Life-cycle Performance, Reliability, Risk, Resilience and Sustainability of Civil Infrastructure

November 1, 2013

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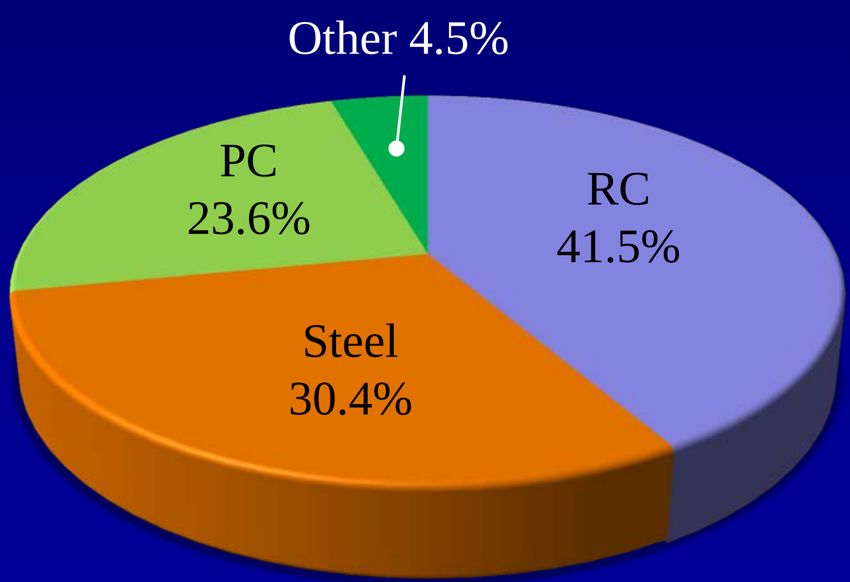
Introduction

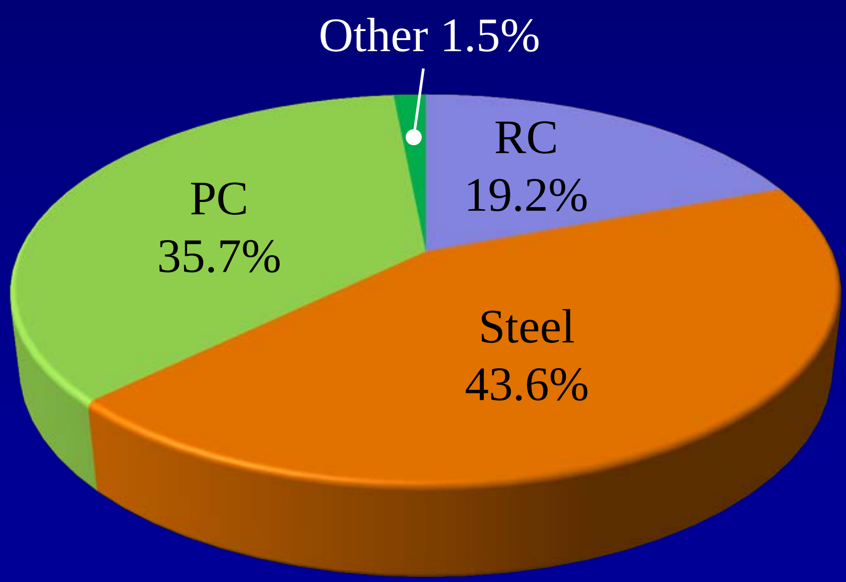
- **The United States has four million (4,067,076) miles of public roads (as of 2010)*.**

- **The road network carries 86% of passenger transportation and 60% of freight transportation.**

- **The road network contains more than 600,000 bridges (604,460) *.**



→ % of bridge types by number

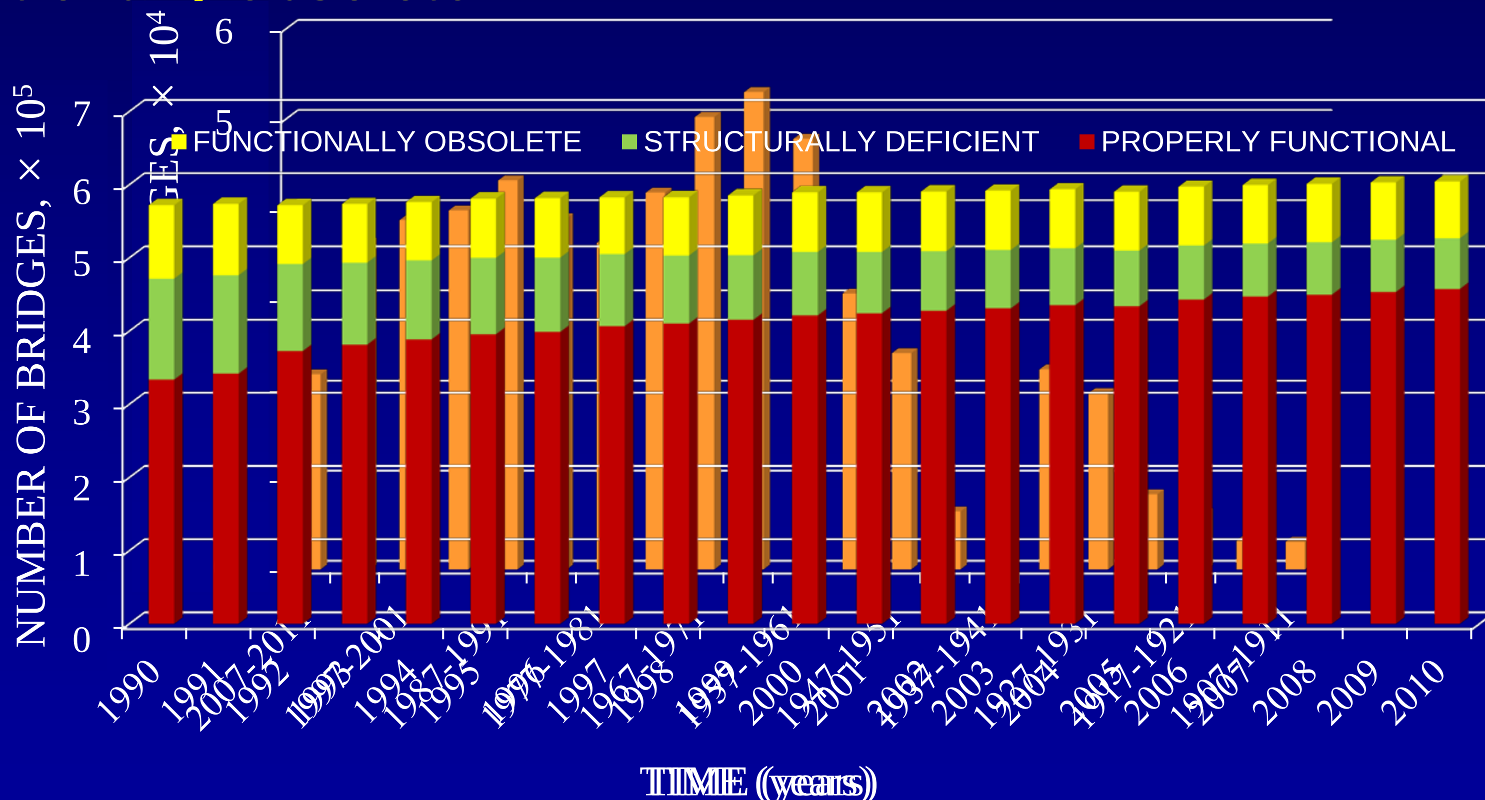


→ % of bridge types by deck area

* FHWA, (2011). "*National bridge inventory*." United States Department of Transportation, Federal Highway Administration.

Introduction

- **Approximately 42% of the bridges in the United States are more than 50 years old*.**
- **24.2% of bridge inventory are either structurally deficient or functionally obsolete*.**



FHWA, (2011). "*National bridge inventory*." United States Department of Transportation, Federal Highway Administration.

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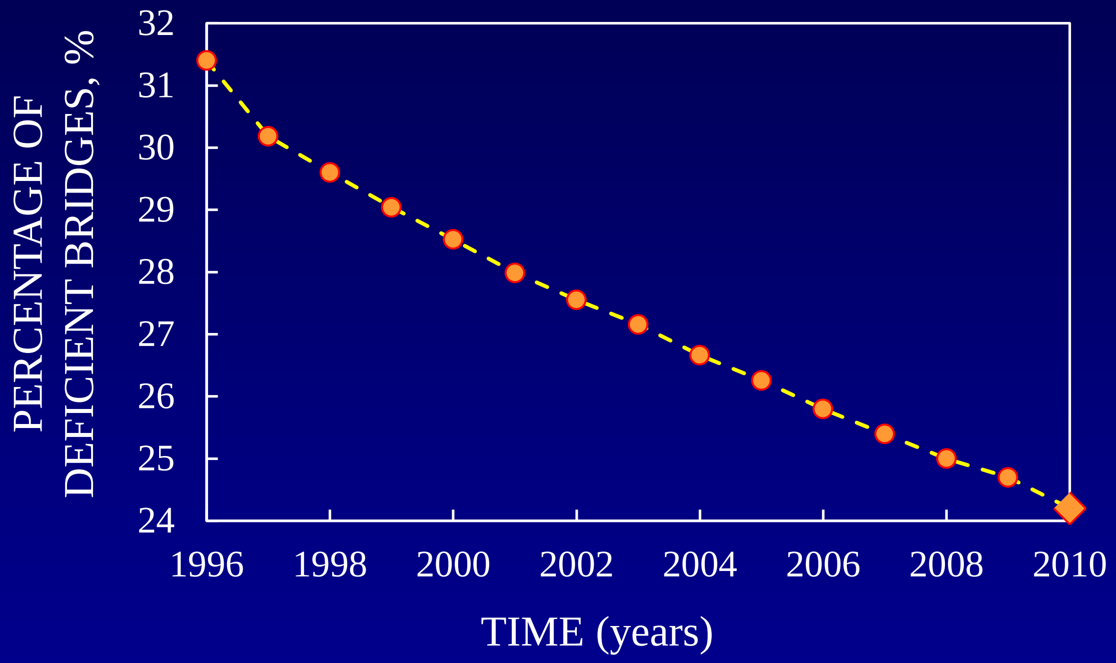
Introduction

- The number of structurally deficient and functionally obsolete is in continuous decrease since 1990.



- Improving the bridge inventory condition requires an average annual investment of $17 billion*.
- In 2004, a total of $10.4 billion was spent on bridge rehabilitation*.

* ASCE, (2009). "*Report Card for America's Infrastructure*." American Society of Civil Engineers.

Introduction

- This deficiency in funding requires innovative structural management techniques to plan for future inspections and repair actions and cost effective maintenance strategies.

- Bridges are mandated to be inspected at least every two years; however, these visual inspections may not ensure that fatal problems will be detected.

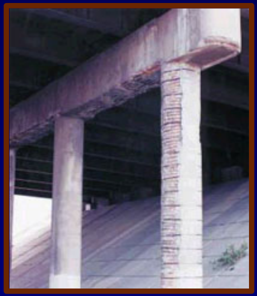
CONCRETE SLAB CRACKS

FATIGUE CRACKS

Different ways of damage occurrence

Aggressive environmental conditions:
- Corrosion

→ Structures deteriorate progressively in time → Reduced safety or collapse if no maintenance



Extreme events:
- Floods
- Hurricanes
- Earthquakes
- Blasts
- Fires

→ Sudden damage → Collapse if cannot withstand adequate amount of local damage

Motivation

How safety, redundancy and durability affect the life-cycle design, assessment, maintenance and management of civil infrastructure systems?

Northeast Blackout 2003

Laval Overpass Collapse 2006

Hurricane Katrina 2005

I35W Minneapolis Bridge 2007

Sources: Meteorological Satellite Program, Associated Press, CCTV News, and Minnesota State Department of Transportation

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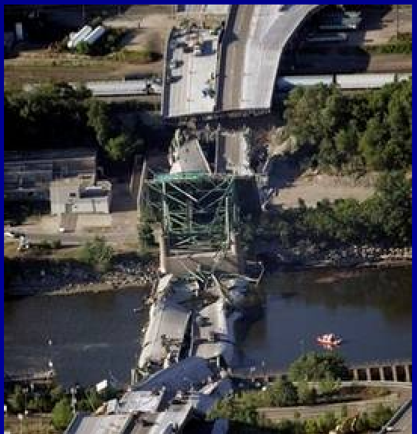
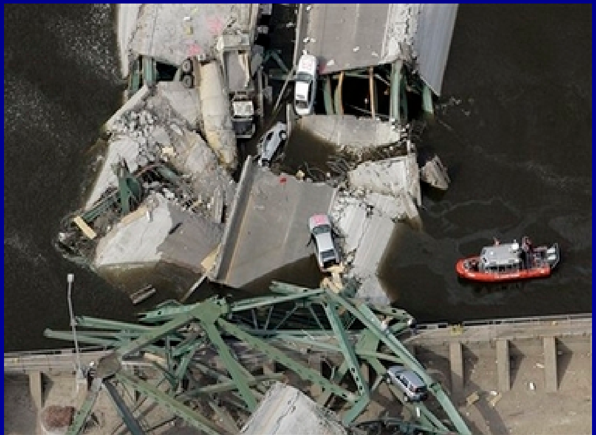
Risk (consequence of failure)

An example to provide an estimate of risk as applied to highway bridges.

Table 1. Estimated costs associated with the collapse of the I35W bridge in Minneapolis, Minnesota, USA, 2007 [11, 12]

Site Recovery Costs	$400 million
Estimated user costs: 140,000 vehicles/day, 10 mile detour, IRS allocated .48 cent/mile, and 365 day construction time of new bridge	$245 Million
Winning bid for new structure	$234 million
State liability cap of $1 million on 13 deaths	$13 million
Estimated $10,000 hospital bill on 100 injured	$ 1 million
Lawsuits, legislation, loss of productivity, and investigation	*(not estimated)*
Total Estimated Consequence of Failure	US$893 million


2013 Report Card for America's Infrastructure
(Gives Nation a D+, Estimates Cost at $3.6 Trillion)

Grades for Insfrastructure Categories According to 2013 Report Card for America’s Infrastructure

AVIATION	D	PORTS	C
BRIDGES	C^+	PUBLIC PARKS AND RECREATION	C^-
DAMS	D	RAIL	C^+
DRINKING WATER	D	ROADS	D
ENERGY	D^+	SCHOOLS	D
HAZARDOUS WASTE	D	SOLID WASTE	B^-
INLAND WATERWAYS	D^-	TRANSIT	D
LEVEES	D^-	WASTEWATER	D

ESTIMATED 5-YEAR INVESTMENT NEEDS IN BILLIONS OF DOLLARS

Cumulative Infrastructure Needs by System Based on Current Trends Extended to 2020 and 2040 (Dollars in $2010 billions)

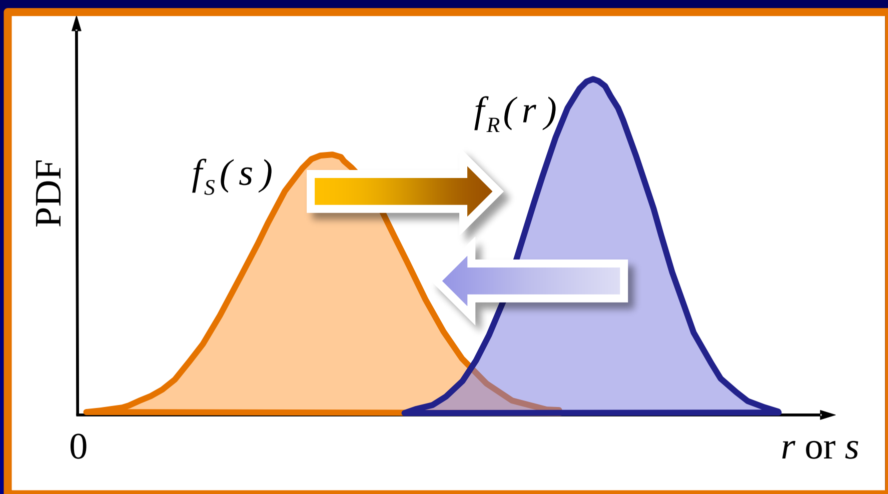
	2020			2040		
INFRASTRUCTURE SYSTEMS	TOTAL NEEDS	EXPECTED FUNDING	FUNDING GAP	TOTAL NEEDS	EXPECTED FUNDING	FUNDING GAP
Surface Transportation	$1,723	$877	$846	$6,751	$3,087	$3,664
Water/Wastewater	$126	$42	$84	$195	$52	$144
Electricity	$736	$629	$107	$2,619	$1,887	$732
Airports*	$134	$95	$39	$404	$309	$95
Inland Waterways & Marine Ports	$30	$14	$16	$92	$46	$46
TOTALS	$2,749	$1,657	$1,092	$10,061	$5,381	$4,681

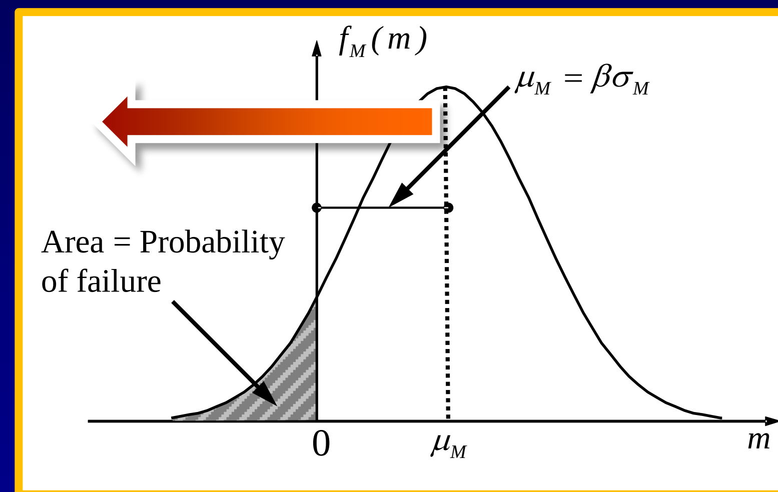
(taken from Failure to Act Report, ASCE, 2013)

BACKGROUND

Performance indicators for civil infrastructure

Reliability → $\beta(t)$ **Time dependence**





Safety Margin ure

$M = R - S$ $(s) f_S(s) ds$

Reliability Index stically nt

$\beta = \dfrac{\mu_M}{\sigma_M}$

Probability of failure

$p_F = \int_{-\infty}^{0} f_M(m)\,dm$ dr

$\beta = \dfrac{\mu_R - \mu_S}{\sqrt{\sigma_R^2 + \sigma_S^2}}$

al

$\beta = \Phi^{-1}(p_S) = \Phi^{-1}(1 - p_F)$

Ang and Tang (1984); Leemis (1995)

BACKGROUND

Performance indicators for civil infrastructure

Risk → $R(t)$ **Time dependence**

Risk is quantified by combining the probability of occurrence and the consequences of events generated by hazards

Instantaneous total risk *R*

$$R = \int\int\cdots\int \kappa(x_1, x_2, \ldots, x_m)\cdot f_X(x_1, x_2, \ldots, x_m)\cdot dx_1 \cdot dx_2 \cdots dx_m$$

$$R = \sum_{i=1}^{n} C_{m,i}$$

$R = p \cdot \chi$

...nsequences of hazard(s)

Simplest formulation

8.0E+06

$C_{m,i}$: monetary value associated with the consequ...

