Bridge Management System with Life Cycle Cost Optimization as a Decision Support Tool: A Case Study in New Jersey.

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Introduction

- Cost evaluation of our transportation infrastructures considering their whole life cycle is one of the key steps to achieving sustainable transportation.
- The current bridge management software tool has been utilized by the NJDOT Bridge team for their bridge management and planning needs since its early days of development. Although the tool provides many advanced functions such as life-cycle cost analysis and optimization, these functions require advanced agency-specific configuration to provide accurate results and customize to NJDOT's specific needs.



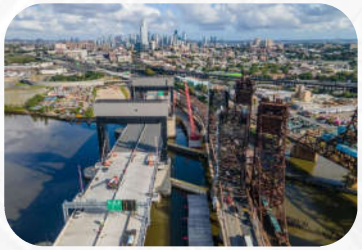
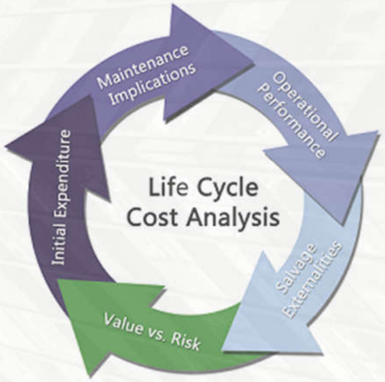

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Image credit: nj.com & construction equipment guide

Approach

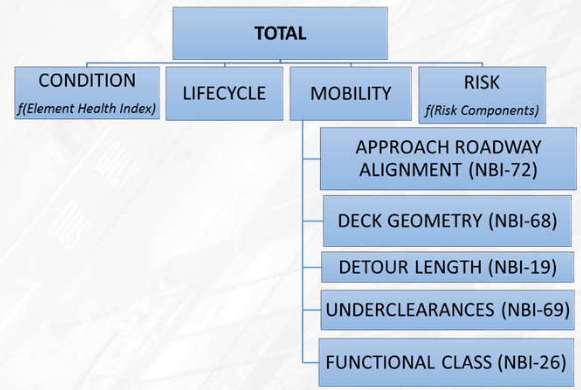
To assist the agency on these issues, Rutgers RIME / NYU C2SMART research team adopted a multi-faceted approach to utilize expert knowledge elicitation with advanced statistical analysis.

Customized Life-Cycle Cost Analysis (LCCA) Formula → **A Lightweight LCCA Decision Support Tool** → **An Interactive Web-based LCCA Tool**

- **Customized Life-Cycle Cost Analysis (LCCA) Formula**: A customized LCCA utility scaling formula for NJDOT
- **A Lightweight LCCA Decision Support Tool**: Spreadsheet-based tool for NJDOT's Bridge Management Activities
- **An Interactive Web-based LCCA Tool**: Provide better Data Visualization and Project Level & Network Level Optimization

Customized Life-Cycle Cost Analysis Formula

- Evaluation of default LCCA utility formula in the current bridge management tool:
  - The current default formula is:
  - $$LCC_{utility} = \left[1 - \frac{LCC}{2 \times Replacement\ Cost}\right] \times 100$$
  - In this formulation, once the LCC value exceeds the "*2xReplacement Cost*" the utility value is not calculated by the existing tool.
  - This default formula is not fully satisfactory in terms of NJDOT's needs.



A customized formula is proposed:

$$\boldsymbol{LCC_{utility} = \left[1 - \frac{CurrentLCC - MinLCC}{MaxLCC - MinLCC}\right] \times 100}$$

The new scaling formula considers the current LCC value between the minimum and maximum possible values given to that asset.

LCCA Excel Tool

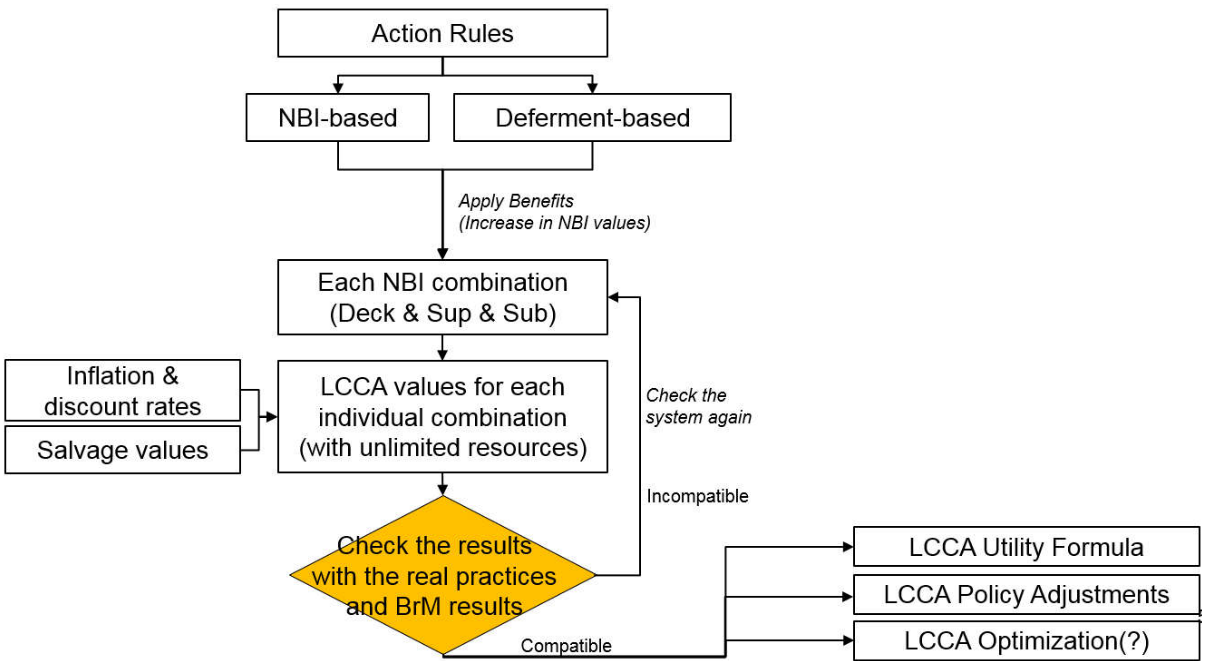
A Decision Support Tool for NJDOT's Bridge Management Activities:

- **EASY TO USE:** A spreadsheet tool is developed which enables users to easily modify LCCA parameters and rules from the built-in spreadsheets instead of database tables or complex menus of the current bridge management tool.
- **FASTER:** The developed excel tool produced comparable analysis results with the current bridge management tool in a fraction of time.
- Provide quick and robust **VALIDATION** capability: This excel tool provides the DOT with a new capability to test and validate new implementation ideas for LCCA in a quick and robust manner before they are incorporated into the current bridge management tool for final usage.

LCCA Excel Tool

- The current Excel tool is capable of calculating the key variables of the LCCA-utility value. These are minimum and maximum LCC values that a bridge can take during its lifecycle.
- Enables NJDOT personnel to evaluate all possible LCCA values by modifying the input sheets. The Excel spreadsheet is capable of performing network-wide LCCA analysis.
- NBI deterioration model and Action-Benefit-Cost modules are successfully validated using real-world data as well as data generated by the existing bridge management tool.

LCCA Excel Spreadsheet Flowchart



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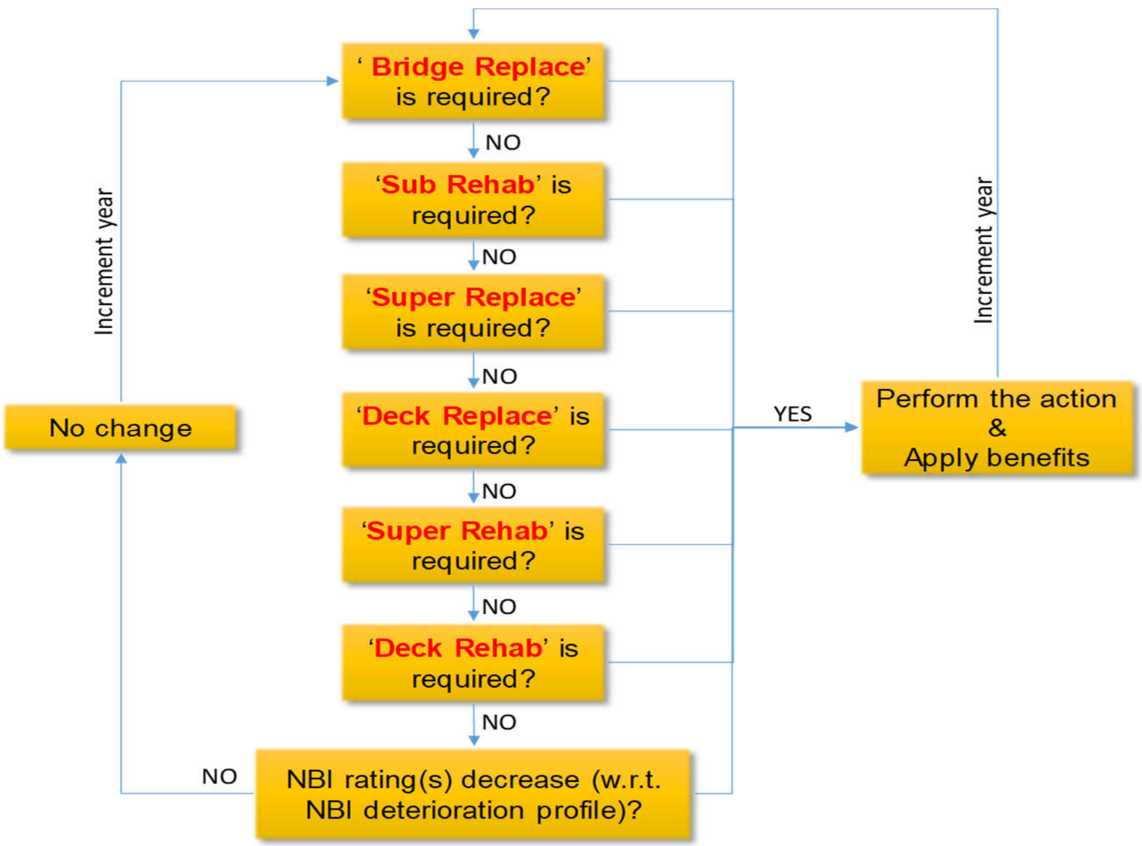
LCCA Excel Tool

The input sheets are present in the Excel tool as follows:

- NBI Action Items
- NBI Deterioration Patterns
- NBI Benefits
- NBI Costs
- NBI Policy Rules
- NBI Status

The output sheets are:

- Output
- Ratings
- Actions
- Costs

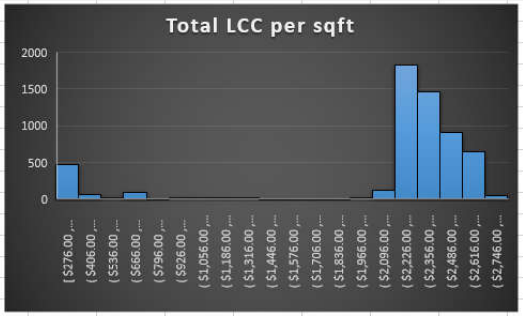


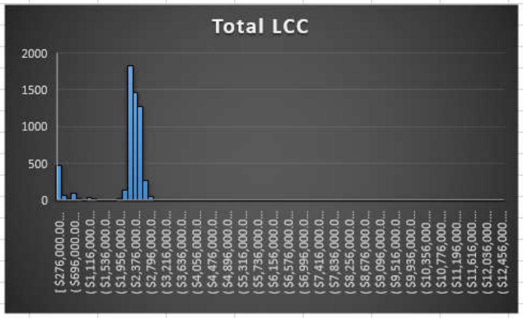
LCCA Excel Tool

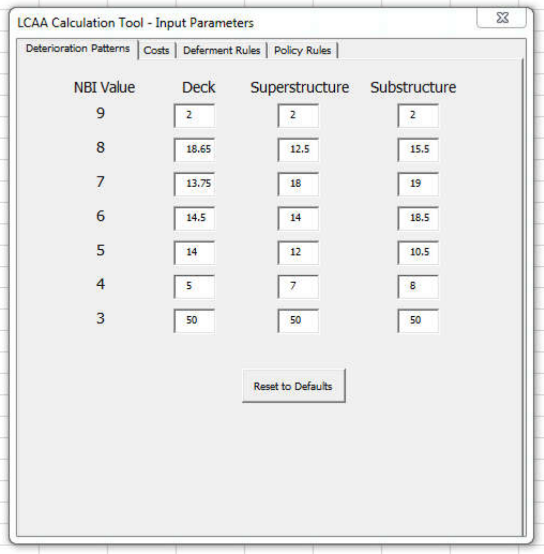
Modify Input Values

TOTAL LCC VALUES FOR EACH INDIVIDUAL BRIDGE

STRUCTURE_NUMBER_008	Area (sqft)	Initial Combined NBI	TOTAL LCC per sqft	TOTAL LCC
1519151	4919.998	8,6,7	$ 2,455.96	$ 12,083,318.29
1011156	4748.768	7,5,7	$ 2,645.71	$ 12,563,862.99
1101163	4696.798	4,6,6	$ 1,353.87	$ 6,358,853.91
1000096	770.8	8,7,7	$ 2,352.46	$ 1,813,276.17
020033A	1000	8,7,7	$ 2,352.46	$ 2,352,460.00
0500008	1000	8,7,7	$ 2,352.46	$ 2,352,460.00
0600002	1000	8,7,6	$ 2,162.71	$ 2,162,710.00
0600033	1000	8,7,7	$ 2,352.46	$ 2,352,460.00
0700088	1000	8,7,8	$ 379.50	$ 379,500.00
0802I09	1000	8,7,7	$ 2,352.46	$ 2,352,460.00
0900034	1000	8,7,8	$ 379.50	$ 379,500.00
1000141	1000	8,7,7	$ 2,352.46	$ 2,352,460.00
10XX300	1000	8,7,7	$ 2,352.46	$ 2,352,460.00
1100046	1000	8,7,8	$ 379.50	$ 379,500.00
13000A7	1000	8,7,8	$ 379.50	$ 379,500.00
1300HL5	1000	8,7,8	$ 379.50	$ 379,500.00
1400629	1000	8,7,7	$ 2,352.46	$ 2,352,460.00
1400999	1000	8,7,8	$ 379.50	$ 379,500.00
1401047	1000	8,7,7	$ 2,352.46	$ 2,352,460.00
1600432	1000	8,7,6	$ 2,162.71	$ 2,162,710.00
18D0702	1000	8,7,8	$ 379.50	$ 379,500.00
18D1103	1000	8,7,7	$ 2,352.46	$ 2,352,460.00
18H1402	1000	8,7,6	$ 2,162.71	$ 2,162,710.00
18L0903	1000	8,7,8	$ 379.50	$ 379,500.00
18L1013	1000	8,7,7	$ 2,352.46	$ 2,352,460.00
1900H16	1000	8,7,6	$ 2,162.71	$ 2,162,710.00
2102335	1000	8,7,7	$ 2,352.46	$ 2,352,460.00
2062152	1000	8,7,6	$ 2,162.71	$ 2,162,710.00
0119151	1000	8,7,7	$ 2,352.46	$ 2,352,460.00
0206185	1000	8,7,6	$ 2,162.71	$ 2,162,710.00
0225162	1000	8,7,6	$ 2,162.71	$ 2,162,710.00
0226167	1000	8,7,7	$ 2,352.46	$ 2,352,460.00
0235156	1000	8,7,7	$ 2,352.46	$ 2,352,460.00







Action List in RD | Cost Breakdown in RD | NBI List in RD | Bridge vs Cost in RD | Utility LCCA Values in RD

Our Previous Research – ASSISTME LCCA

A developed web-based LCCA tool that has not been integrated with NJDOT work but is applicable to what has been discussed .

Goal: To provide an interactive LCCA tool and quantify the life cycle costs of new material and technologies that link laboratory-measured parameters to actual field performance.

This tool is developed under the following project:

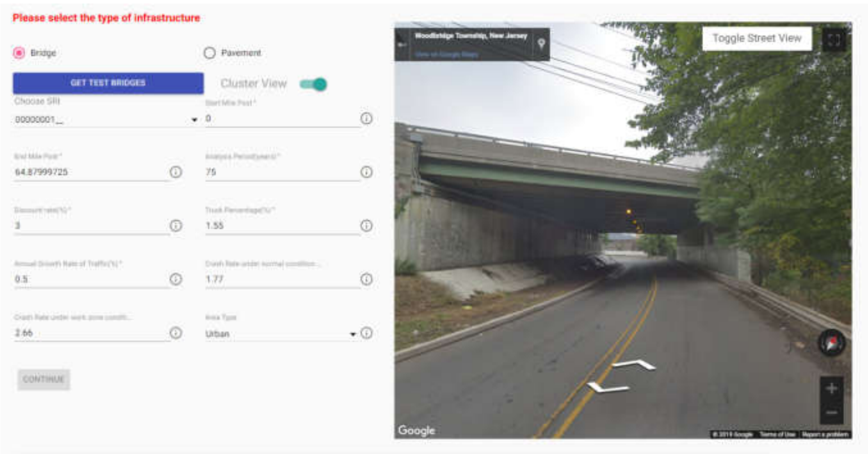
RE-CAST

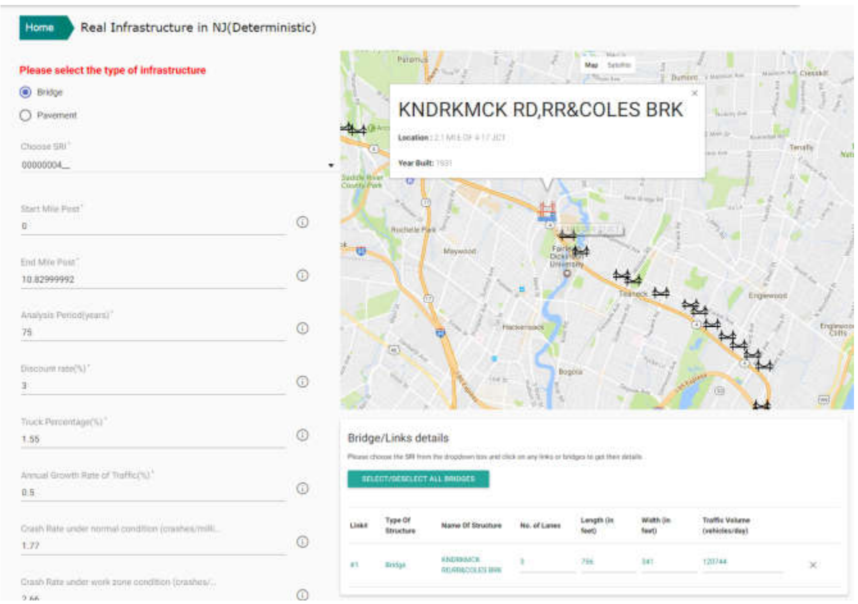
REsearch on Concrete Applications for Sustainable Transportation Led by the [RE-CAST Tier 1 UTC]() based at Missouri S&T

Gao, Jingqin, et al. "Stochastic Multi-Objective Optimization-Based Life Cycle Cost Analysis for New Construction Materials and Technologies." *Transportation Research Record* 2673.11 (2019): 466-479.

ASSISTME-LCCA
WEB-BASED TOOL

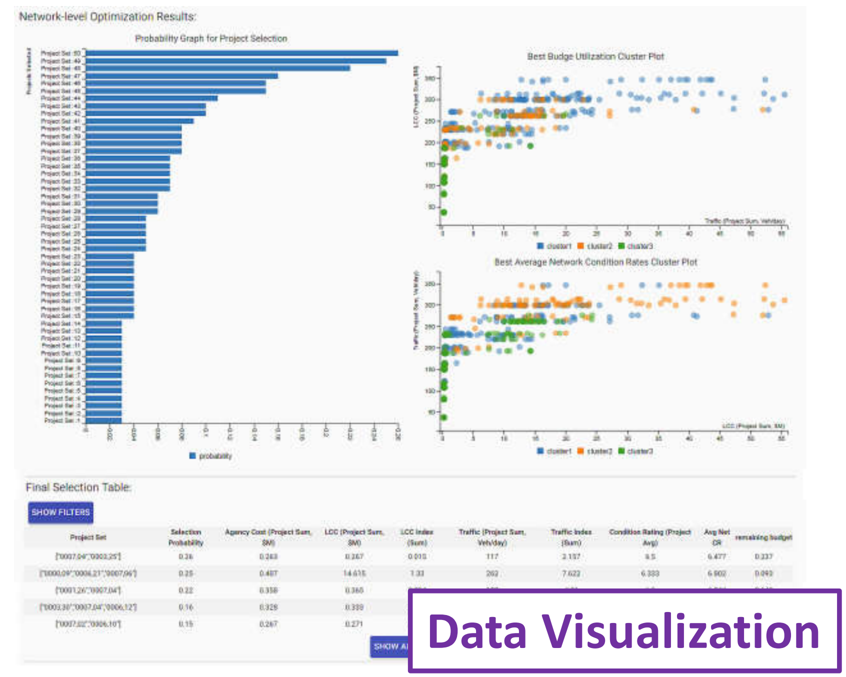
1. A web-based LCCA software tool that can access state-wide infrastructure data is being developed. This tool is able to automatically extract road and traffic data for each link.
2. A flexible and user-friendly interface is being developed to define performance functions specific to the construction materials and technologies used.
3. Web-based tool for performing LCCA has been tested and validated using New Jersey specific network data.

