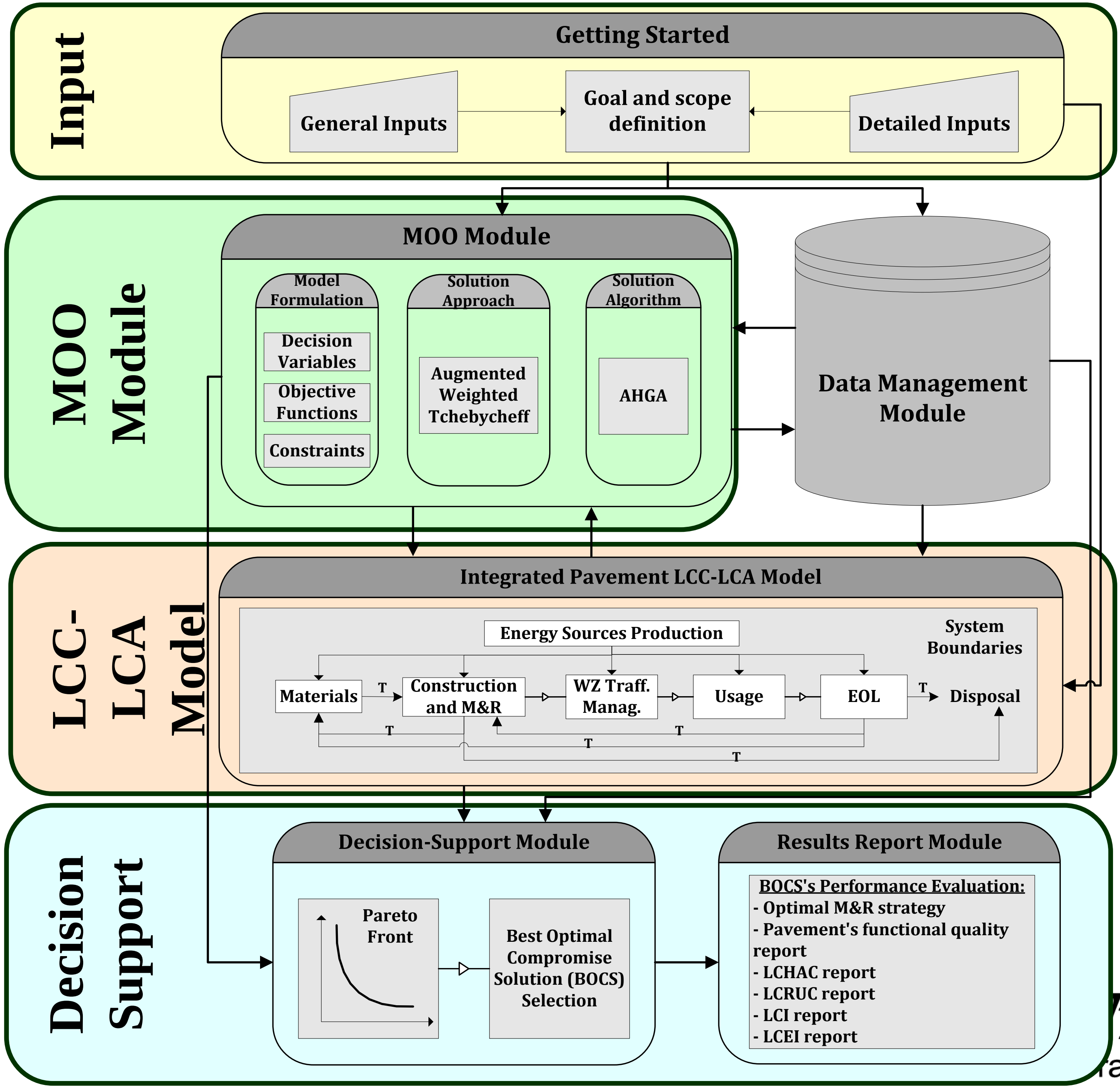
Multi-Objective Optimization-Based Decision Support System for Sustainable Pavement Management



DEC-UC

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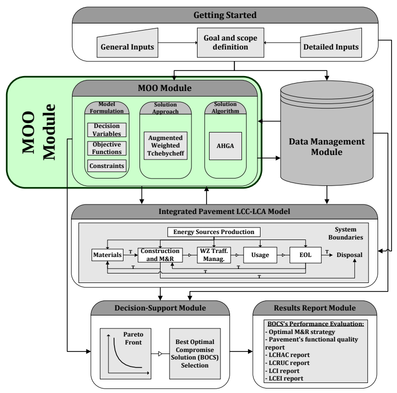
Multi-Objective Optimization Model Formulation