Sustainability

$P[H_i]$: ...ence of an event resulting from a hazard

$P[F \mid$ ... probability given the occurr...

- Societal
- Environmental
- Economic

n : to... ...nsidered within the analys...

...g ...ity

Time (years) Zhu *et al.* (2015)

Ang and De Leon (2005); CIB (2001); Ellingwood (2001); Decò and Frangopol (2011)

BACKGROUND

Hazard Analysis

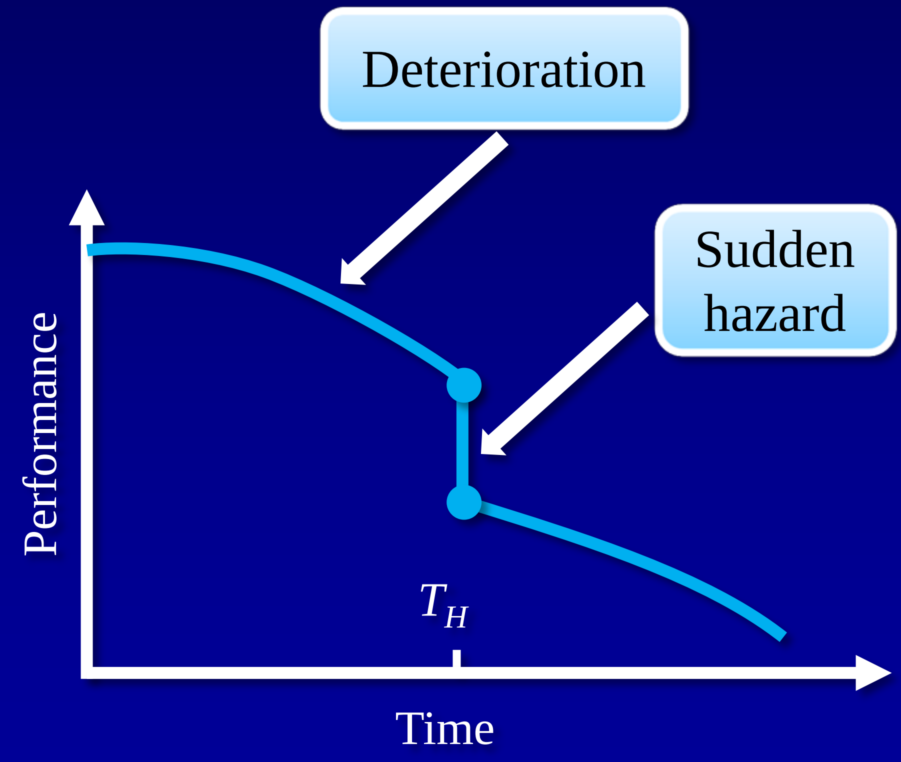
Hazards are actions that pose potential harm to a structure or the persons occupying a structure

1) Man made hazards

- Explosions
- Accidents
- Terrorism

2) Natural hazards

- Earthquakes
- Floods
- Wind
- Fires



BACKGROUND

Consequence evaluation

Necessary step of risk assessment

- The consequences of component and system failure depend on the type, size, and importance of the structure
- Each consequence is quantified in terms of monetary values
- The consequences are categorized as direct and indirect costs

Example: bridge

The **direct** cost of a bridge girder failure

$$C_{Direct}(t) = c_g \cdot G_g \cdot L_g$$

Replacement cost of a bridge girder

Future value of an expenditure

$$FV(t) = PV \cdot (1+r)^t$$

The **indirect** cost of rebuilding a bridge structure

$$C_{Reb}(t) = c_{Reb} \cdot W \cdot L$$

- Running cost of the detoured vehicles,
- Time loss due to the unavailability of the highway segment

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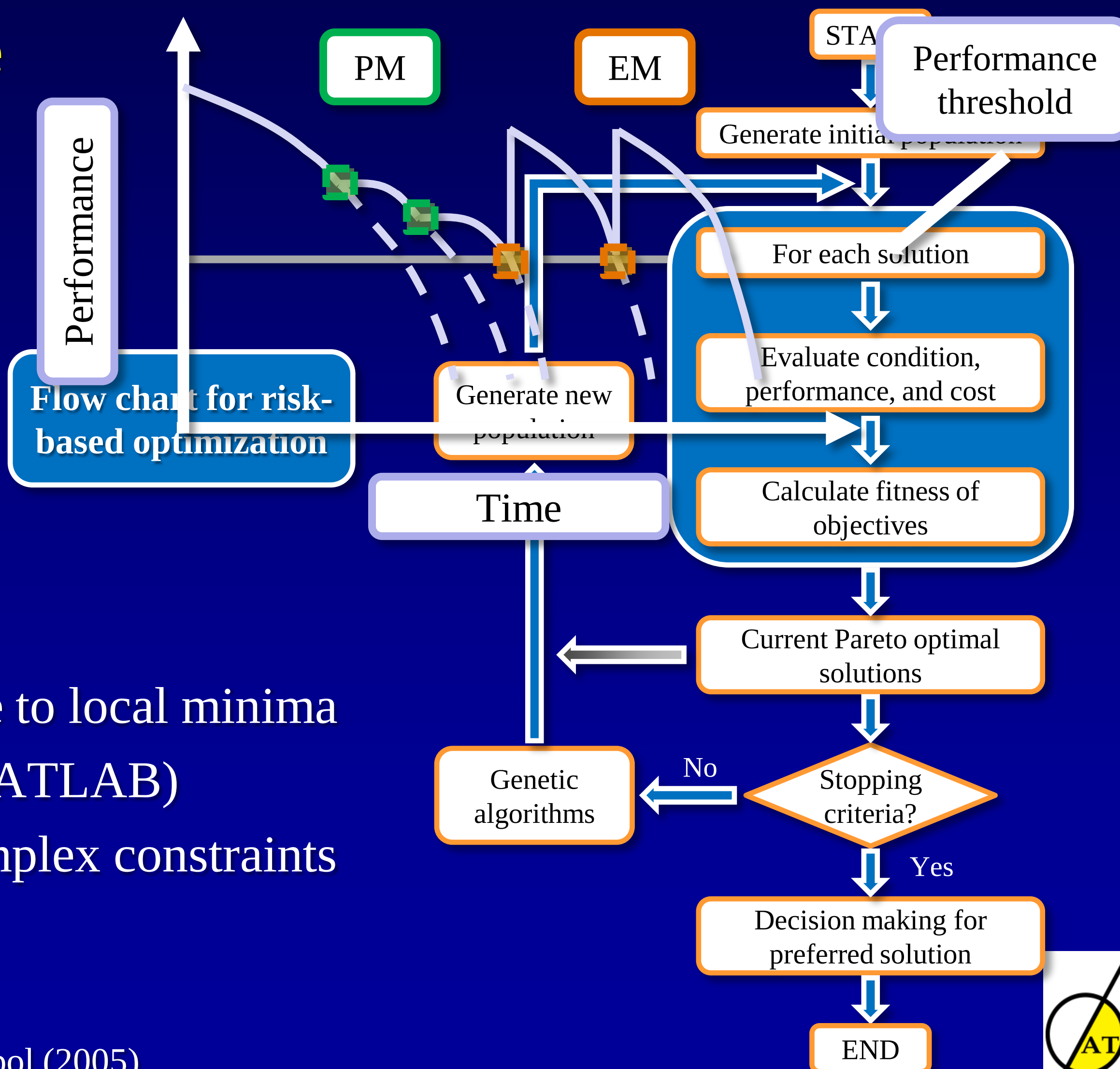
Saydam *et al.* (2013b)

BACKGROUND

Integrated probabilistic life-cycle management framework

Effects of maintenance

Preventative maintenance (PM)
Essential maintenance (EM)



Optimization

Genetic algorithms are used

- Robust against convergence to local minima
- Ease of implementation (MATLAB)
- Multiple objectives and complex constraints

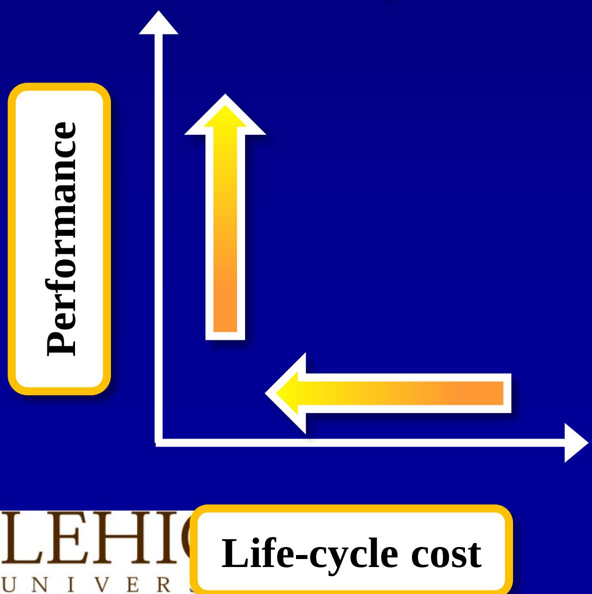
Liu and Frangopol (2005)

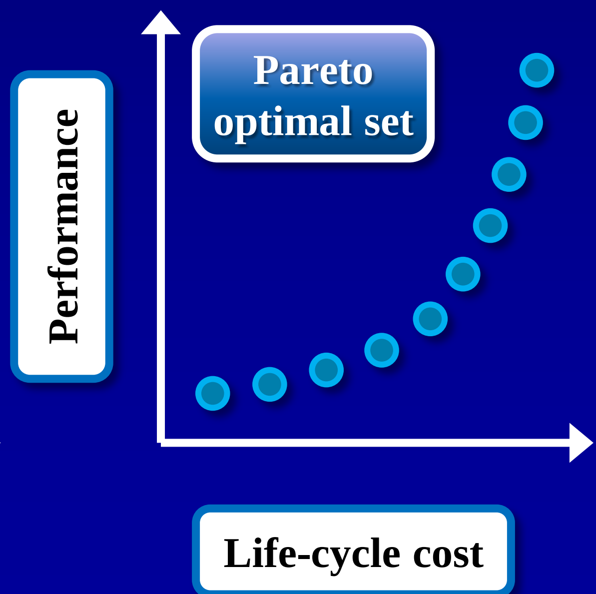
BACKGROUND

Life-cycle management, optimization, and decision making

Life-cycle performance assessment and intervention scheduling

- Predict a structure's performance throughout its lifetime
- Determine possible intervention strategies and associated costs
- Perform optimization to determine optimal intervention planning scheduling (*inspection*, *maintenance*, *monitoring*, *removal*, and *renewal* actions)





Design variables:

- $t_1, t_2, \dots, t_n$ (time intervention actions are performed)
- $IA_1, IA_2, \dots, IA_n$ (respective intervention actions)