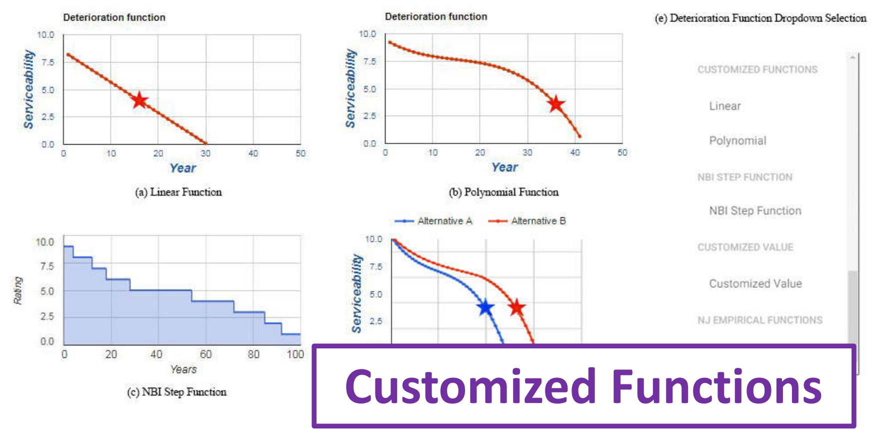




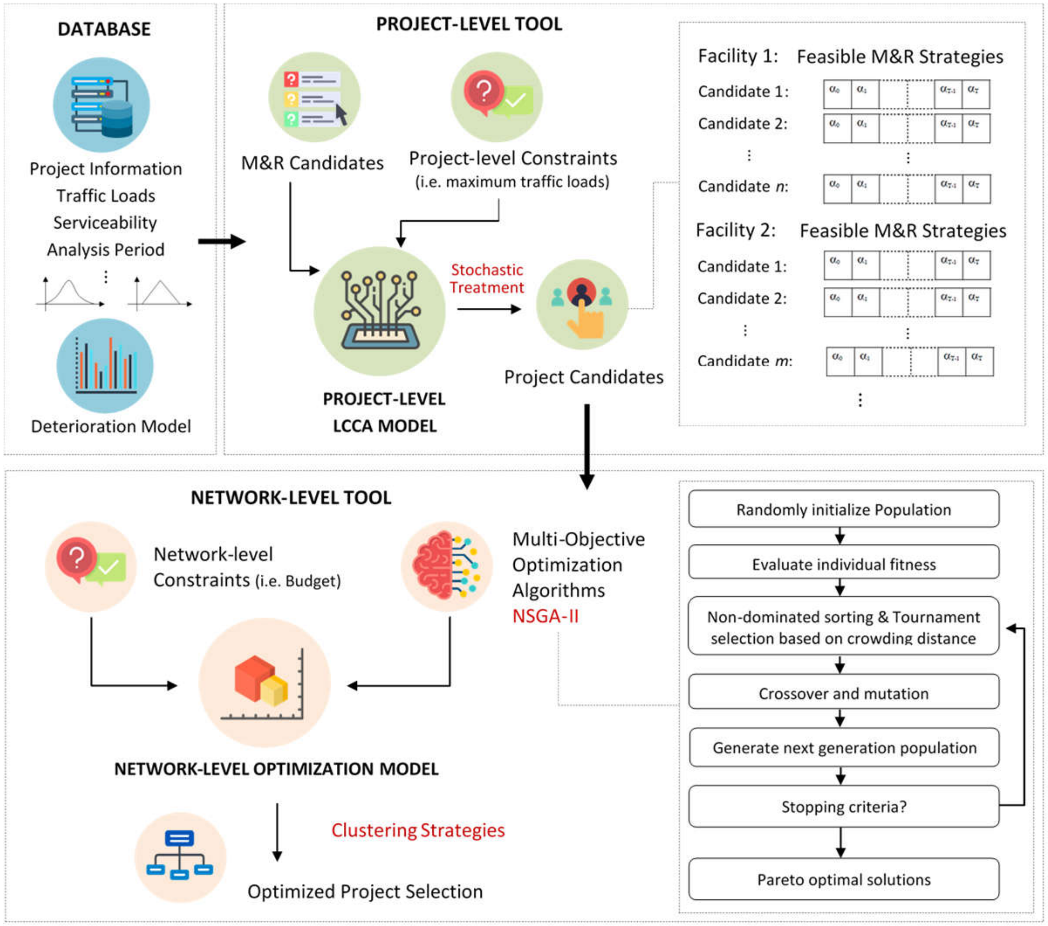
ASSISTME-LCCA
WEB-BASED TOOL

- ✓ Web-based Graphic User Interface
- ✓ Creates multiple hypothetical and real infrastructure LCCA scenarios for different types of transportation assets
- ✓ Performs project- and network-level analysis
- ✓ Performs deterministic and probabilistic analysis
- ✓ Pre-defined/customized performance functions
- ✓ Unified database - Automatically extract roadway, traffic, Weigh-in-Motion, and National Bridge Inventory data
- ✓ Highly interactive with various data visualization, analysis functions and reporting features





Two level bottom-up approach



SOFTWARE ARCHITECTURE

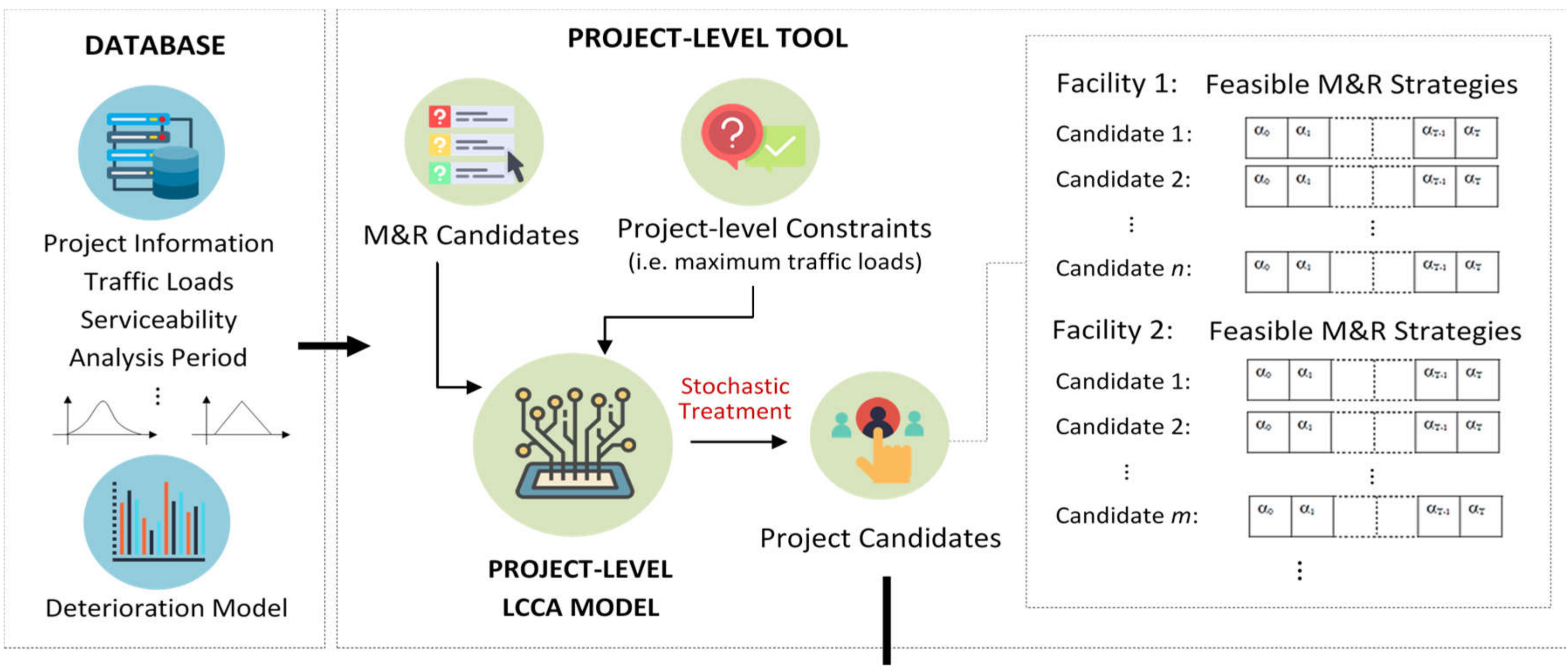
- Support multi-objective decision making while considering time effect and agency, user, and social costs
- Provide stochastic treatment of the inherent uncertainties
- Integrate project- and network-level optimization-based models
- Provide clear outcome interpretation.