Objective Functions

Agency Cost

$$\text{Minimize} \quad OF_1 = \sum_{t=1}^{50} \frac{1}{(1+d)^t} \times \sum_{r=1}^{6} \left(C_{rt}^{MatExtProd} + C_{rt}^{C.M\&R} + C_{rt}^{TM} \right) \times X_{rt}$$

User Costs

$$\text{Minimize} \quad OF_2 = \sum_{t=1}^{50} \frac{1}{(1+d)^t} \times \left\{ \left[\sum_{r=1}^{6} \left(VOC_{rt}^{WZTM} + TDC_{rt}^{WZTM} \right) \times X_{rt} \right] + VOC_t^{Usage} \right\}$$

Env. Impacts

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

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

Define a combined Objective Function

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

with additional constraints

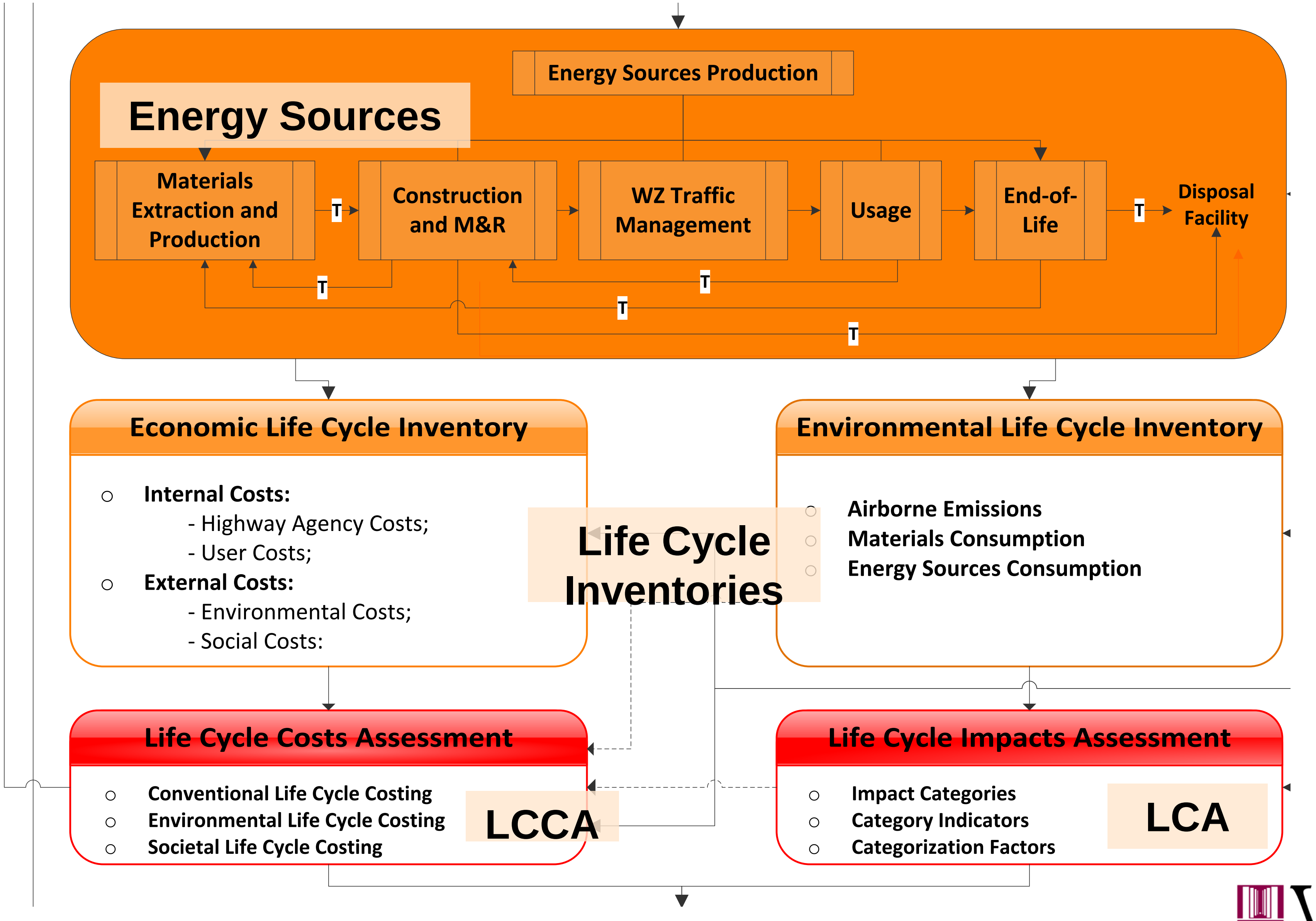
Subjected to:

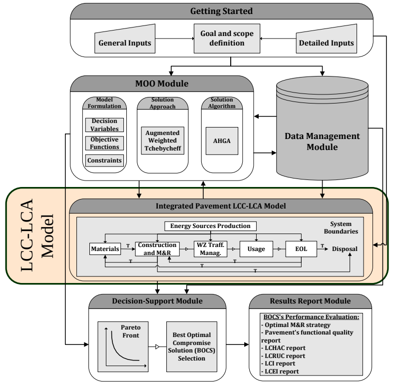
$$w_i + \rho > 0, \quad i = 1,\ldots,N_{obj}$$

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

Solve using and Adaptive Hybrid Genetic Algorithm

LCC-LCA Model





Santos, J., Flintsch, G. and Ferreira, A. “Environmental and economic assessment of pavement construction and management practices for enhancing pavement sustainability,” *Resources, Conservation & Recycling*, 2017, 116, pp. 15-31.

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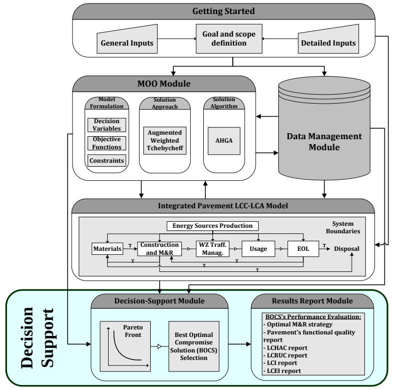
Decision Support Model



- ✓ 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)

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

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

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

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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: *In-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

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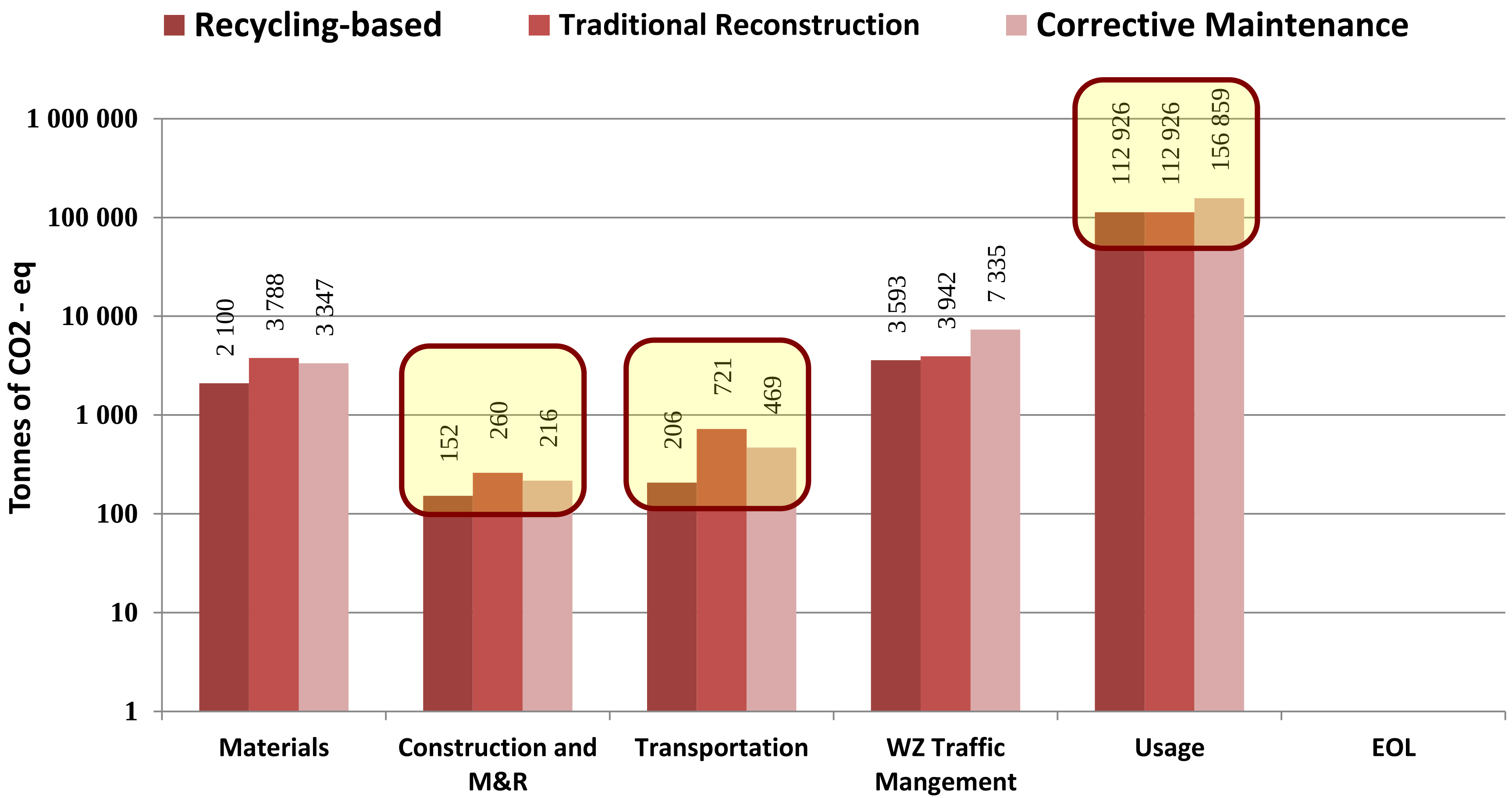
Example of LCA Results
Impact on Climate Change