CONTENTS

INTRODUCTION

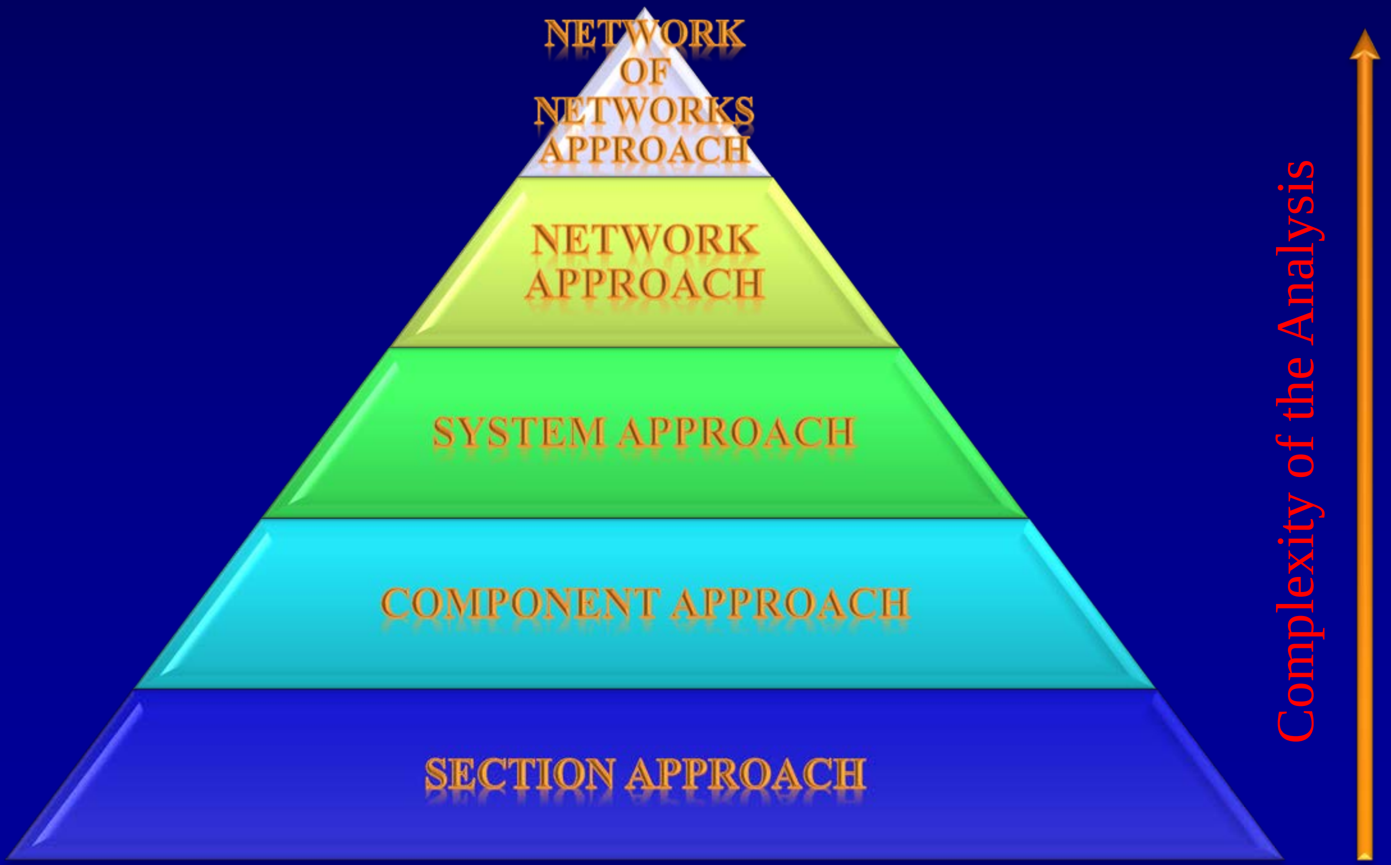
SYSTEM PERFORMANCE ASSESSMENT AND PREDICTION

INTEGRATION OF SHM IN LCM

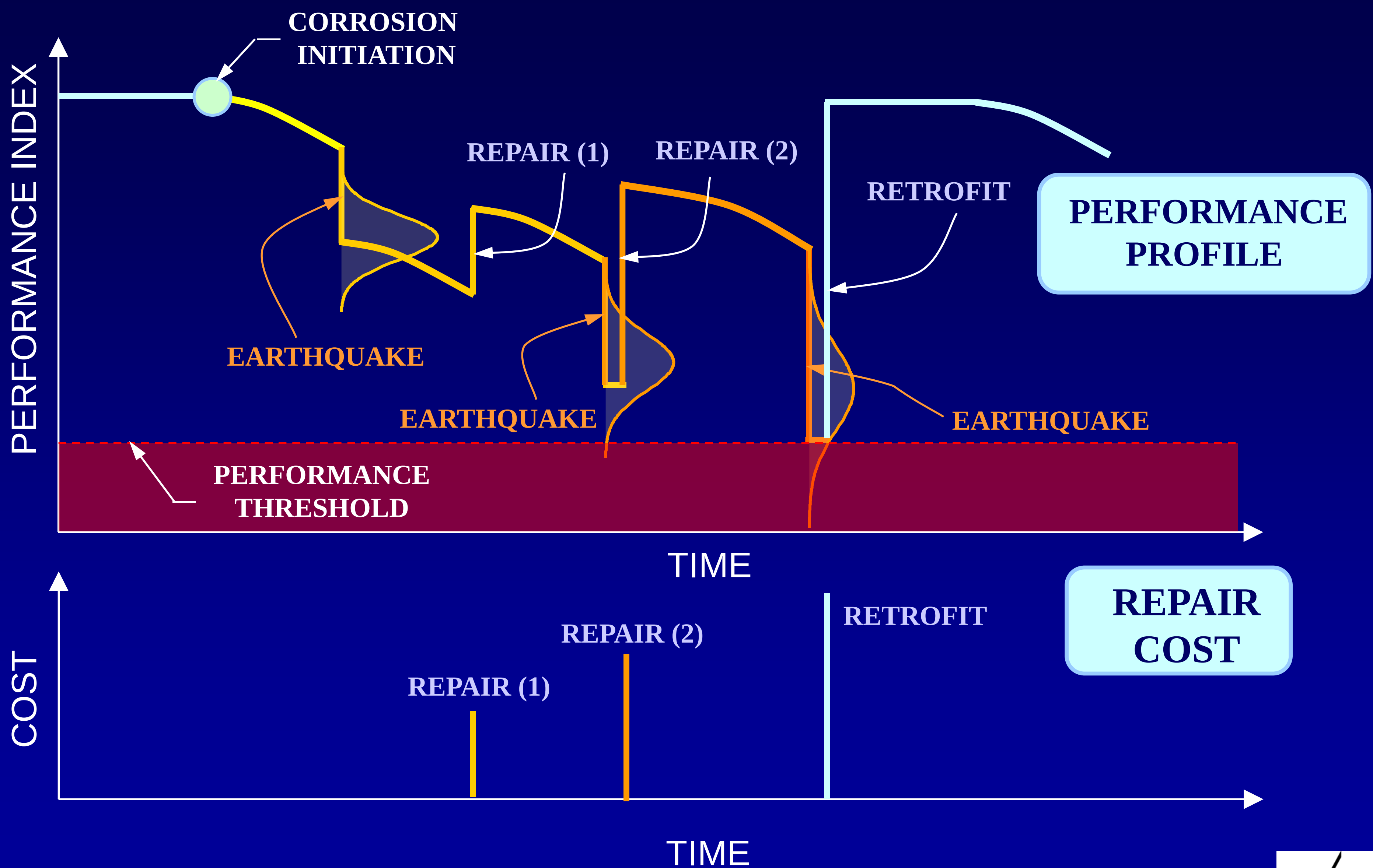
ROLE OF OPTIMIZATION

CONCLUSIONS

LEVELS OF PERFORMANCE QUANTIFICATION

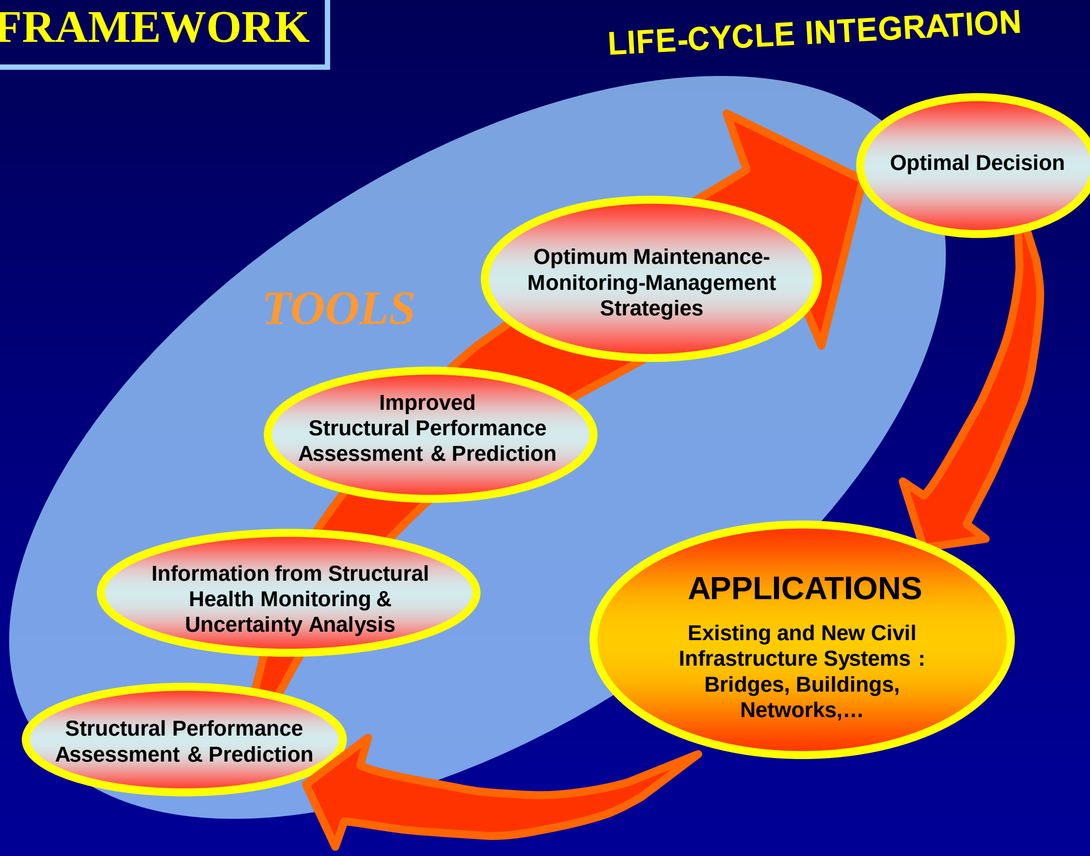


PERFORMANCE PROFILE WITH CORROSION AND SEISMIC ACTION



INTRODUCTION

LIFE-CYCLE INTEGRATED MANAGEMENT FRAMEWORK



CONTENTS

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SYSTEM PERFORMANCE ASSESSMENT AND PREDICTION

Commonly employed methodology to design based on component analysis:

- Considerable waste of resources due to over-conservatism for redundant systems
- Overestimation of the actual load carrying capacity for weakest-link systems

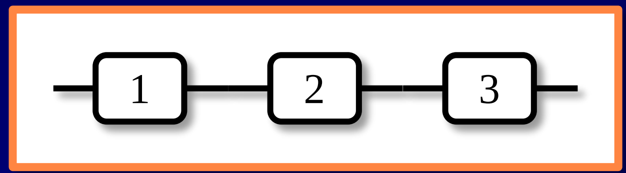
System Reliability

Performance indicators

System reliability $g_i(t) = R_i(t) - S_i(t)$

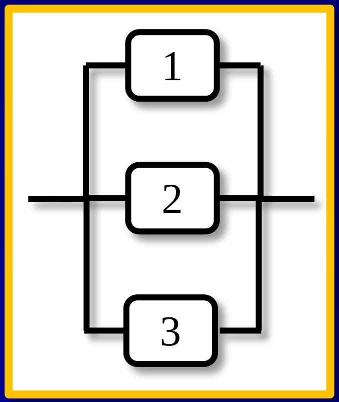
- Load and resistance modeling
- Limit state equations for components
- System analysis

Series system



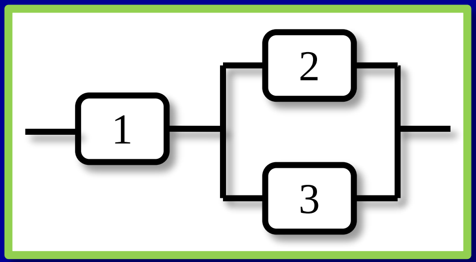
$$p_F = p\left(\bigcup_{i=1}^{N}\left\{g_i\left(\mathbf{X}\right) \le 0\right\}\right)$$

Parallel system



$$p_F = p\left(\bigcap_{i=1}^{N}\left\{g_i\left(\mathbf{X}\right) \le 0\right\}\right)$$

Series-parallel system



$$p_F = p\left(\bigcup_{k=1}^{M}\bigcap_{i=1}^{K}\left\{g_{i,k}\left(\mathbf{X}\right) \le 0\right\}\right)$$

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SYSTEM PERFORMANCE ASSESSMENT AND PREDICTION

System Redundancy and Robustness

• System redundancy

→ the ability of a structural system to redistribute the applied load after reaching the ultimate capacity of its main load-carrying members

• Robustness

→ the ability of a structural system to resist extreme actions without suffering from damages disproportionate with respect to the causes that have generated them

SYSTEM PERFORMANCE ASSESSMENT AND PREDICTION

System Redundancy and Robustness

- Time-variant redundancy indices (Okasha and Frangopol, Structural Safety, 2009)

$$RI_1(t) = \frac{P_{y(sys)}(t) - P_{f(sys)}(t)}{P_{f(sys)}(t)}$$

$P_{y(sys)}(t)$ = probability of first member failure occurrence at time t

$P_{f(sys)}(t)$ = probability of system failure occurrence at time t

$$RI_2(t) = \beta_{f(sys)}(t) - \beta_{y(sys)}(t)$$

$\beta_{y(sys)}(t)$ = reliability index wirth respect to first member failure occurrence at time t

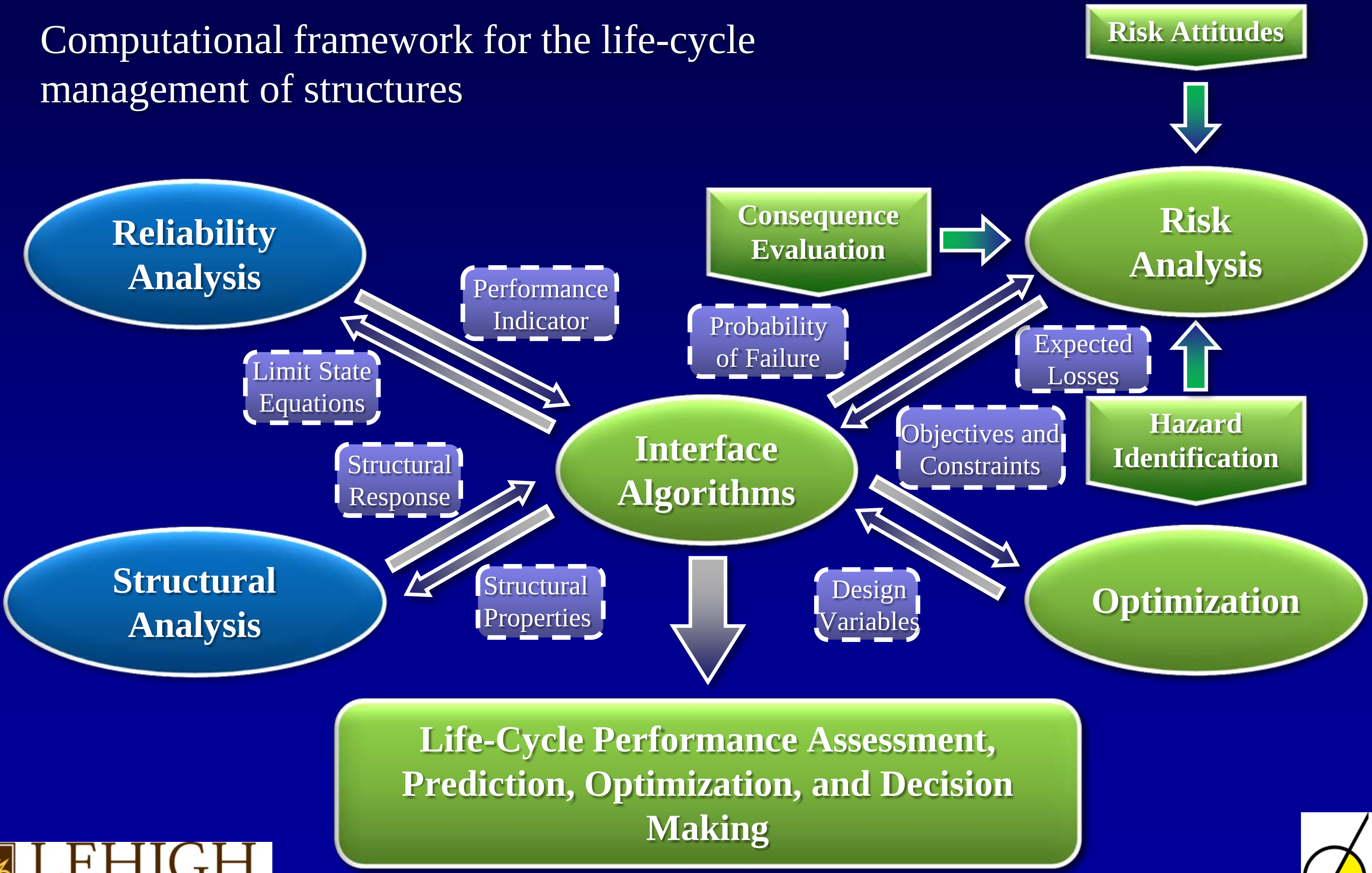
$\beta_{f(sys)}(t)$ = reliability index with respect to system failure at time t

$$RI_3(t) = \frac{An_{wc}(t) - An_s(t)}{An_s(t)}$$

$An_s(t)$ = unavailability of the system at time t

$An_{wc}(t)$ = unavailability of the weakest component at time t

Computational framework for the life-cycle management of structures



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Decò, A. and Frangopol, D. M. (2011). “Risk Assessment of Highway Bridges under Multiple Hazards,” *Journal of Risk Research*, Taylor & Francis, 14(9), 1057–1089.

QUANTITATIVE RISK ASSESSMENT

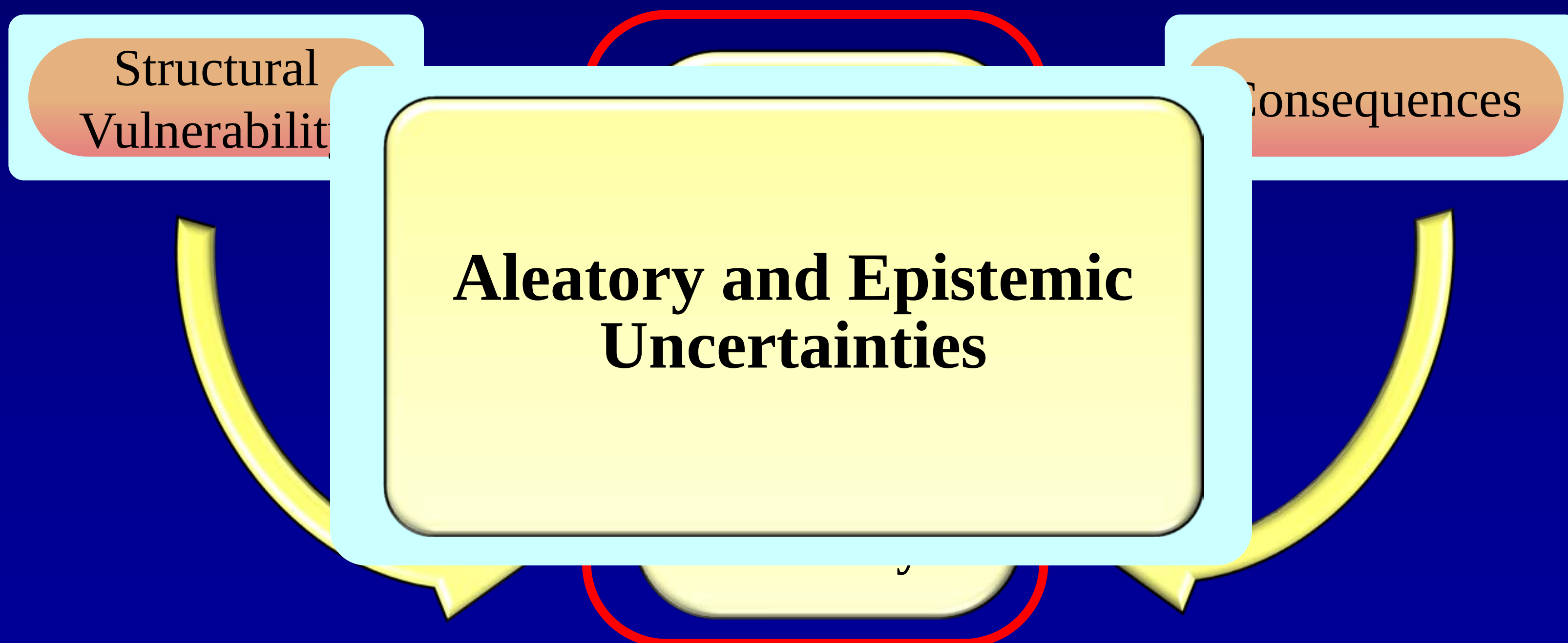
Risk Definition

(Ang and De Leon 2005)

$$R = P_f \cdot \chi$$

P_f probability of failure

χ consequences caused by failure in terms of monetary loss



Performance indicators

Risk

Hazard Analysis

- Natural hazards
- Man-made hazards

Probability of occurrence → $P(H)$

Vulnerability Analysis

Reliability Analysis

System probability of failure given hazard occurrence → $P(F \mid H)$

Consequence Evaluation

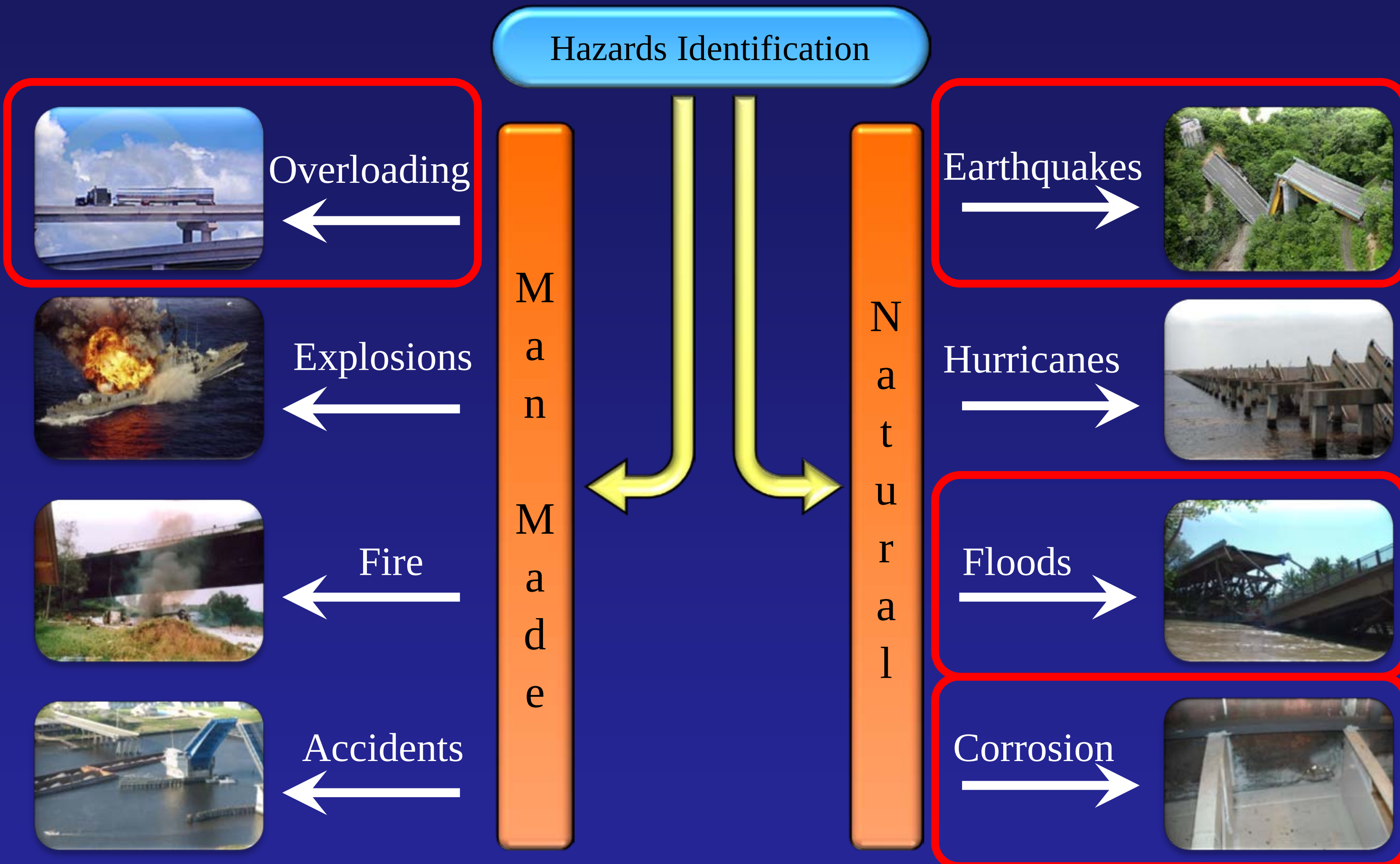
- Commercial losses
- Safety loss
- Impact to society
- Environmental impact