Project Level Tool

A "project candidate" is defined as a life-cycle activity profile that contains a sequence of M&R activities for a transportation facility over certain analysis period.

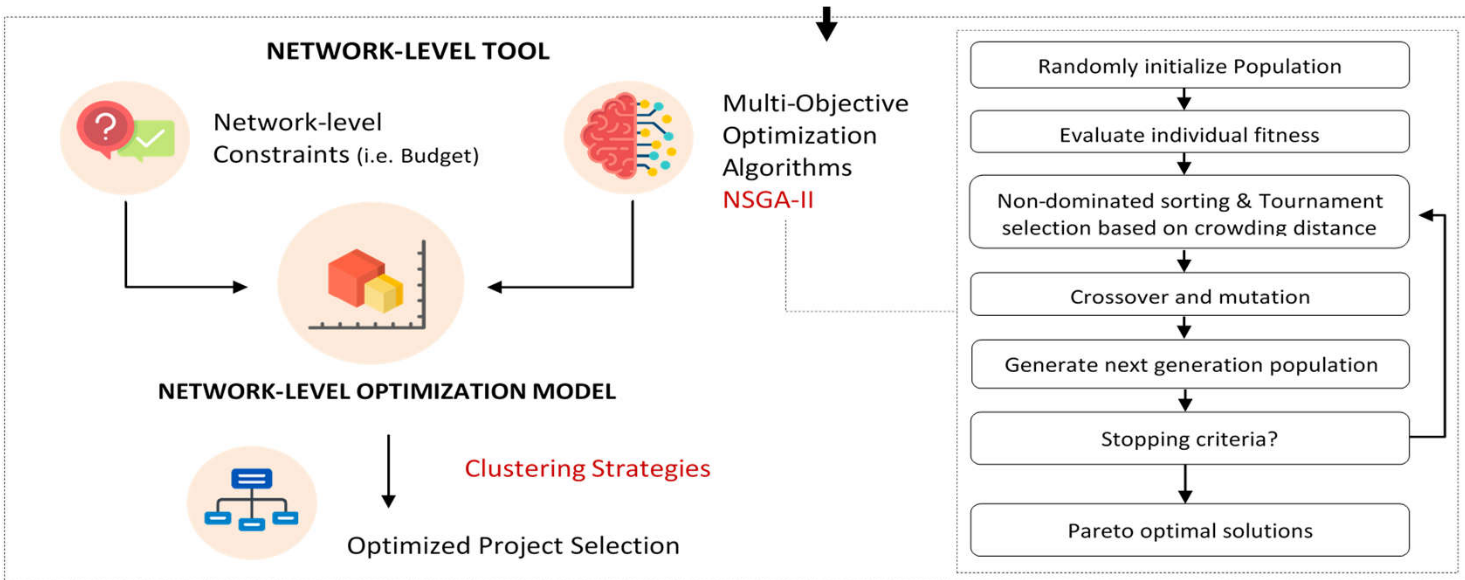
In the project-level, we first find "project candidates" -- all feasible M&R strategies for each facility based on project-level constraints, such as the facility's maximum traffic load or minimum acceptable serviceability and calculate the associated cost for each candidate.

1. **Agency Cost** (Residual Value included)
2. **User Cost**
3. **Social Cost**



Network Level Tool

- We solve the multi-objective optimization to find the best combination of projects to meet network-level goals.
- Economic/engineering models with optimization algorithms are used to balance the trade-off between objectives.



ASSISTME-LCCA
Optimization Algorithms
Non-dominated Sorting Genetic Algorithm II (NSGA-II)


Research Article

TRR

Stochastic Multi-Objective Optimization-Based Life Cycle Cost Analysis for New Construction Materials and Technologies

Jingqin Gao[1], Kaan Ozbay[2,3], Hani Nassif[4], and Onur Kalan[1]

SAGE

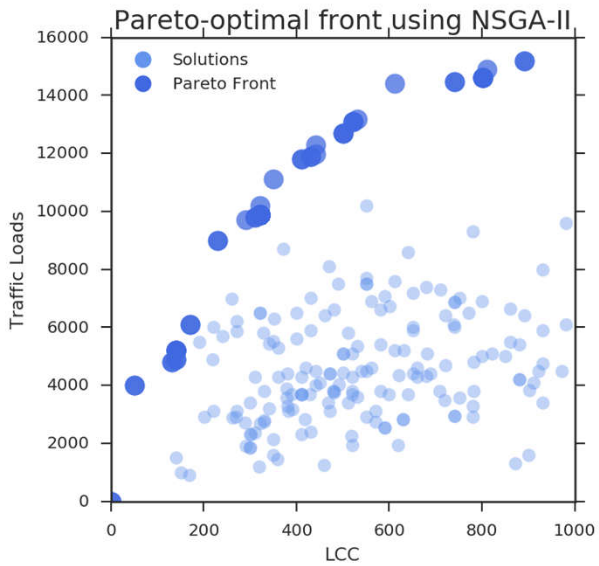
Performs constrained optimization to recommend a set of bridge projects that meet network level goals subject to constraints such as budget.