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.

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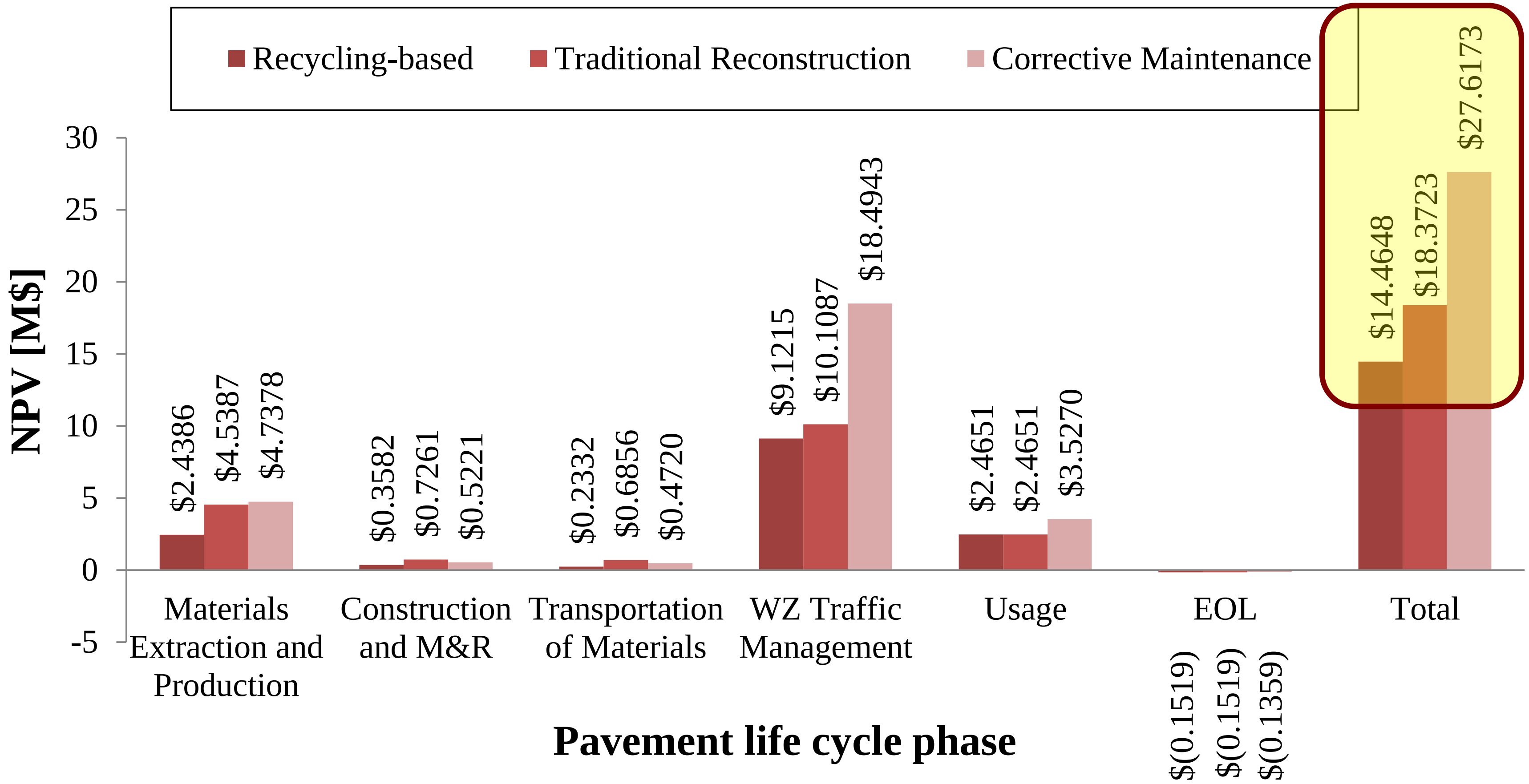
LCCA Comparison