Monetary cost associated with structural failure → C_f

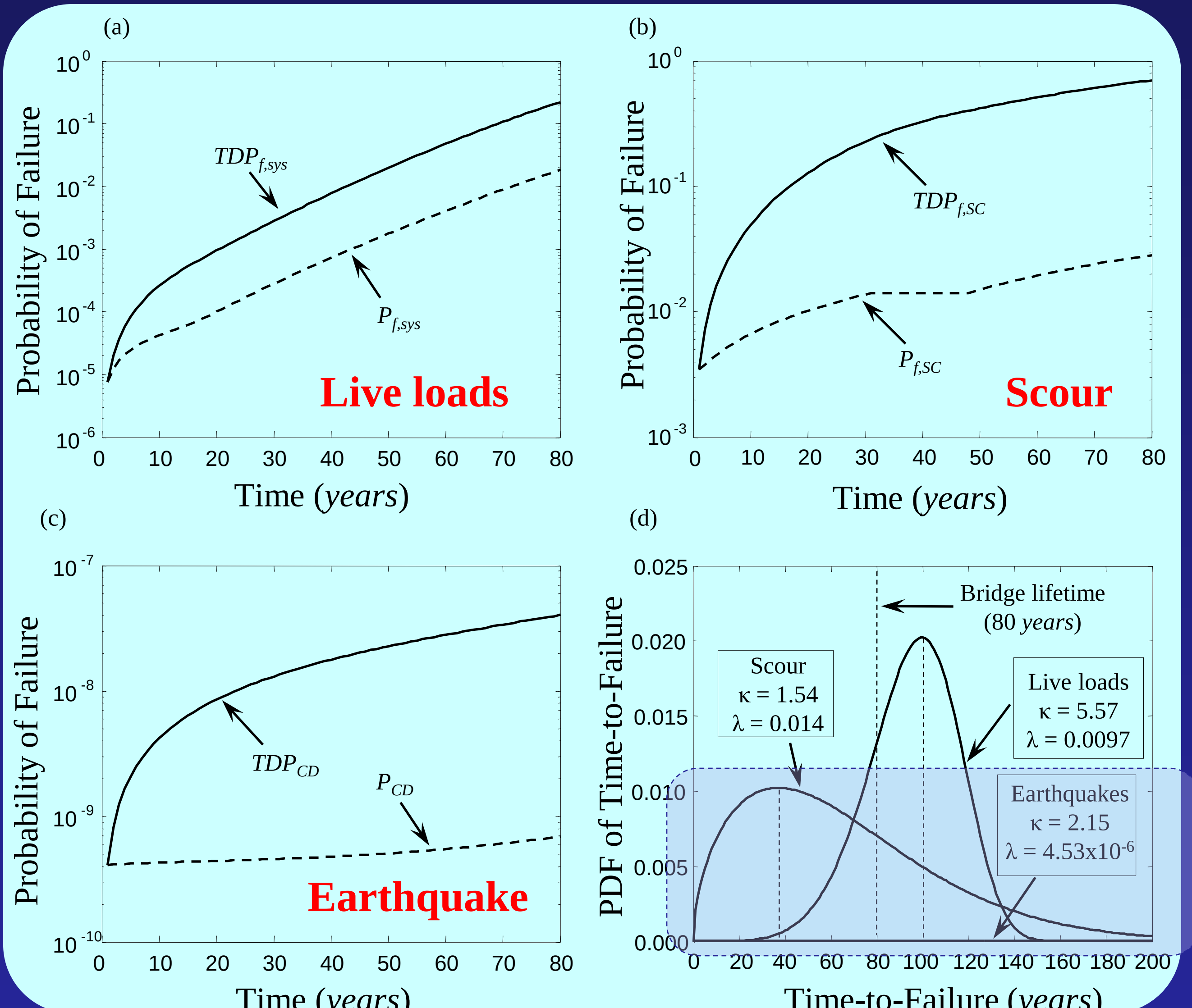
Risk Assessment

$$\text{Risk} = P(H) \cdot P(F \mid H) \cdot C_f$$

Sustainability


Hazards Identification
Man Made
Natural
Overloading
Explosions
Fire
Accidents
Earthquakes
Hurricanes
Floods
Corrosion

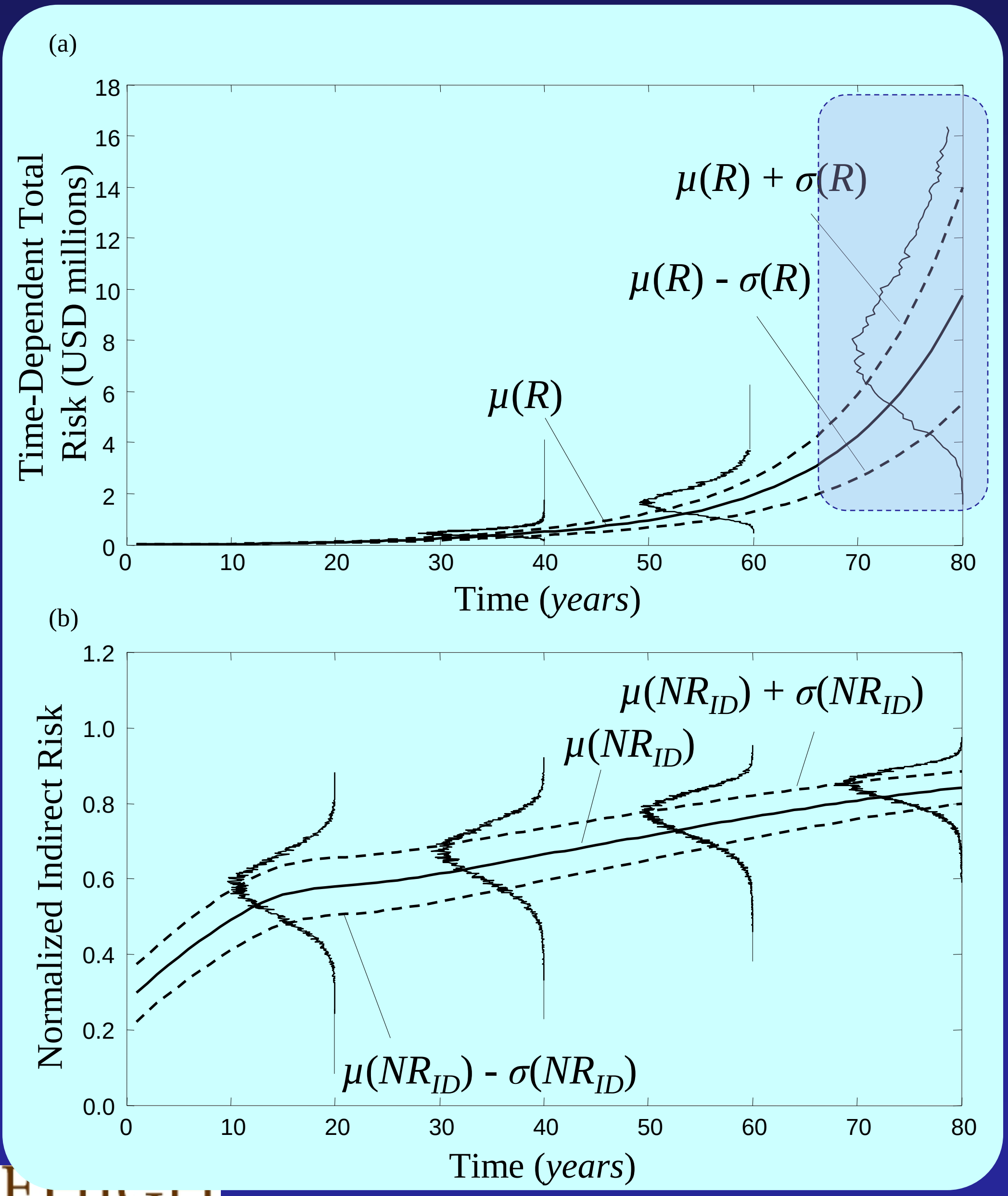
I-39 Northbound Bridge over the Wisconsin River



Time-dependent Vulnerability

CDFs of the Time-to-Failure

PDFs of the Time-to-Failure



Profiles of the Time-Dependent Total Risk

Standard deviation of the time-dependent total risk grows over time

Profiles of the Time-Dependent Normalized Indirect Risk Index

$$NR_{ID}(t) = \frac{R_{ID}(t)}{R_D(t) + R_{ID}(t)}$$

CONTENTS

INTRODUCTION

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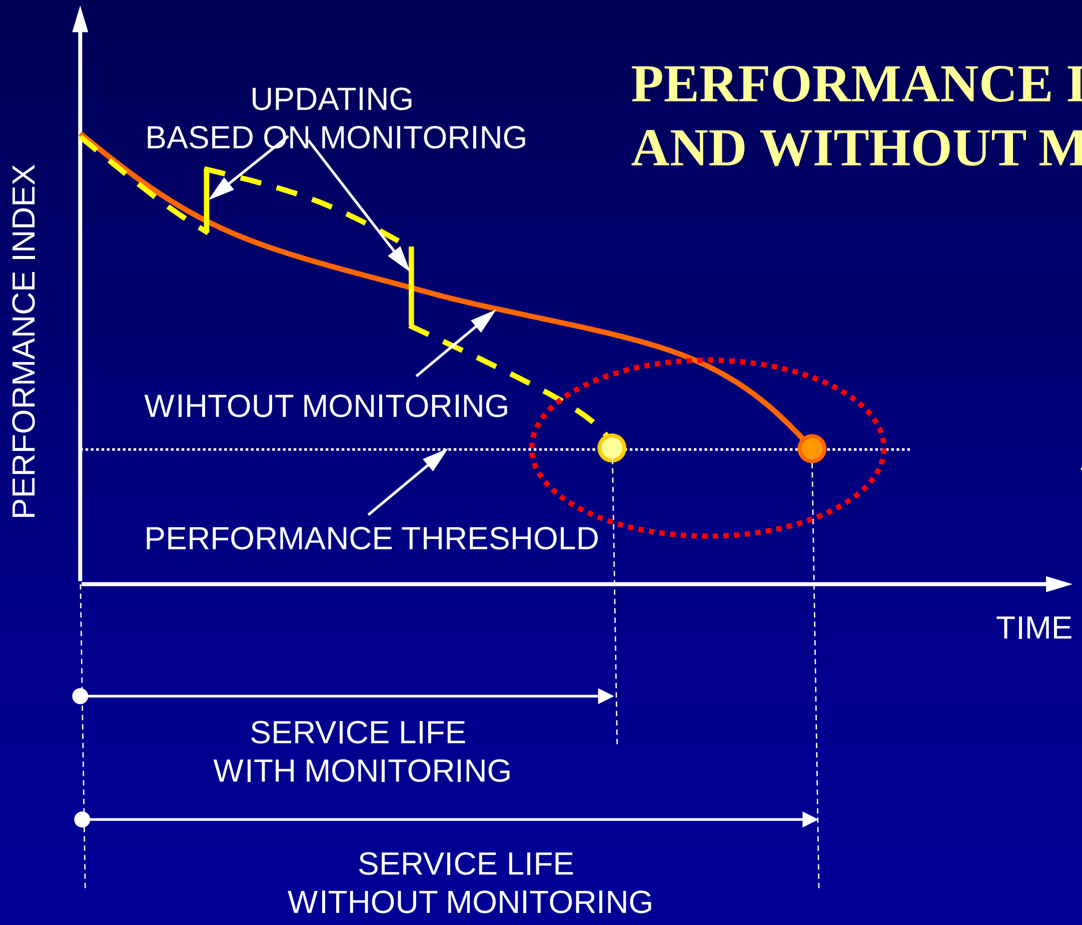
ROLE OF OPTIMIZATION

CONCLUSIONS

INTEGRATION OF SHM IN LCM



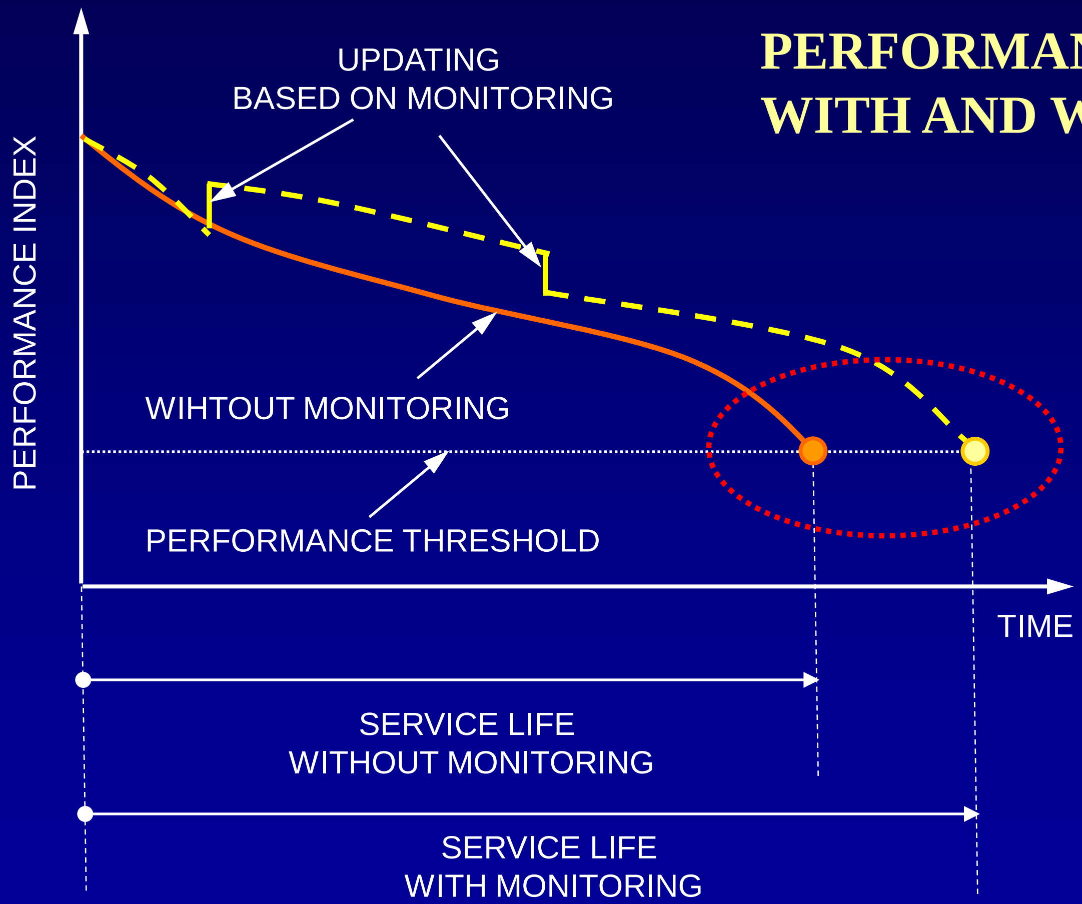
PERFORMANCE INDEX PROFILE WITH AND WITHOUT MONITROING

WITHOUT MONITORING

Inaccurate prediction

→ Tremendous consequences due to failure occurrence (later reaching of the threshold is predicted)

INTEGRATION OF SHM IN LCM



PERFORMANCE INDEX PROFILE WITH AND WITHOUT MONITROING

WITHOUT MONITORING

Inaccurate prediction

→ Unnecessary Maintenance Action

(earlier reaching of the threshold is predicted)

Combining SHM & LCM

Combining SHM and LCM has the benefit that each method's advantages complement the other's disadvantages

Structural Health Monitoring

Actual Structural Data

Predictive in nature?
Actionable Information?

Life-Cycle Management

Predictive Management Tool

Accuracy of random variables?
Limited use of structure-specific structural data

Combined Approach

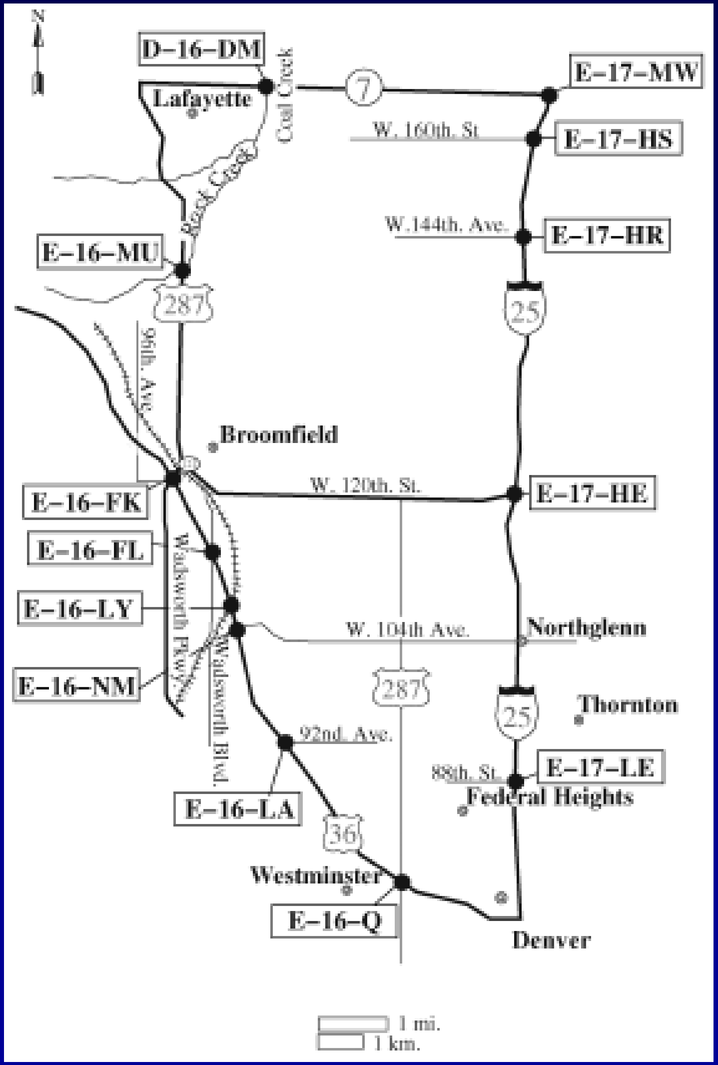
Predictive Tool

Actual Structural Data

Actionable Information for the bridge manager

Frangopol and Messervey "Maintenance Principles for Civil Structures," Chapter 89 in Encyclopedia of Structural Health Monitoring, John Willey & Sons, 2009

SHM design considerations: Bridge Importance



A bridge manager will likely desire to focus effort on the most critical bridge, or bridges in a network. Such an analysis requires the consideration of connectivity, user satisfaction, and network reliability.

$$RIF_i = \frac{\partial \beta_{net}}{\partial \beta_{sys,i}}$$

The reliability importance factor (RIF) is defined as the sensitivity of the bridge network reliability with respect to a change in an individual bridge's reliability

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MONITORING WITHIN A LIFE-CYCLE CONTEXT

THE MOST WIDELY USED DESIGN CRITERION

→ MINIMUM EXPECTED LIFE-CYCLE COST

General form of the expected LCC

$$C_{ET} = C_T + C_{PM} + C_{INS} + C_{REP} + C_F$$

C_{ET}= expected total cost, C_T= initial cost,

C_{PM}= expected cost of maintenance, C_{INS}= expected cost of inspection,

C_{REP}= expected cost of repair, and C_F= expected cost of failure

Inclusion of monitoring cost

$$C_{ET}^0 = C_T^0 + C_{PM}^0 + C_{INS}^0 + C_{REP}^0 + C_F^0 + C_{MON}$$

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MONITORING WITHIN A LIFE-CYCLE CONTEXT