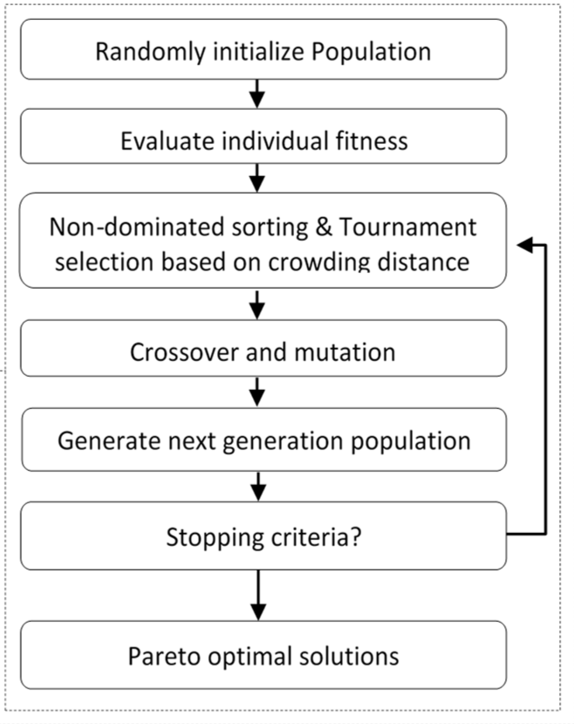
Evolutionary algorithms

NSGA-II

- Efficient/fast algorithm
- Maintains population diversity and excellent individuals

Multi-choice, multidimensional knapsack problem (MCMDKP)





Network-level Multi-Objective Optimization Model

Assuming that all facilities are independent and given a set of constraints (i.e. budget), the network-level optimization can be formulated as a multi-choice, multi-dimensional knapsack problem

$$\text{Minimize} \sum_{i=1}^{n} \sum_{j \in M_i} NPV_{ij} x_{ij}$$

← Minimize the total LCC of selected project candidates

$$\text{Maximize} \sum_{i=1}^{n} \sum_{j \in M_i} AADT_i x_{ij}$$

← Consider facility importance

Subject to:

$$B_l \leq \sum_{i=1}^{n} \sum_{j \in M_i} AC_{ij} x_{ij} \leq \mathrm{B}_u$$

← Budget Limits

$$\sum_{j \in M_i} x_{ij} \leq 1, \qquad (1 \leq i \leq n)$$

← One facility one project candidates

$$\sum_{i=1}^{n} \sum_{i \in M_i} x_{ij} \leq S$$

← Agency Resource limitations

(Maximum # projects)

$$x_{ij} = 0 \text{ or } 1$$

Where,

$x_{ij} = 1$ if candidate j of bridge i is selected, $x_{ij} = 0$ otherwise.

NPV_{ij} = Net Present Value of candidate j for bridge i

$AADT_i$ = Current annual average daily traffic of bridge i

CR_{0i} = Current condition rating of bridge i

AC_{ij} = Agency cost of candidate j for bridge i

B = Budget ($)

S = Maximum number of candidates selected

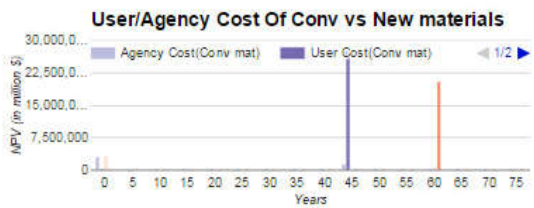
Project-level LCCA Output

Deterministic

Output

Agency Cost

	Name Of Sub Cost	Conventional Material	New Material
1	Initial Construction Cost	$ 3,108,020	$ 3,484,510
2	Maintenance Cost	$ 852,456	$ 955,719
3	Rehabilitation Cost	$ 1,479,385	$ 1,064,586
4	Salvage Value	$ -203,162	$ -512,488
5	Total Agency Cost	$ 5,236,699	$ 4,992,328

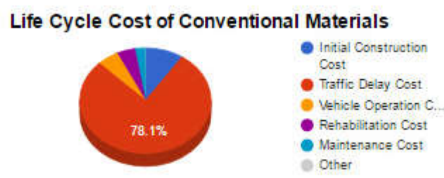


User Cost

	Name Of Sub Cost	Conventional Material	New Material
1	Traffic Delay Cost	$ 25,734,074	$ 19,218,118
2	Vehicle Operation Cost	$ 1,728,107	$ 1,280,466
3	Crash Risk Cost	$ 25,295	$ 15,747
4	Total User Cost	$ 27,487,476	$ 27,487,476

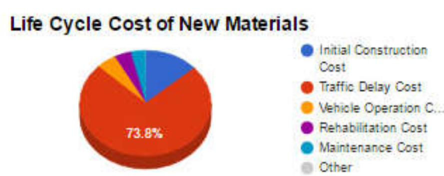
Social Cost

	Name Of Sub Cost	Conventional Material	New Material
1	Air Pollution Cost	$ 7,307	$ 4,549
2	Noise Pollution Cost	$ 0	$ 0
3	Environmental Energy Cost	$ 0	$ 0
4	Total Social Cost	$ 7,307	$ 4,549