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)

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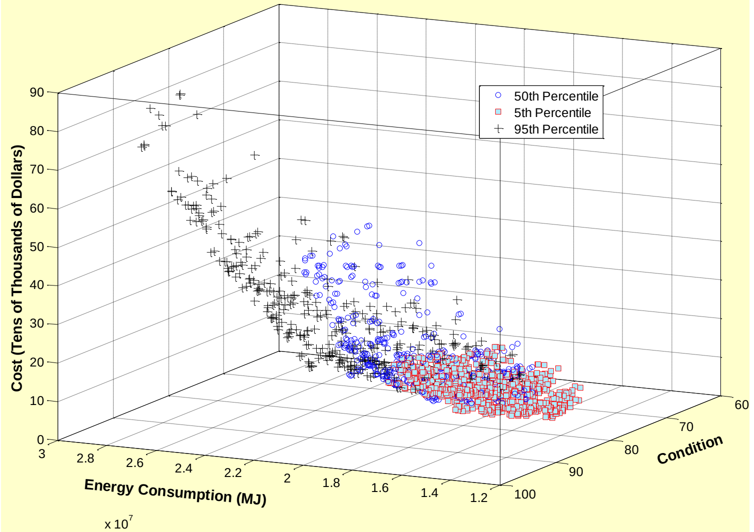
Example II - Incorporating the use-phase into LCA for pavements

- ✓ Project-level LCA tool
- ✓ Compared energy consumption at <u>network level</u> for use (mainly roughness) and maintenance phases
- ✓ Probabilistic Network-level LCA
- ✓ Multi-criteria Analysis
  - → Incorporating Stakeholder's input

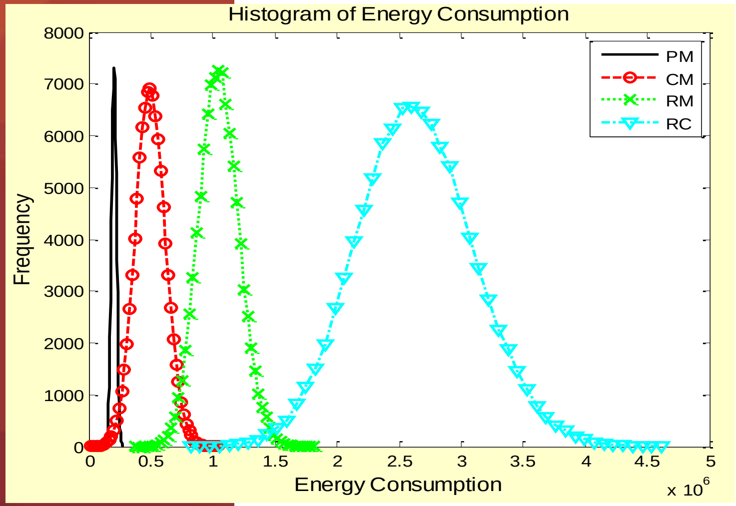


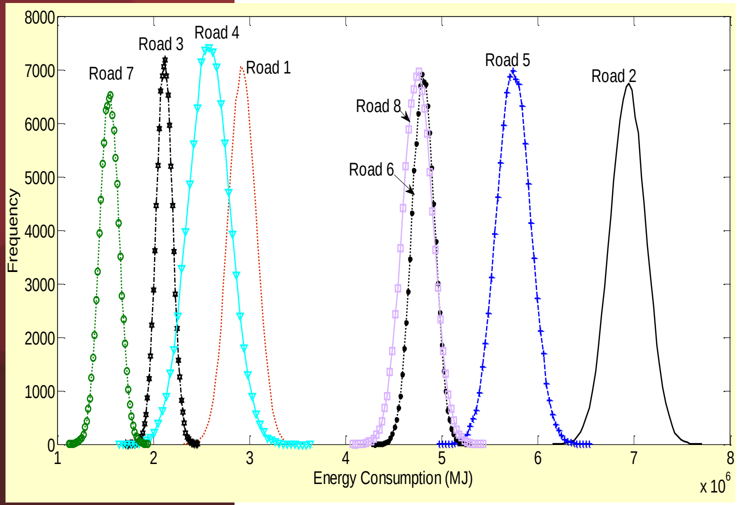
Bryce, J., Katicha, S., Flintsch, G.W., Sivaneswaran, N., Santos, J. "Probabilistic Lifecycle Assessment as a Network-Level Evaluation Tool for the Use and Maintenance Phases of Pavements." *Journal of the Transportation Research Board*, 2014, vol. 2455 (1), pp. 44-53