COST OF MONITORING C_{MON}

$$C_{MON} = M_T + M_{OP} + M_{INS} + M_{REP}$$

M_T= expected initial design/construction cost of the monitoring system,

M_{OP}= expected operational cost of the monitoring system,

M_{INS}= expected cost of inspection of the monitoring system,

M_{REP}= expected cost of repair cost of the monitoring system

---

BENEFIT OF THE MONITORING SYSTEM, B_{MON}

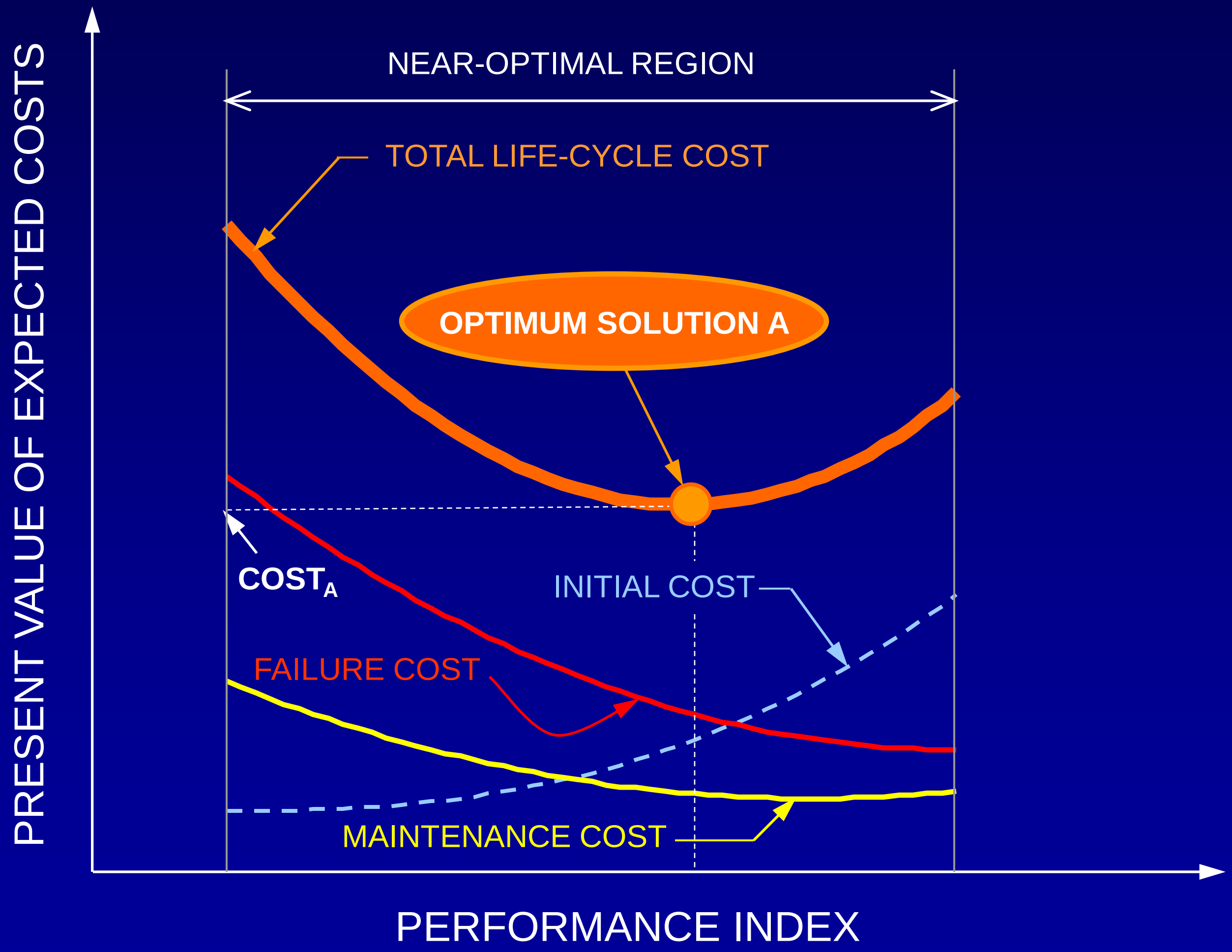
$$B_{MON} = C_{ET} - C_{ET}^0$$

Timely maintenance intervention,

Reduction of failure cost

MONITORING WITHIN A LIFE-CYCLE CONTEXT

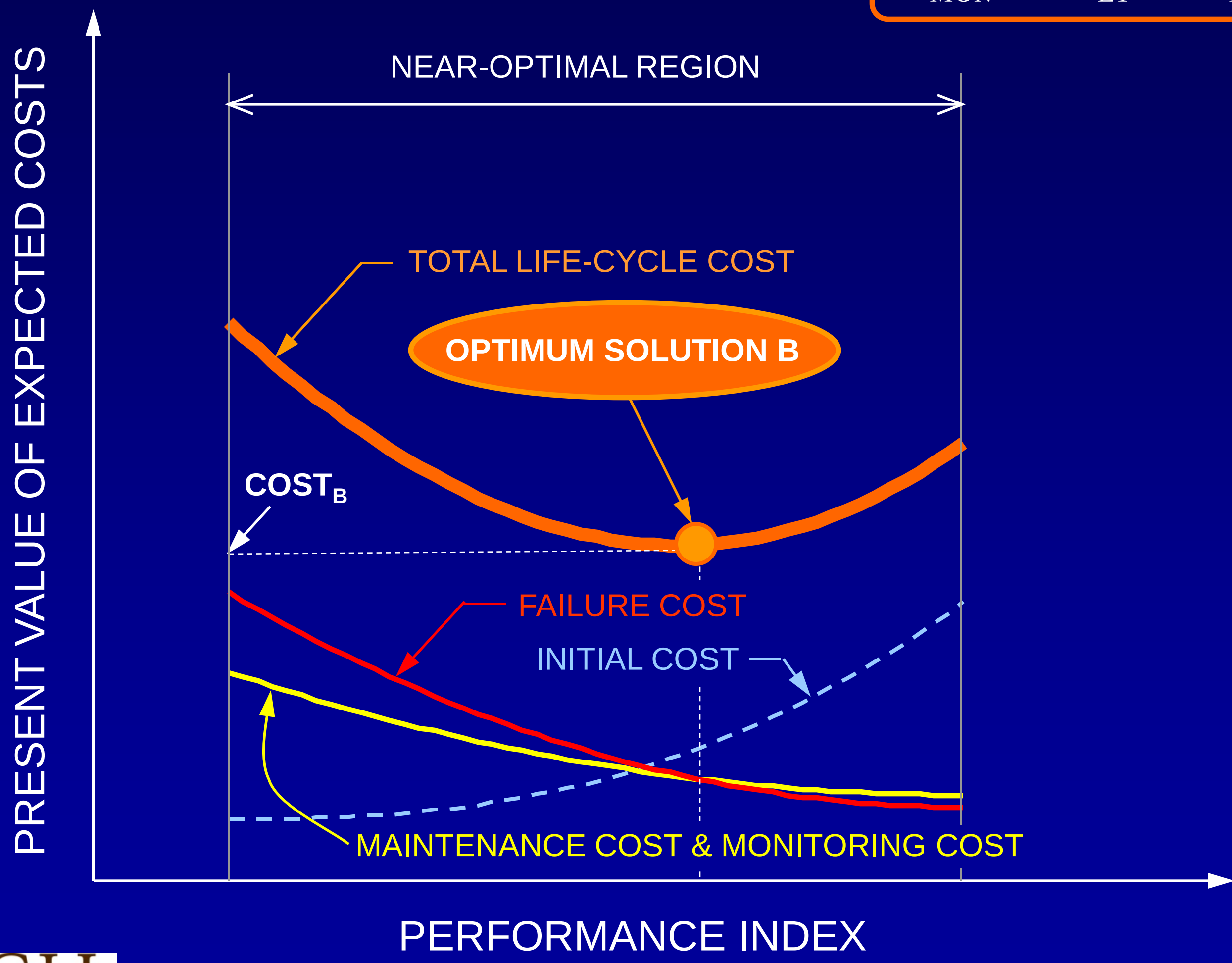
Optimum Solution based on LCC Minimization without Monitoring



MONITORING WITHIN A LIFE-CYCLE CONTEXT

Optimum Solution based on LCC Minimization with Cost-Effective Monitoring

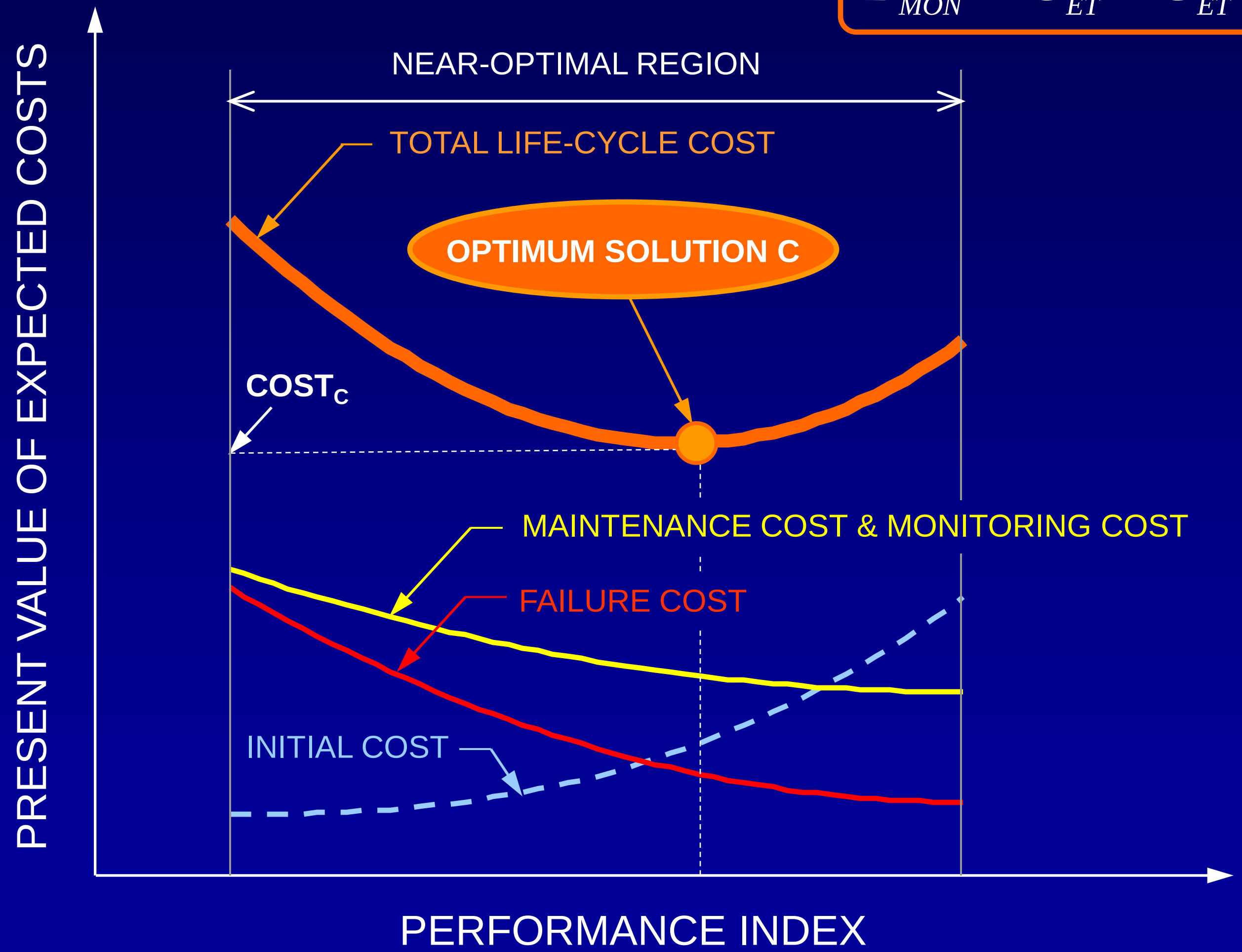
$$B_{MON} = C_{ET} - C_{ET}^{0} > 0$$



MONITORING WITHIN A LIFE-CYCLE CONTEXT

Optimum Solution based on LCC Minimization without Cost-Effective Monitoring

$$B_{MON} = C_{ET} - C_{ET}^{0} < 0$$



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CONTENTS

INTRODUCTION

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ROLE OF OPTIMIZATION

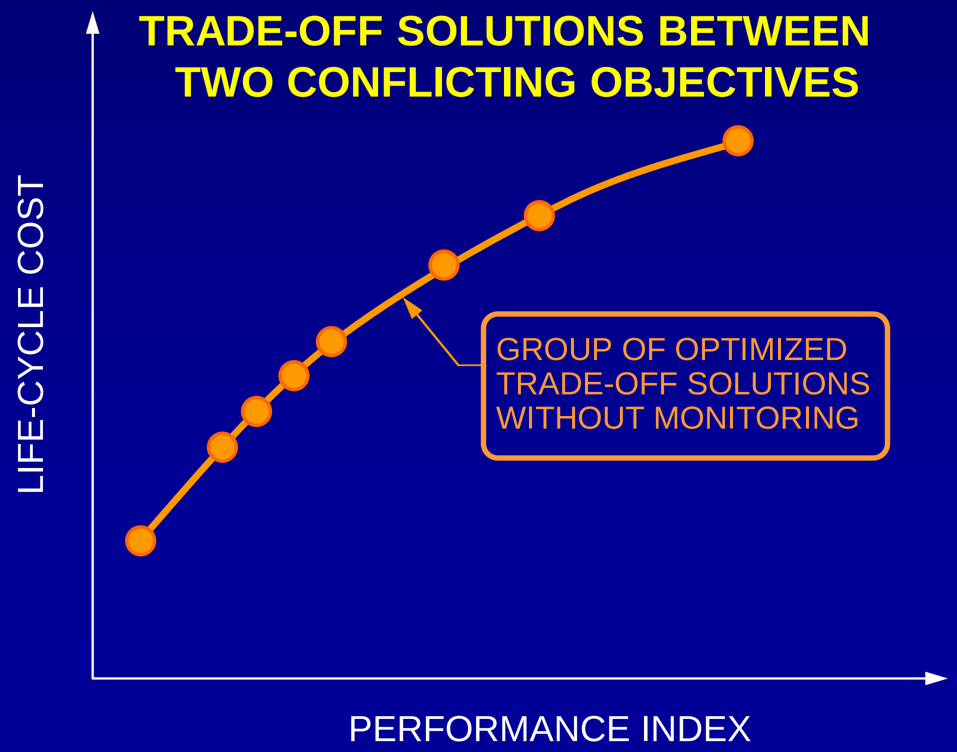
CONCLUSIONS

ROLE OF OPTIMIZATION

- Under uncertainty, decision related to the civil infrastructure management should be made by

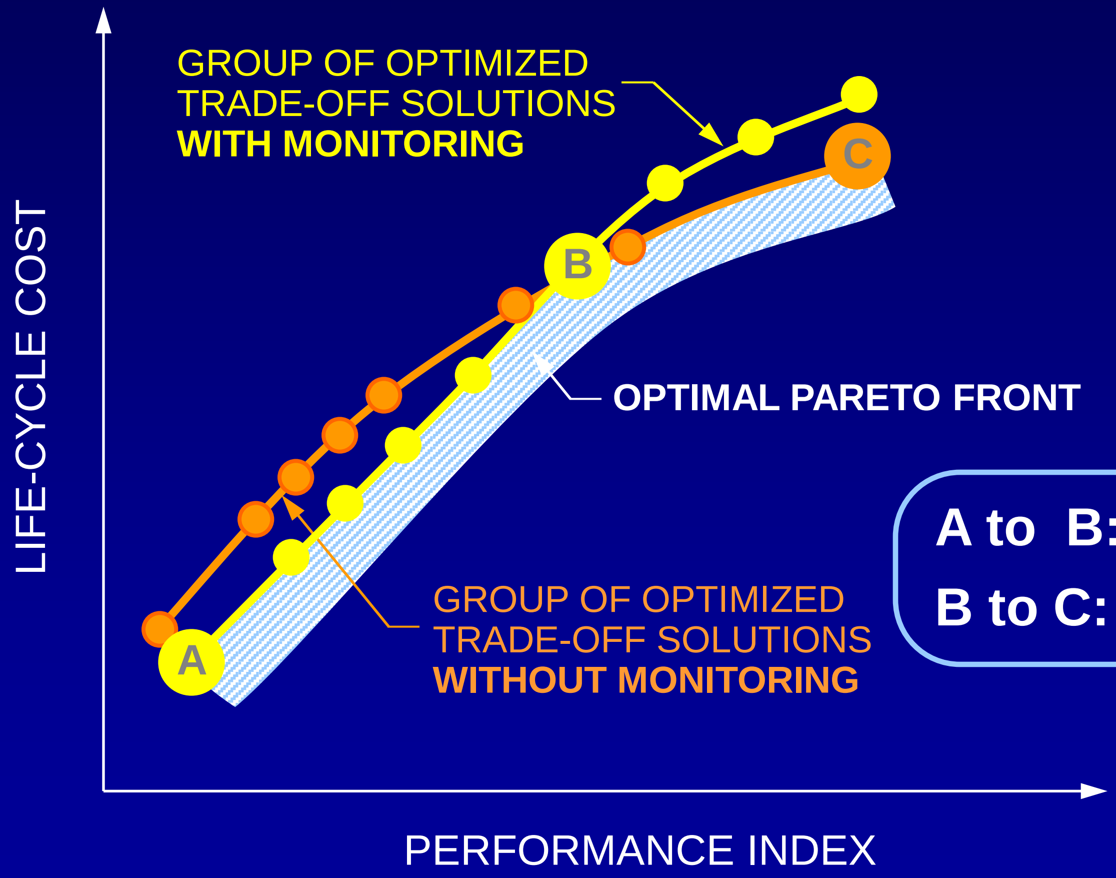
maximizing the structural performance &
minimizing the life-cycle cost

→ **Design and Maintenance planning** can be best formulated as **a multi-objective optimization problem**



ROLE OF OPTIMIZATION

TRADE-OFF SOLUTIONS BETWEEN TWO CONFLICTING OBJECTIVES



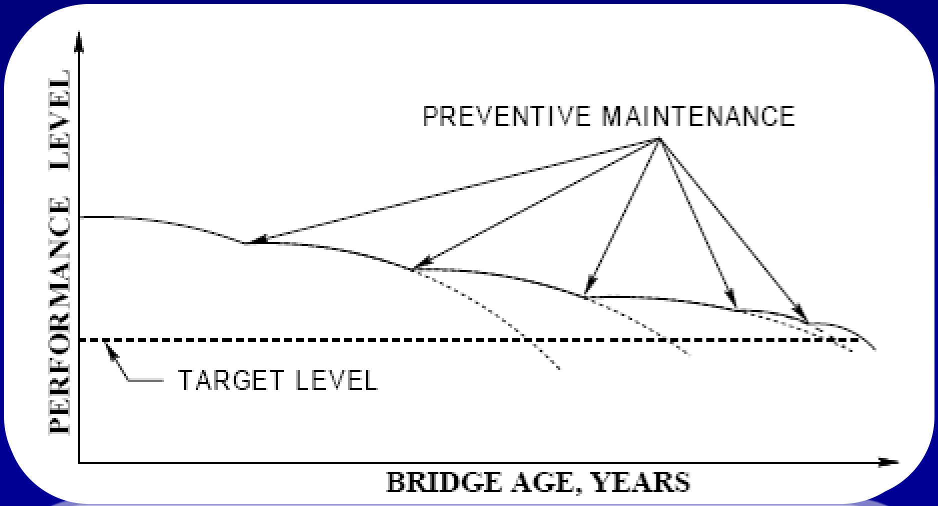
A to B: Cost-Effective SHM

B to C: Not Cost-Effective SHM

Risk-based Optimum Maintenance

Risk mitigation strategies:

- Reducing the failure probabilities of the structure under hazards
- Reducing the consequences caused by structure failure

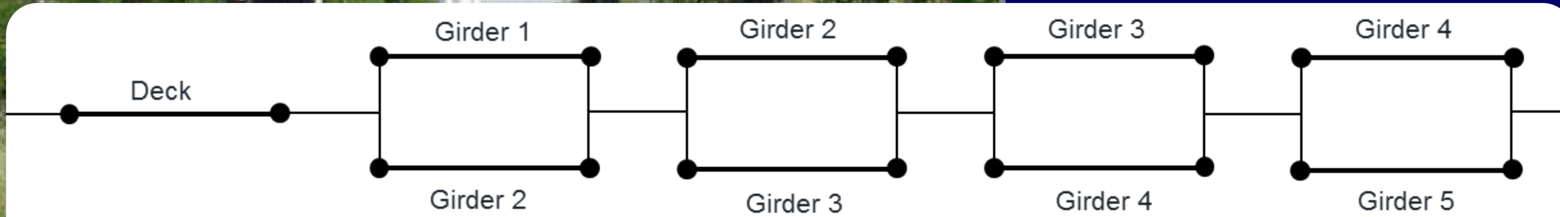


Kong et al. (2000)

Two types:

- Essential maintenance
- Preventive maintenance

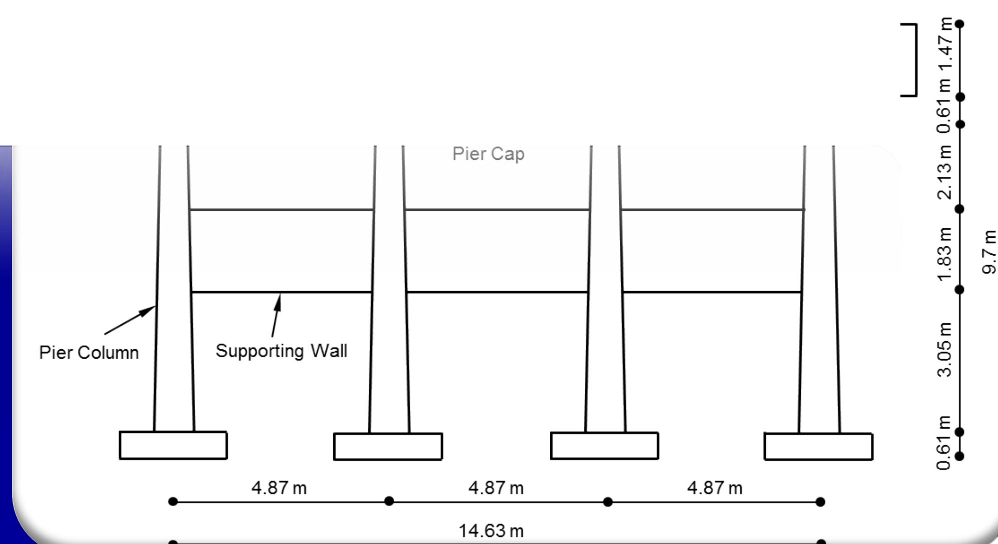
Application: E-17-AH Highway Bridge



Girder 1: Exterior girder

Girder 2: Exterior-interior girder

Girders 3 to 5: Interior girders

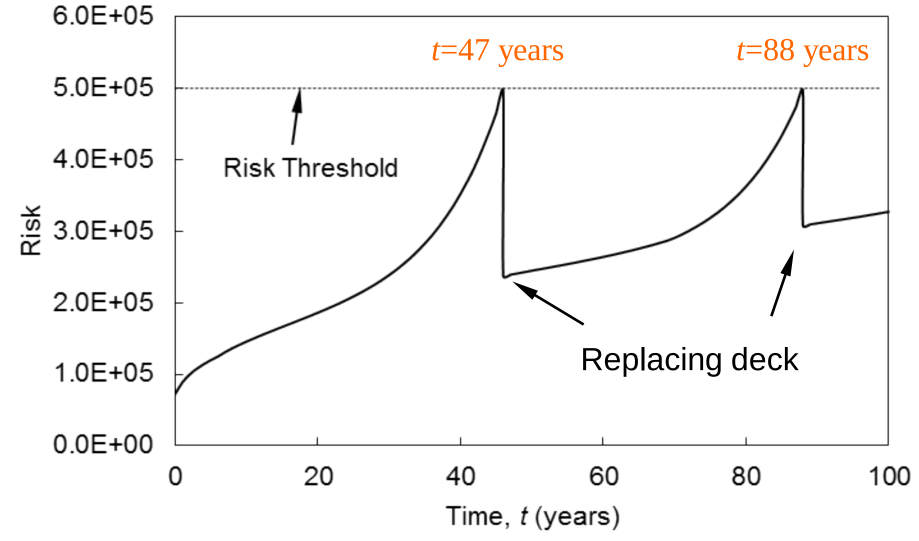


Case Study: E-17-AH Bridge

Essentials maintenance:

- Risk threshold: 5.0×10^5
- Optimum: the lowest cost per year increase of service life

Options	Cost ($)
Replacing deck	225,600
Replacing exterior girders	229,200
Replacing deck and exterior girders	341,800
Replacing superstructure	487,100

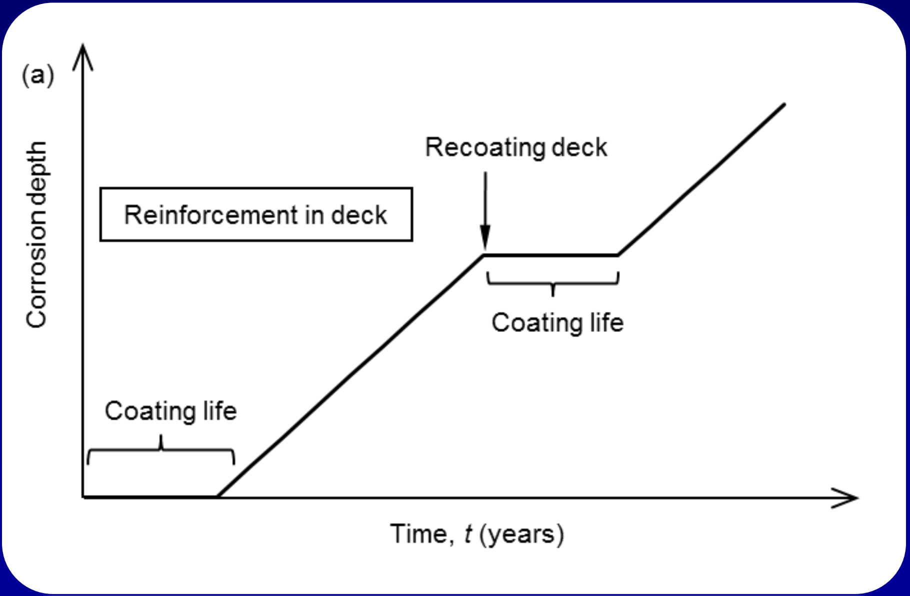


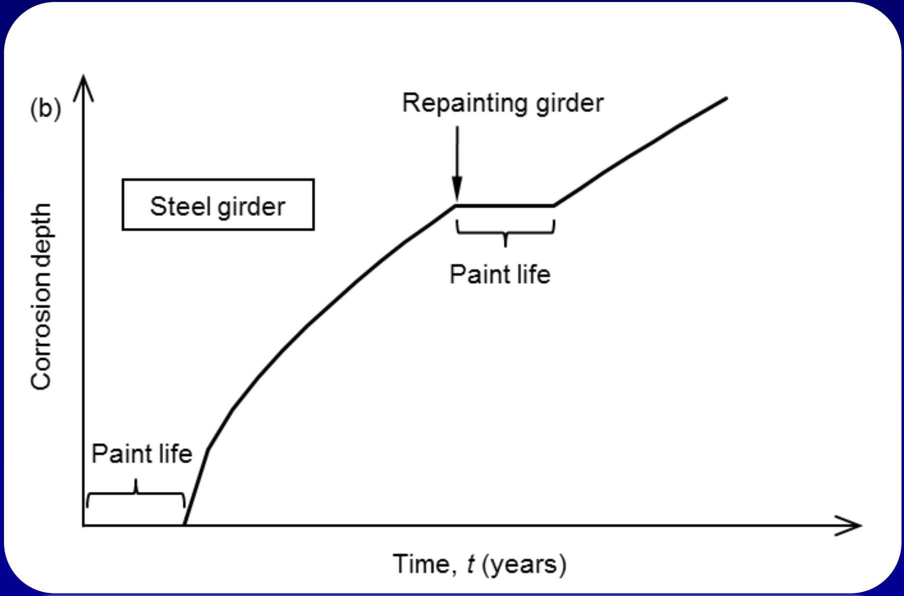
Estes (1997)

Case Study: E-17-AH Bridge

Preventive maintenance:

- Risk threshold: 5.0×10^5
- Optimum: the lowest cost per year increase of service life

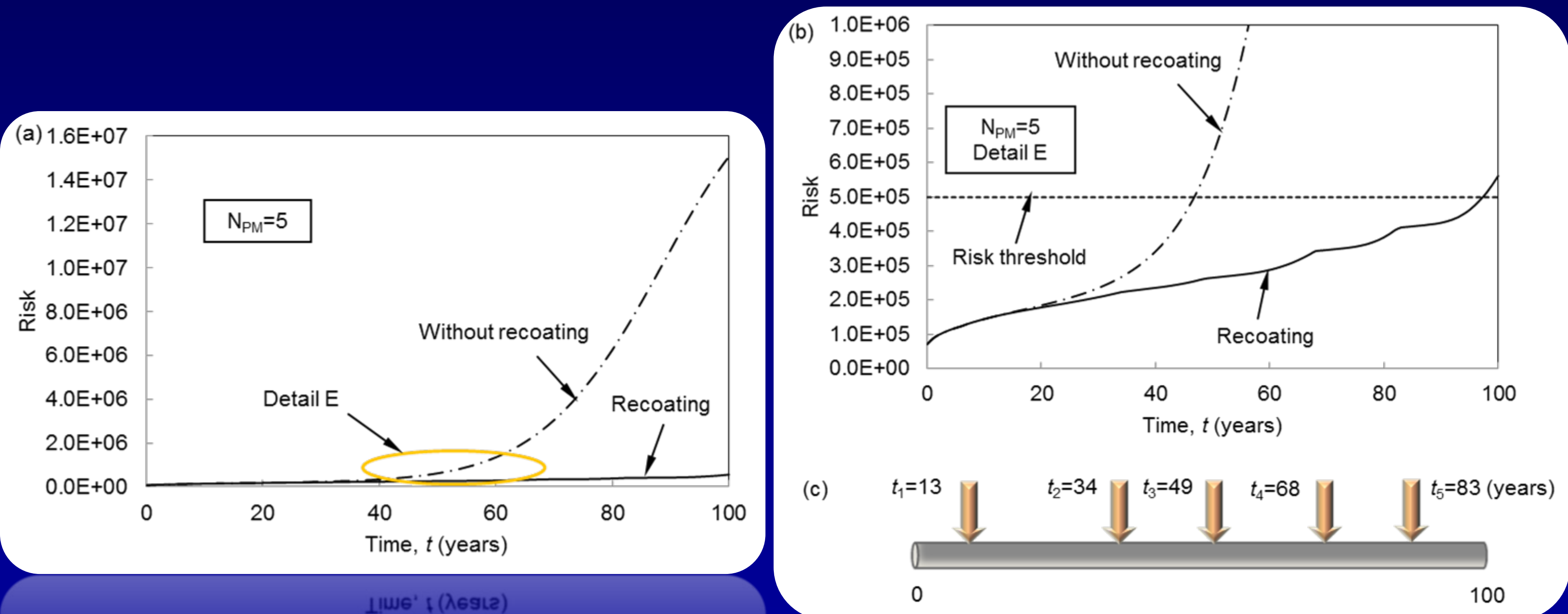




Case Study: E-17-AH Bridge

Preventive maintenance:

- Number of PM =5

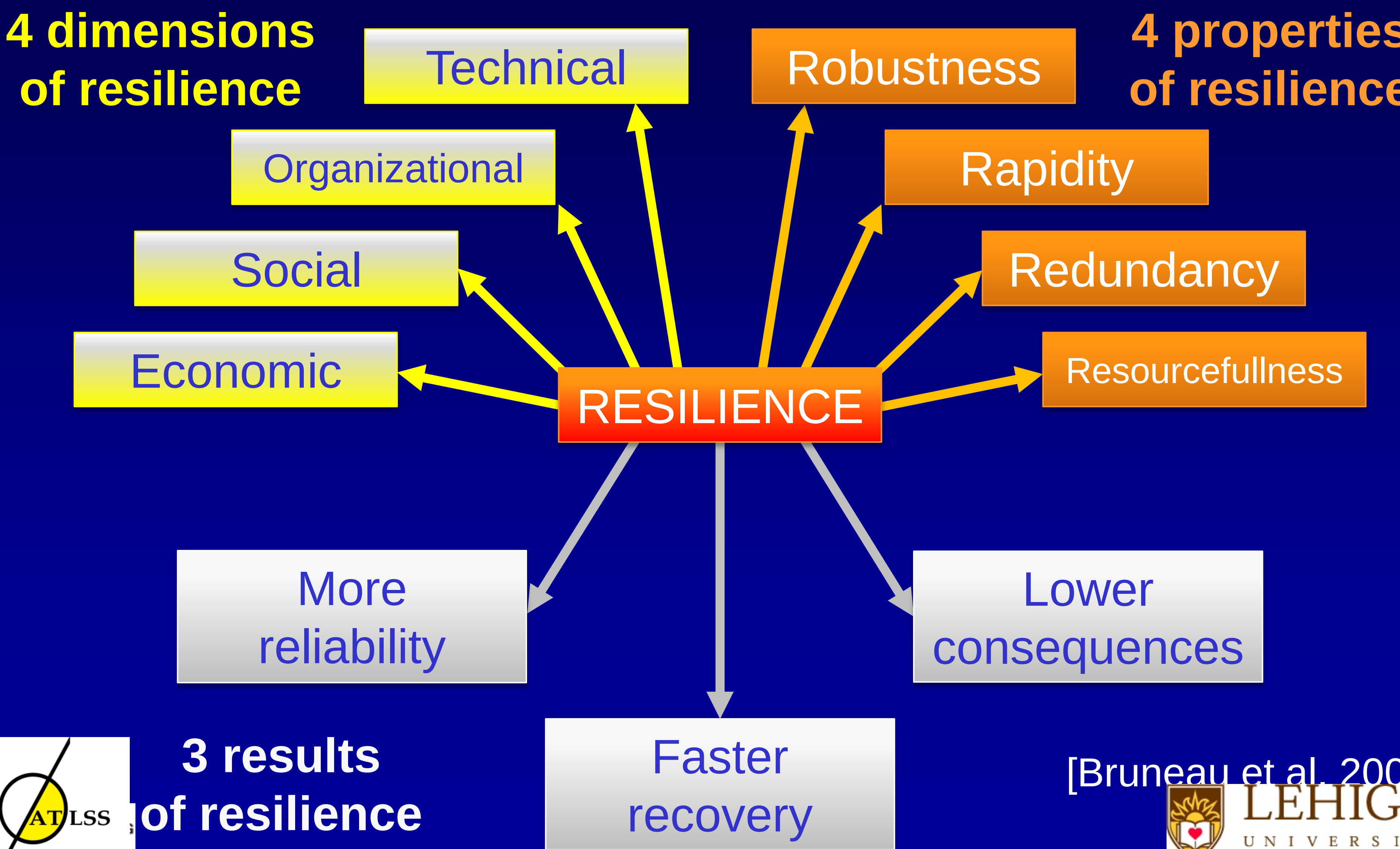


Dan M. Frangopol Dist.M.ASCE and Paolo Bocchini M.ASCE

Resilience as Optimization Criterion for the Rehabilitation of Bridges Belonging to a Transportation Network Subject to Earthquake

Advanced Technology for Large Structural Systems (ATLSS) Engineering Research Center
Department of Civil and Environmental Engineering
Lehigh University

DESCRIPTIVE DEFINITIONS OF RESILIENCE



[Bruneau et al. 2003]

PROPOSED APPROACH

RESILIENCE

- Robustness
- Rapidity
- Redundancy
- ...
- ...
- Social impact
- Economic impact
- ...
- Reliability
- Risk
- ...
- ...