Life Cycle Cost

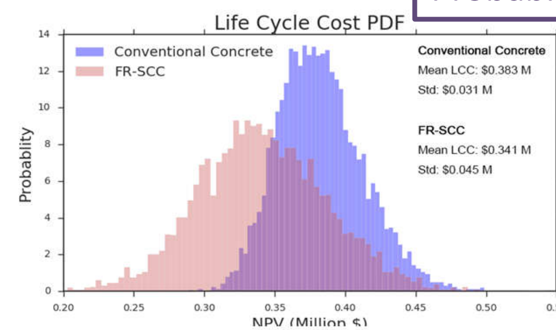
	Name Of Sub Cost	Conventional Material	New Material
1	Total Cost	$ 13,490,249	$ 11,151,176

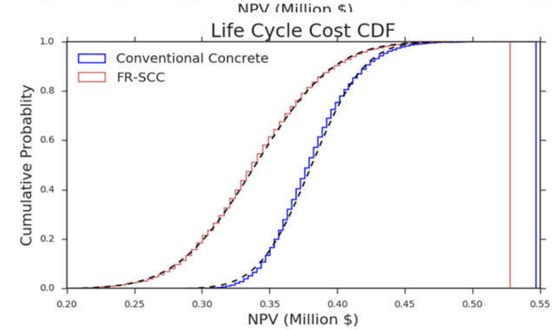


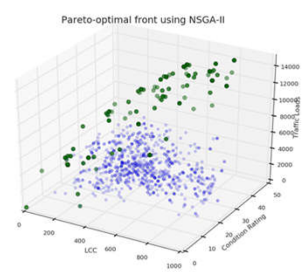
Cost Breakdown

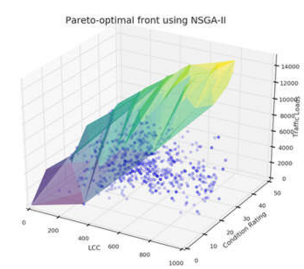
		CE of Global warming potential ($/lb co2 -eq reduced)	CE of Primary Energy Consumption ($/mg co2 -eq reduced)
1	Cost Effectiveness	$ 0.11	$ 21.36

Probabilistic









Network-level LCCA Outputs

Output contains all pareto-optimal solutions. Selection probability indicates how many times this solution is selected as a pareto-optimal solution during all probabilistic runs.

Network-level Outputs:

- Project sets
- Total agency cost
- Total life cycle cost
- Total traffic loads
- Average Network Condition Rate
- Remaining Budget
- Selection probability for each set (Probabilistic approach only)

Project Set	Selection Probability	Agency Cost (Project Sum, $M)	LCC (Project Sum, $M)	LCC Index (Sum)	Traffic (Project Sum, Veh/day)	Traffic Index (Sum)	Condition Rating (Project Avg)	Avg Net CR	remaining budget
['0007,04','0003,25']	0.26	0.263	0.267	0.015	117	2.157	6.5	6.477	0.237
['0000,09','0006,21','0007,06']	0.25	0.407	14.615	1.33	262	7.622	6.333	6.802	0.093
['0001,26','0007,04']	0.22	0.358	0.365	0.024	159	4.31	6.5	6.544	0.142
['0003,30','0007,04','0006,12']	0.16	0.328	0.333	0.017	187	3.803	6.333	7.453	0.172
['0007,02','0006,10']	0.15	0.267	0.271	0.016	149	3.803	6	5.863	0.233

Summary

Customized LCCA scaling formula and EXCEL tool for decision making

Introduce a probabilistic LCCA-based framework

- Integrate project- and network-level analysis
- Includes stochastic treatment of the inherent uncertainties
- Consider out-of-pocket costs
- Consider multiple performance measures and effect of time
- Unified databased ready for NJ

Capable of dealing with new material or construction technologies

- Link laboratory performances onto the future field performance predictions
- Present novel probabilistic approaches that are able to deal with the high level of uncertainty of novel materials / construction technologies

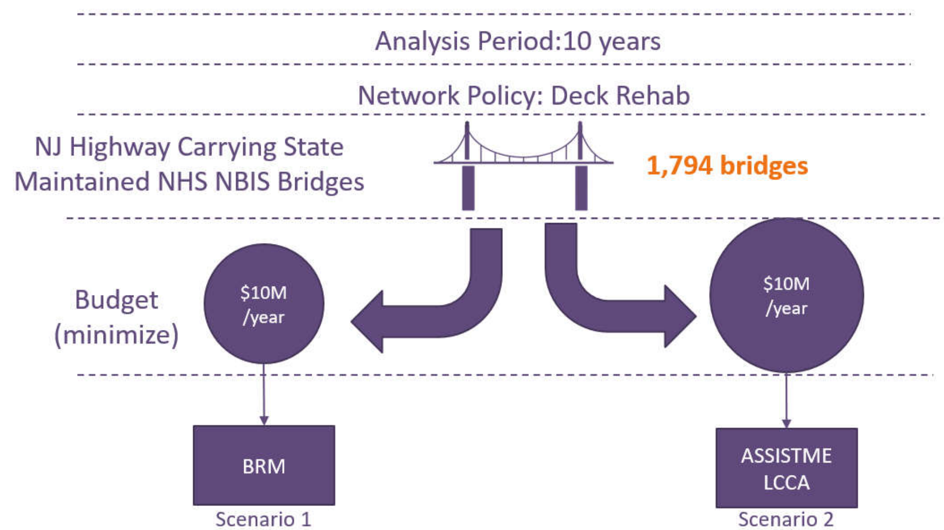
Future Work

Small-scale and large-scale tests confirmed that ASSIST-ME LCCA optimizer results in the selection of larger size bridges than the optimizer in the current bridge management software used by NJDOT and has almost full utilization of the total budget for the given study period.

However, ASSISTME-LCCA is not a production tool and requires customization and input data manipulation to be able to run different scenarios.

Future work:

- Combine with the LCCA EXCEL tool to build a pre-processor to make it easier to process data from the current bridge management software used in NJDOT
- Extend ASSIST-ME LCCA to be able to run for multi-policies



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