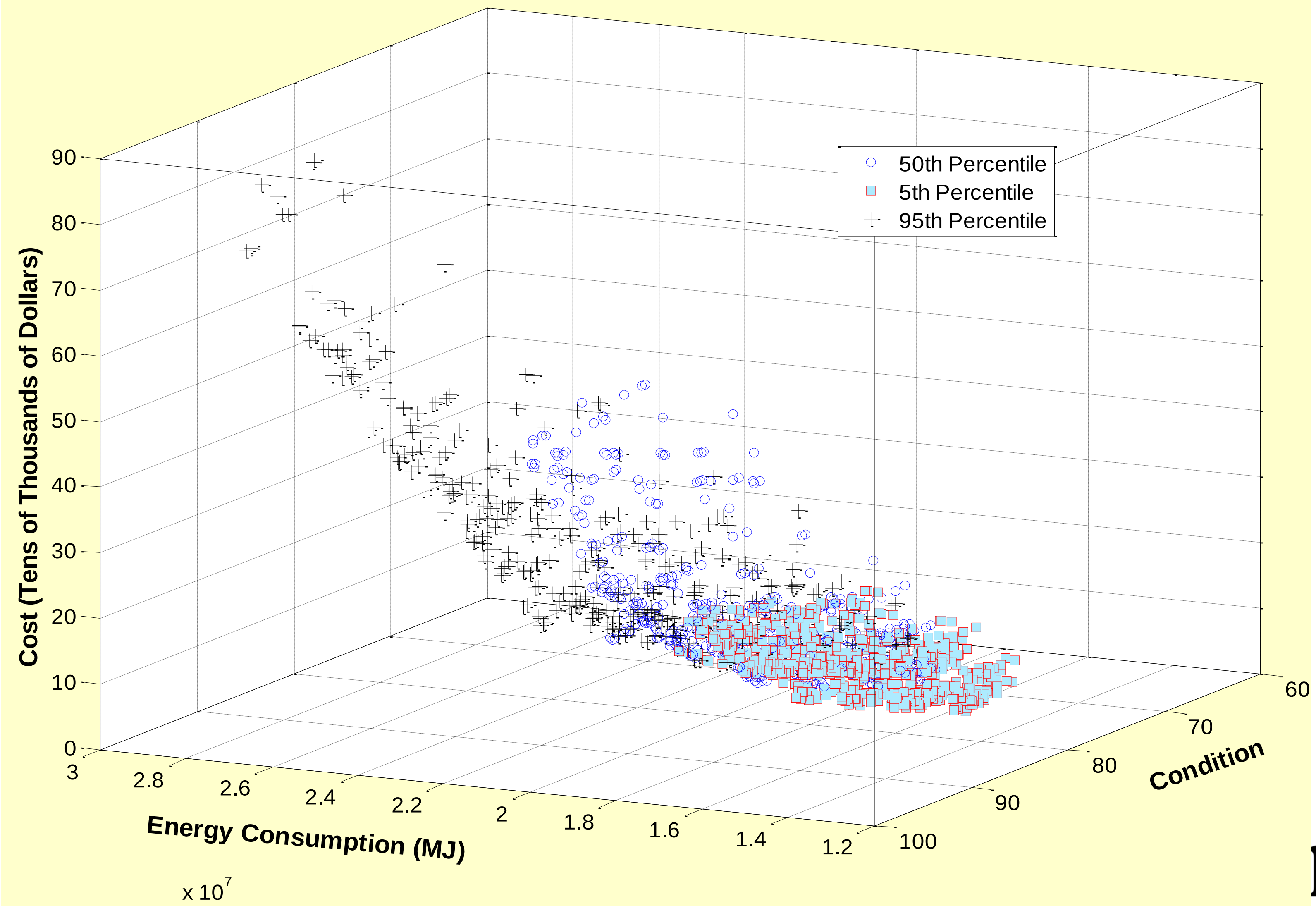
Methodology

- ✓ Defined a marginal energy consumption
  - –RR energy
  - –EM energy consumption due to maintenance action
    - Materials and Construction, Impact of roughness on vehicles
- ✓ Evaluate tradeoff between cost, condition and energy consumption
  - –Each variable has uncertainty
  - –Used a simple synthetic network
  - –Monte Carlo Simulation
  - –Assumed that preventive maintenance impact condition but not pavement roughness