Multi-criteria Pareto Efficiency

MULTI-CRITERIA APPROACH

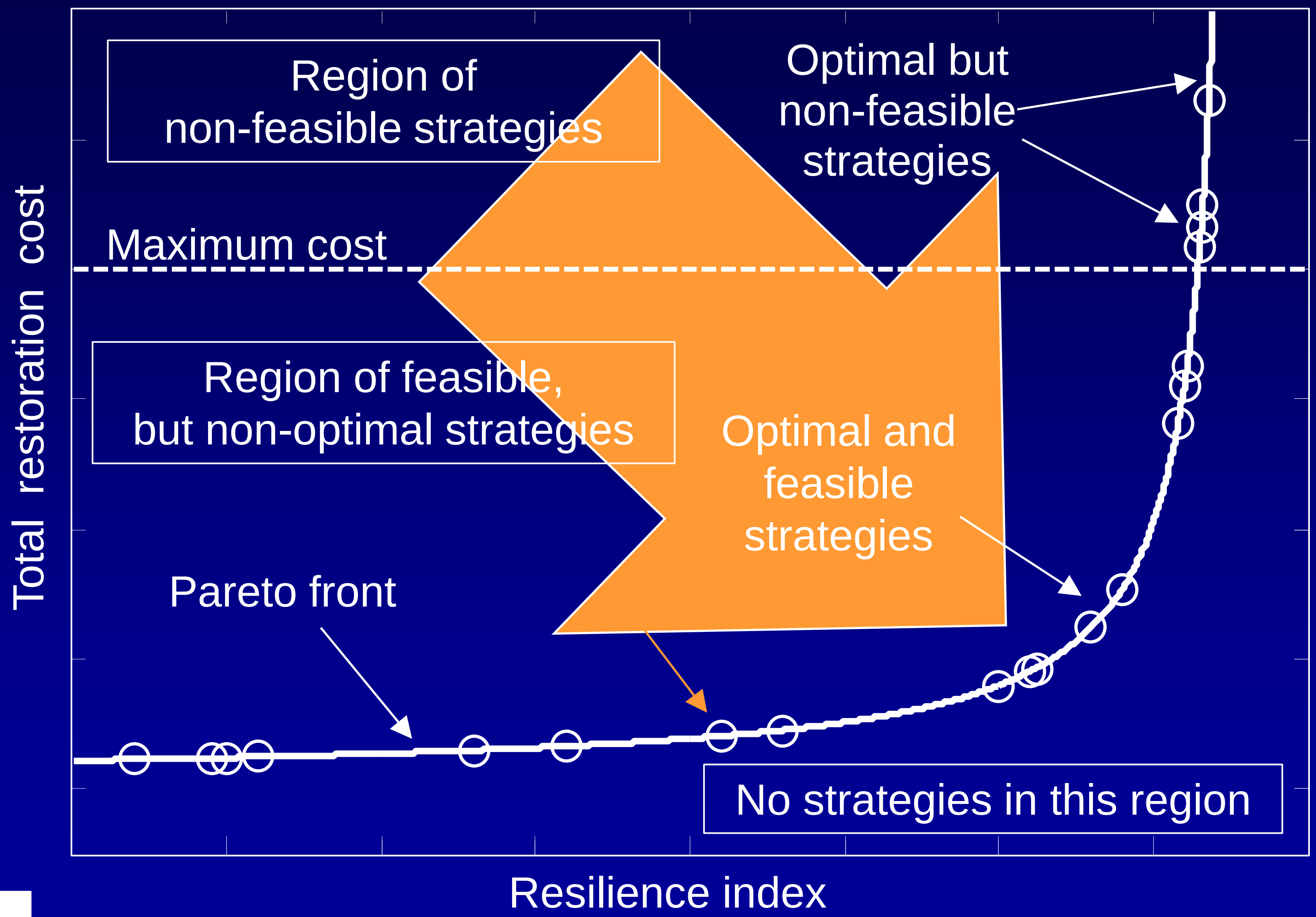
POSSIBLE OBJECTIVES

- Maximize **resilience** index R_4
- Minimize the total **cost** of interventions (associated with resourcefullness)
- Minimimize the total recovery time (**rapidity**)
- Minimize the time required to reach a target functionality level (**advanced use of rapidity**)
- Minimize the impact of an [illegible]eme event (**robustness**)

POSSIBLE CONSTRAINTS

- Total **cost** has to be lower than the available budget.
- Deliver minimum **functionality levels** at certain instants (minimum acceptable recovery path)
- Maximum number of simultaneous interventions (associated with **resourcefullness**)
- additional constraints on the **rehabilitation parameters**

PARETO FRONT



APPLICATION TO BRIDGE NETWORKS

System: bridge network

Functionality $Q(t)$: ability to effectively redistribute traffic flows

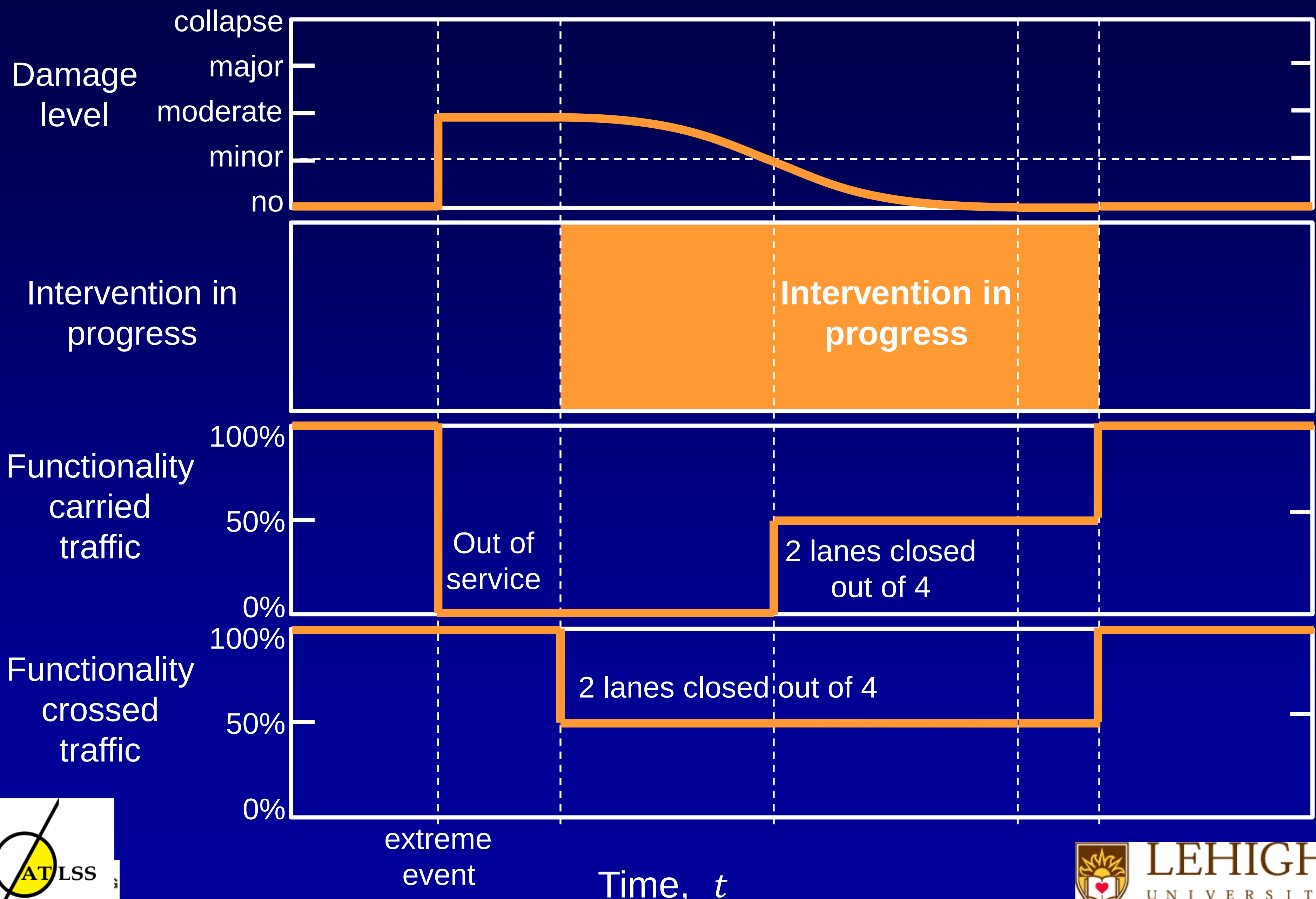
Data: damage level of all the bridges after an earthquake

Rehabilitation strategies: defined by the schedule of the interventions and the recovery speed (budget)

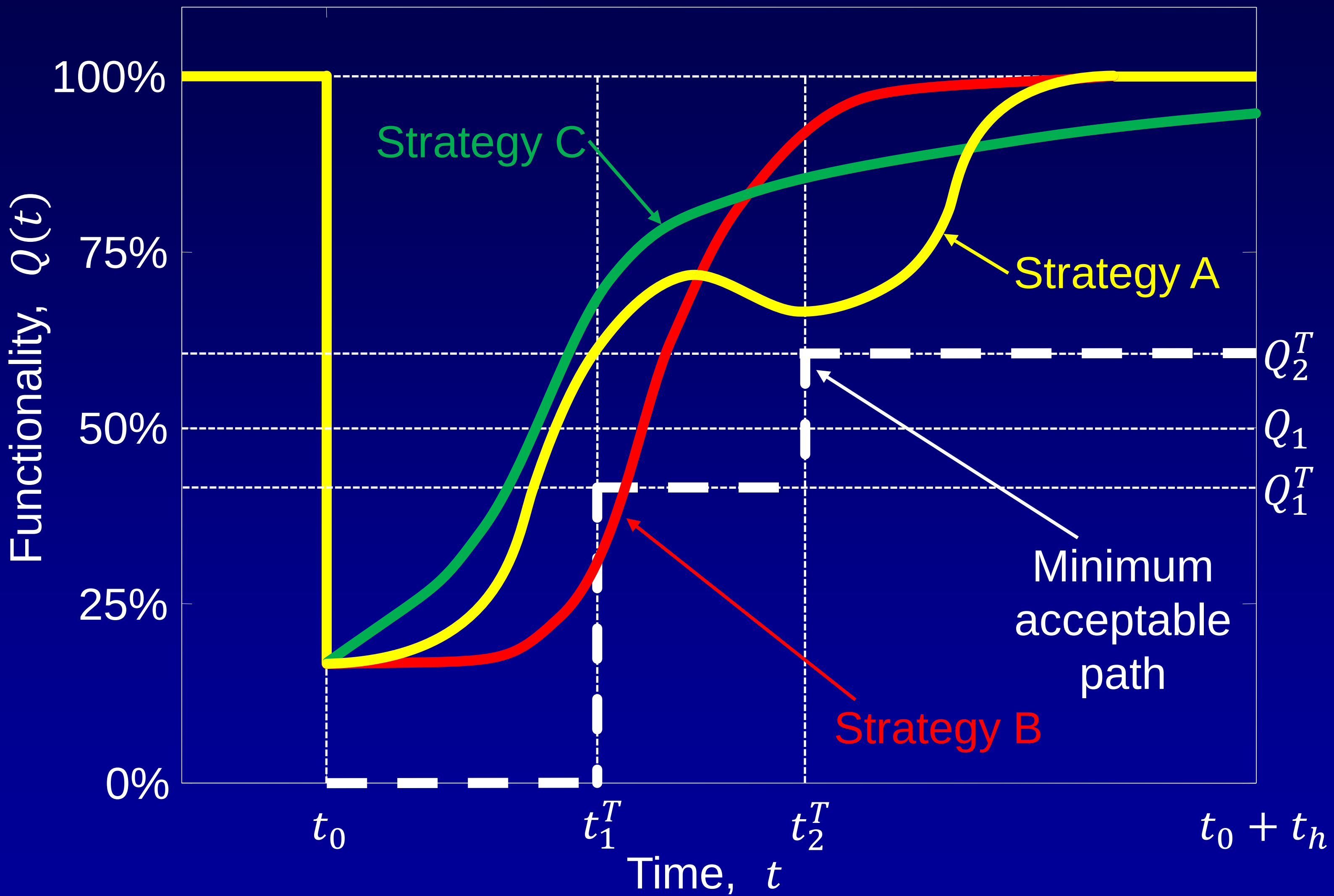
Objectives: maximize resilience index, minimize cost of interventions

Constraints: maximum budget, maximum simultaneous interventions, limited ranges for design variables

RECOVERY PROCESS OF A BRIDGE



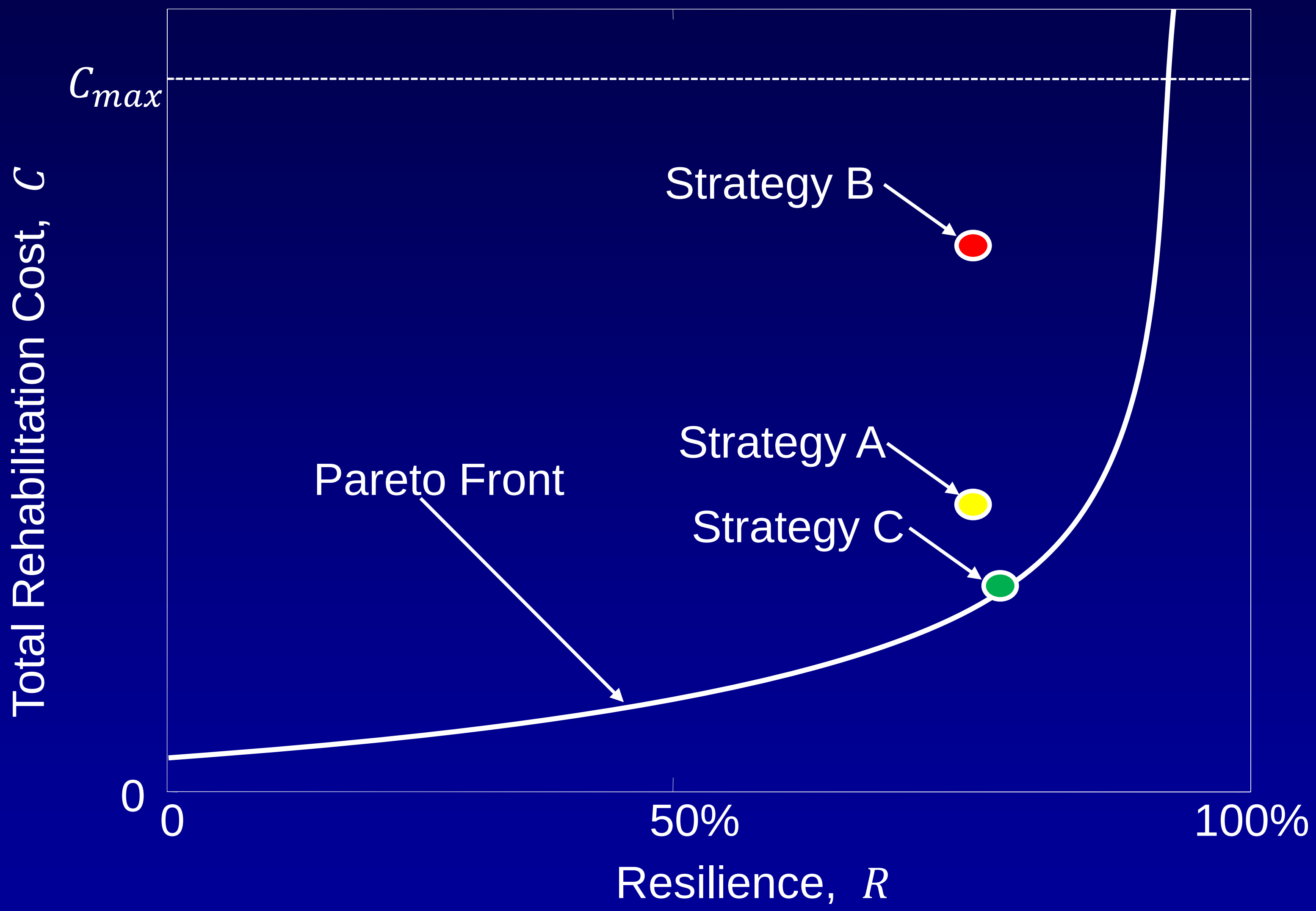
ILLUSTRATIVE EXAMPLE



STRUCTURAL ENGINEERING INSTITUTE

LEHIGH UNIVERSITY

ILLUSTRATIVE EXAMPLE



COMPUTATIONAL PROCEDURE

Network level

Functionality over time

Interface

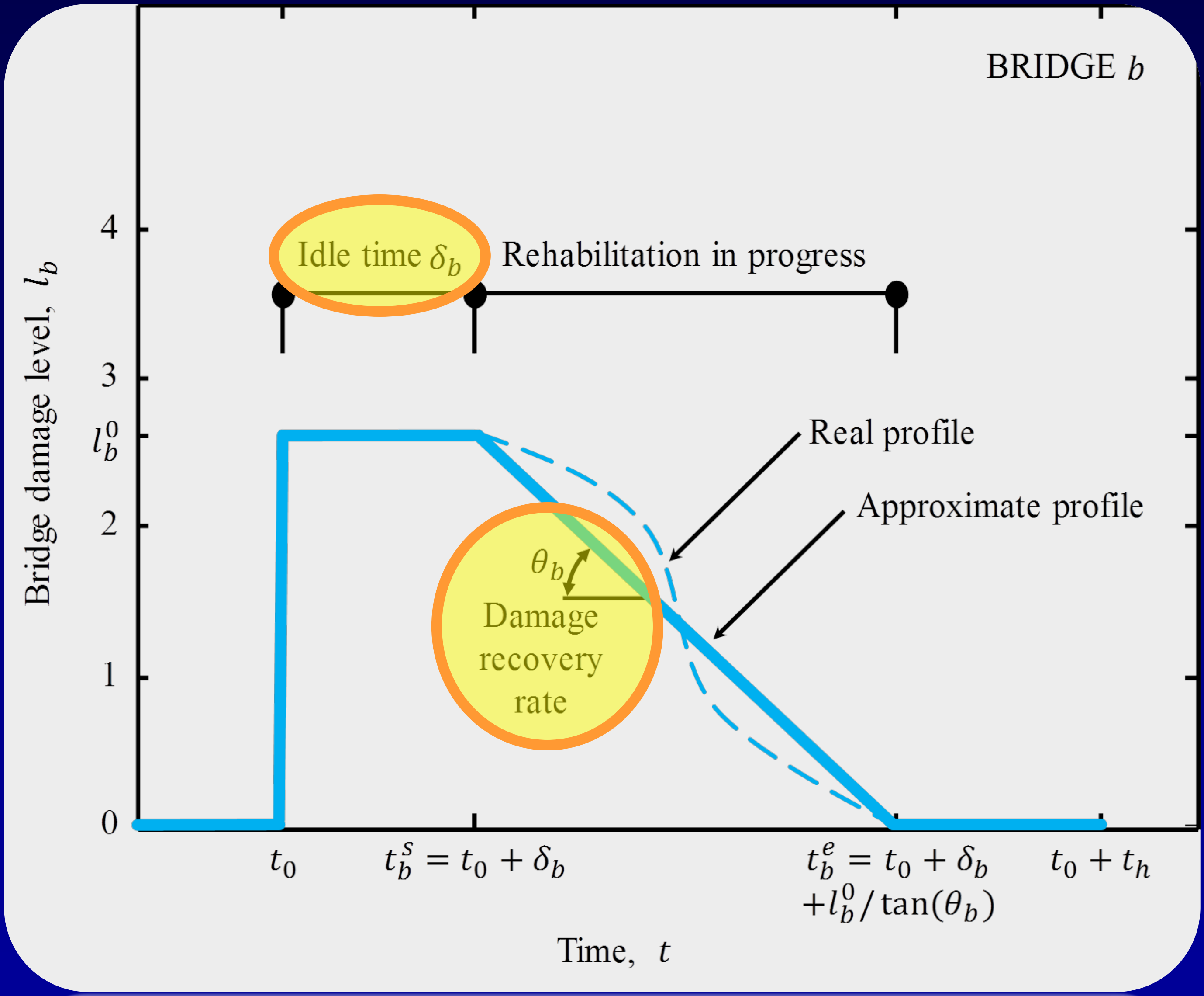
Traffic assignement and distribution

Individual bridge level

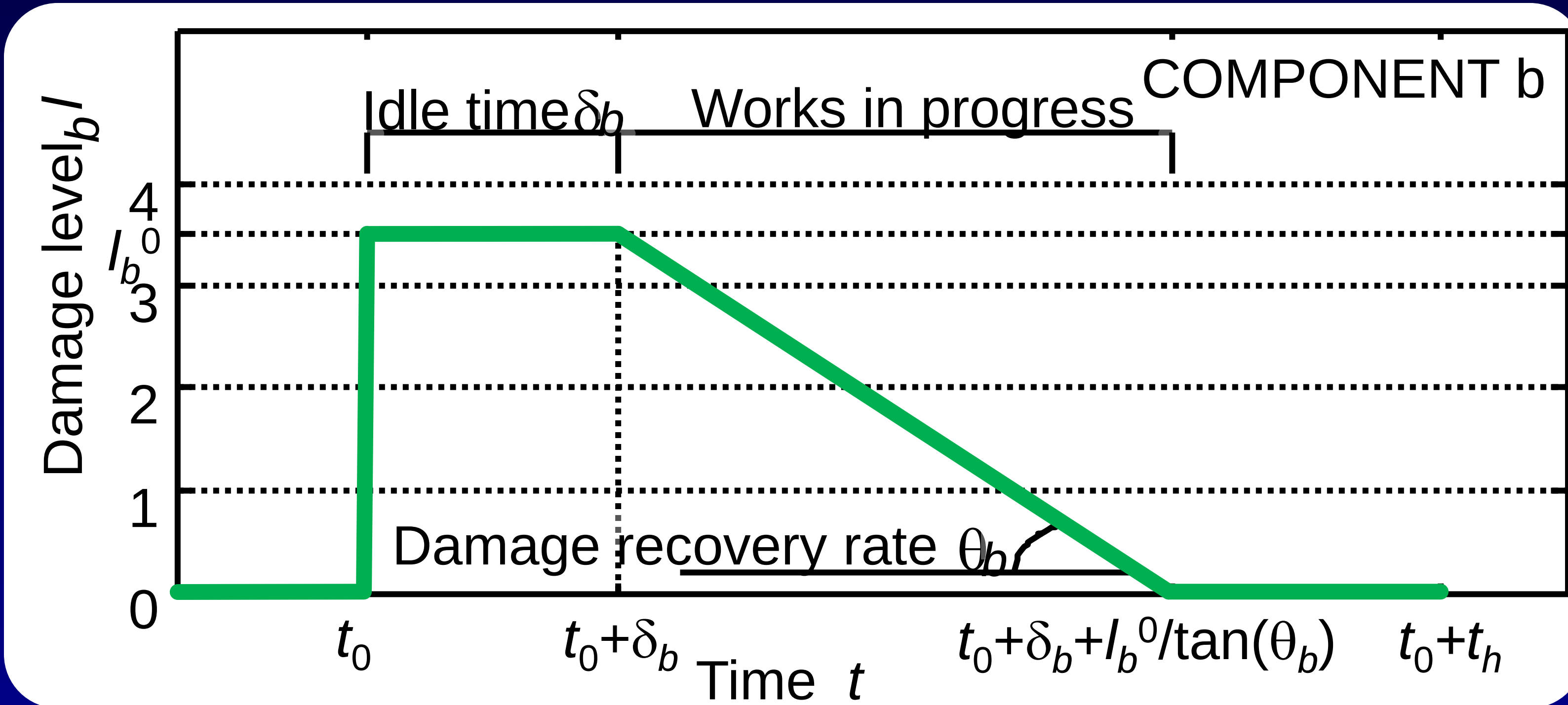
Serviceability over time

MULTI-OBJECTIVE OPTIMIZATION

DESIGN VARIABLES: (i) time between occurrence of an extreme event and the beginning of the rehabiliattion activities, and (ii) damage recovery rate



CONSTRAINTS ON DESIGN VARIABLES



θ_b cannot be higher than an upper limit (maximum recovery speed 80°). Moreover θ_b is never convenient below a lower limit (30°).