Results


Histogram of Energy Consumption
Frequency
Energy Consumption
x 10^6
PM
CM
RM
RC


Road 7
Road 3
Road 4
Road 1
Road 8
Road 6
Road 5
Road 2
Frequency
Energy Consumption (MJ)
x 10^6


Cost (Tens of Thousands of Dollars)
Energy Consumption (MJ)
x 10^7
Condition
50th Percentile
5th Percentile
95th Percentile

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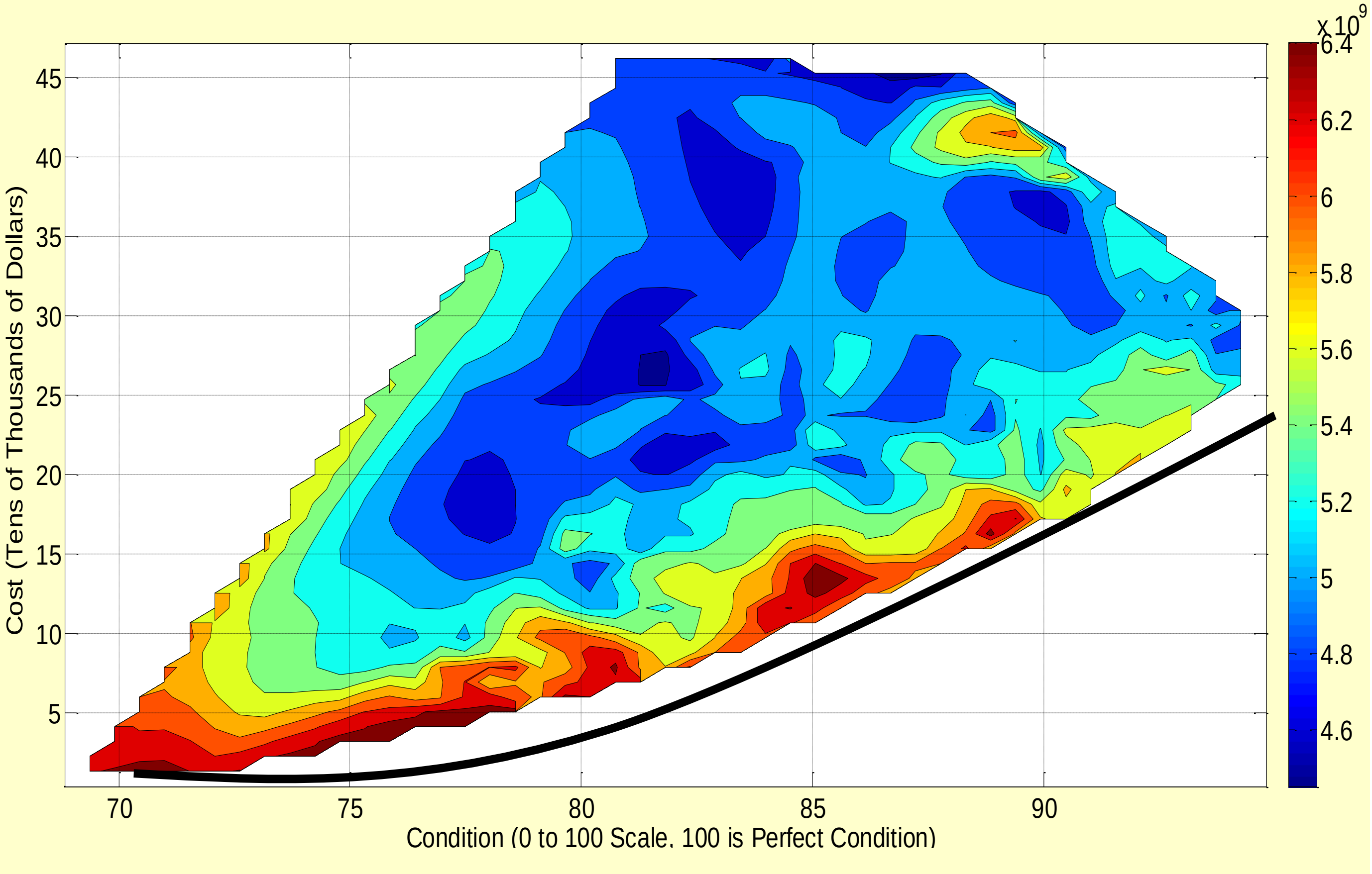
Discussion & Example of Findings



- ✓ Multi-criteria approach to pavement management
  - Tradeoff between maintenance and RR
  - Probabilistic approach facilitates the consideration of uncertainties and confidence for decision making
  - Increasing maintenance costs up to a point decreases total energy consumption

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Example III – Environmental and Economic Assessment of Pavement Construction and Management Practices for Enhancing Pavement Sustainability

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

Santos, J., Flintsch, G. and Ferreira, A. "Environmental and economic assessment of pavement construction and management practices for enhancing pavement sustainability," *Resources, Conservation & Recycling*, 2017, 116, pp. 15-31.

Formulation

✓ 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:

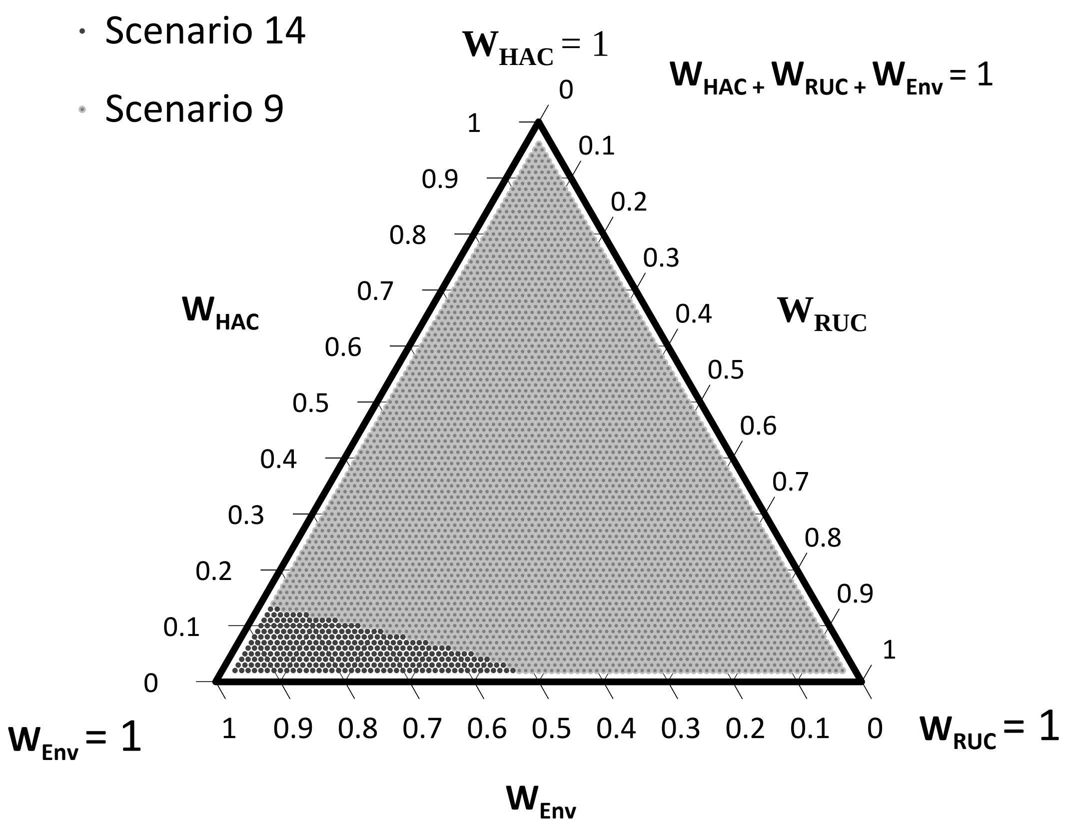
$$CCI(t) = CCI_0 - e^{a + b \times c^{ln\left(\frac{1}{t}\right)}}$$

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

Solution

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.



Some Findings

- ✓ Allowed to compare different pavement management strategies that can then be applied at the network level
- ✓ For the conditions considered in this case study
  - THMACO-based preventive maintenance strategy has proven to be the most environmentally-friendly solution.
    - It may be linked to current application criteria
  - Recycling-based VDOT M&R strategy (HMA containing 30% of RAP) provides a generally "optimal" balance in a MCDM.

Santos, J., Flintsch, G. and Ferreira, A. "Environmental and economic assessment of pavement construction and management practices for enhancing pavement sustainability," *Resources, Conservation & Recycling*, 2017, 116, pp. 15-31.

Conclusions

Final Remarks

- ✓ Customizable optimization-based pavement management DSS:
  - Integrated pavement LCC-LCA model
  - An AHGA mechanism for optimizing the pavement life cycle
  - MOO-based pavement life cycle optimization model
- ✓ Application in real and simulated case studies
  - Demonstrated that is applicable and practical
  - Provided insights on the efficiency of pavement engineering and management solutions in improving and balancing environmental and economic impacts of pavement management

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