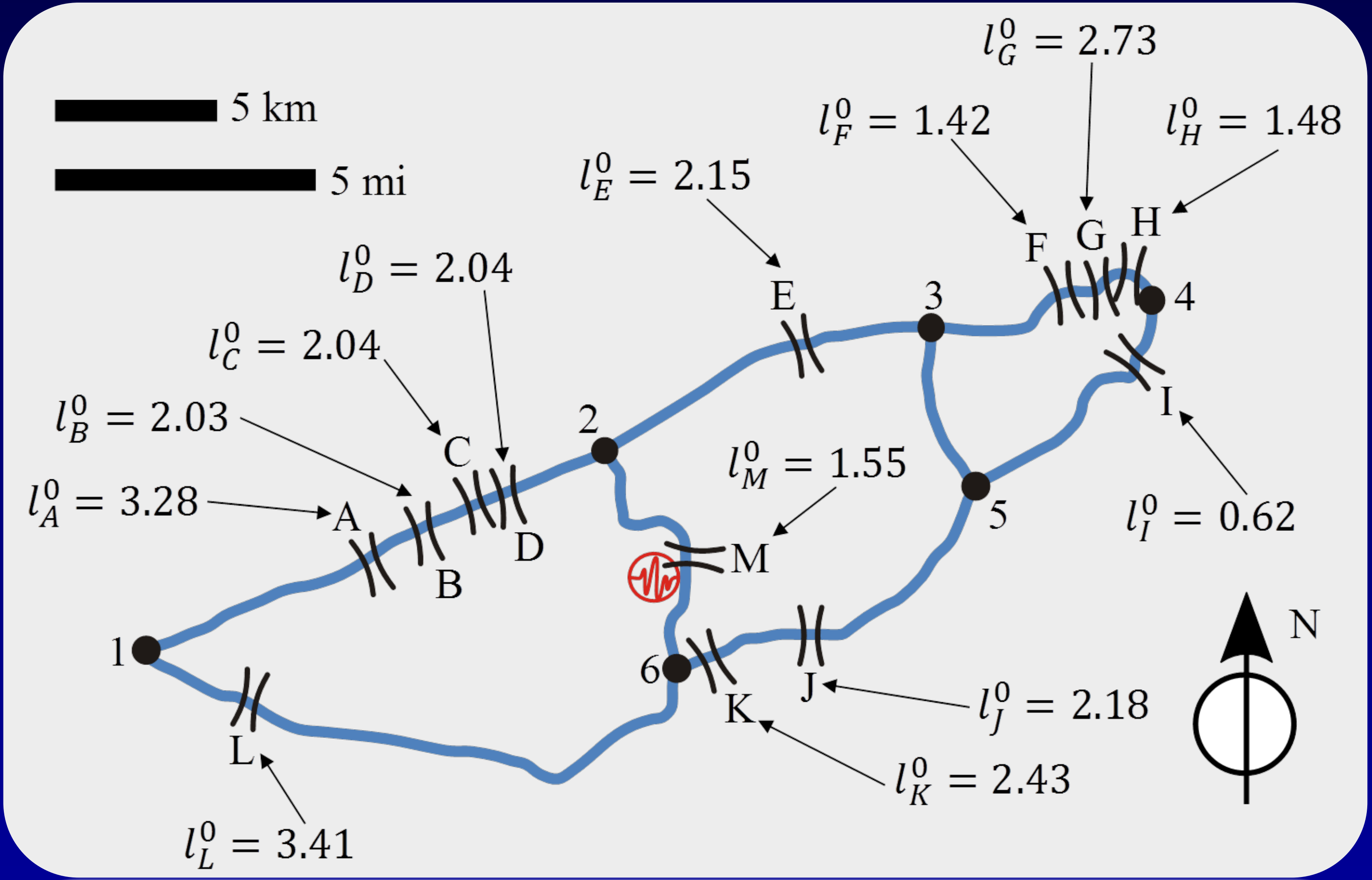
δ_b has to be included in [0, t_h] = [0, 2 years]

ximum number of simultaneous interventions: 6

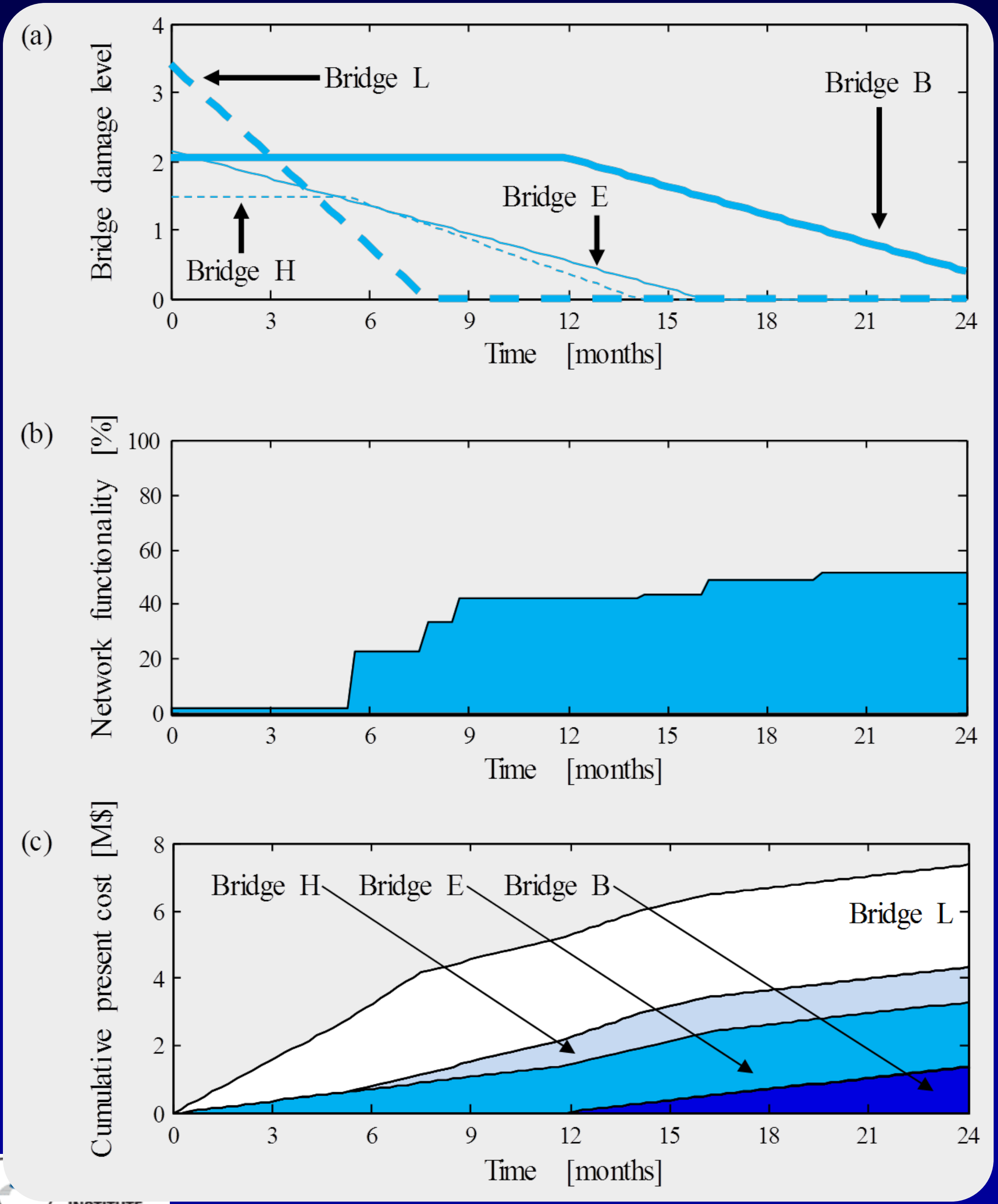
ANALYTICAL FORMULATION

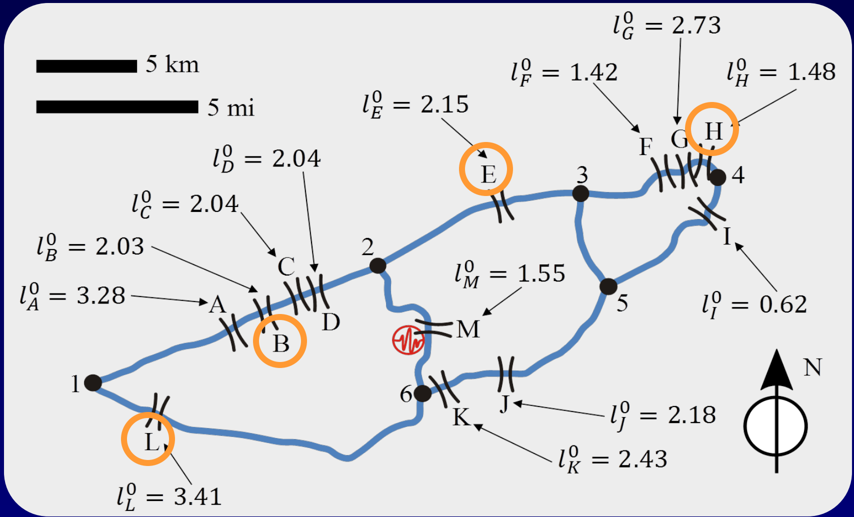
Given: **(input)**	network topology; traffic data; road capacities; secondary detour routes characteristics; bridge locations; approximate rehabilitation costs; discount rate of money; l_b^0 (post-event damage level for bridge b) $\forall\, b = 1,2, \dots, N_B$;
find: **(design variables)**	δ_b (idle time for bridge b) $\forall\, b = 1, 2, \dots, N$; θ_b (damage recovery rate for bridge b) $\forall\, b = 1, 2, \dots, N_B$;
so that: **(objectives)**	$R = maximum$; $C = minimum$;
subject to: **(constraints)**	$0 \leq \delta_b \leq t_h$, $\forall\, b = 1, 2, \dots, N_b$; $\theta_{min} \leq \theta_b \leq \theta_{max}$, $\forall\, b = 1, 2, \dots, N_b$; $C \leq C_{max}$; $N_{SI}(t) \leq N_{SImax}$, $\forall t \in [t_0, t_0 + t_h]$.

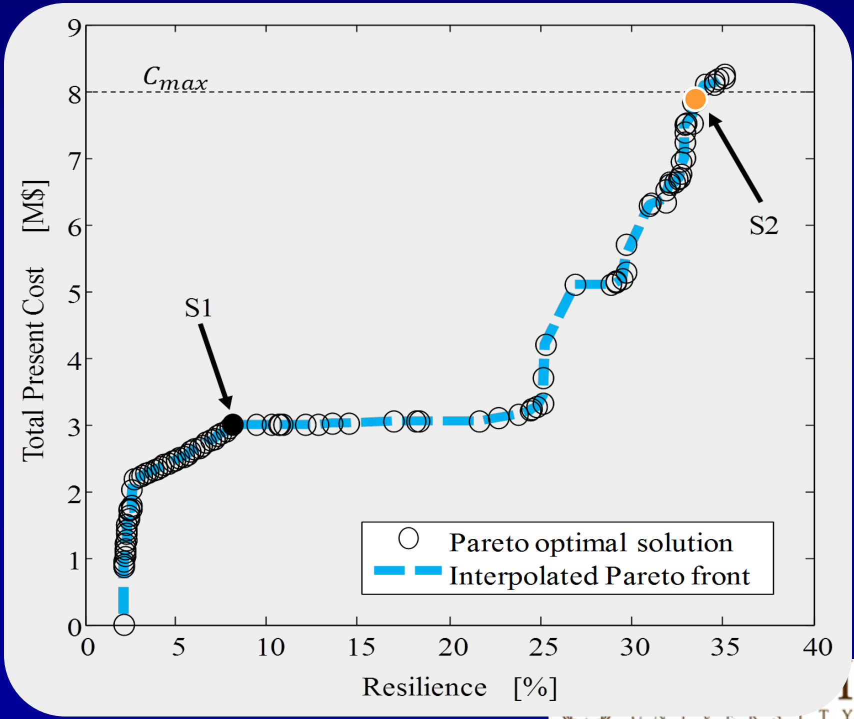
NUMERICAL EXAMPLE (Bocchini and Frangopol, Prob. Eng. Mech. 2011)



REPRESENTATIVE SOLUTION S2

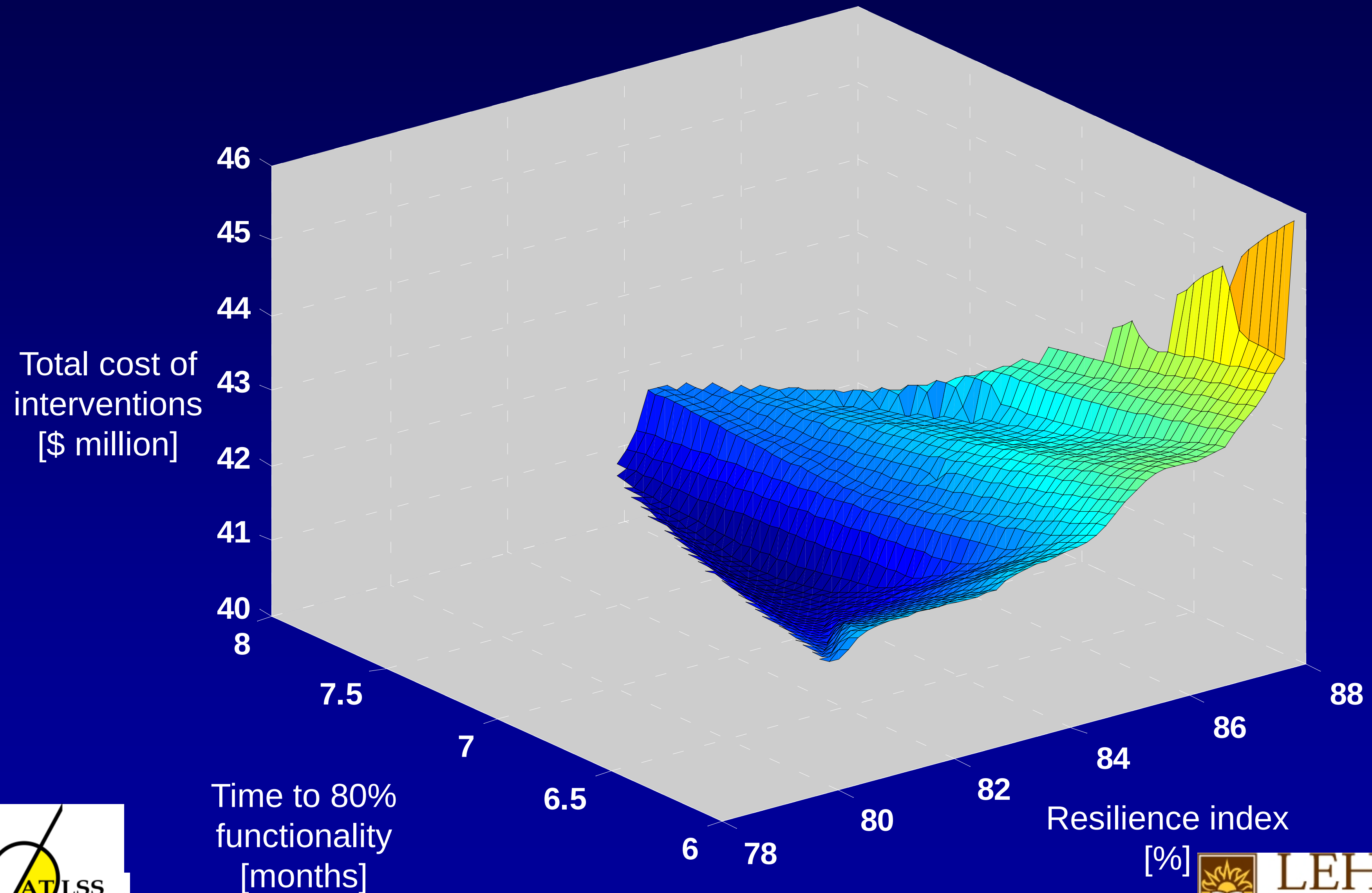






LATEST APPLICATION: SANTA BARBARA

LATEST APPLICATION: SANTA BARBARA



FUTURE TARGET: SF BAY AREA

Credits: Duygu Saydam

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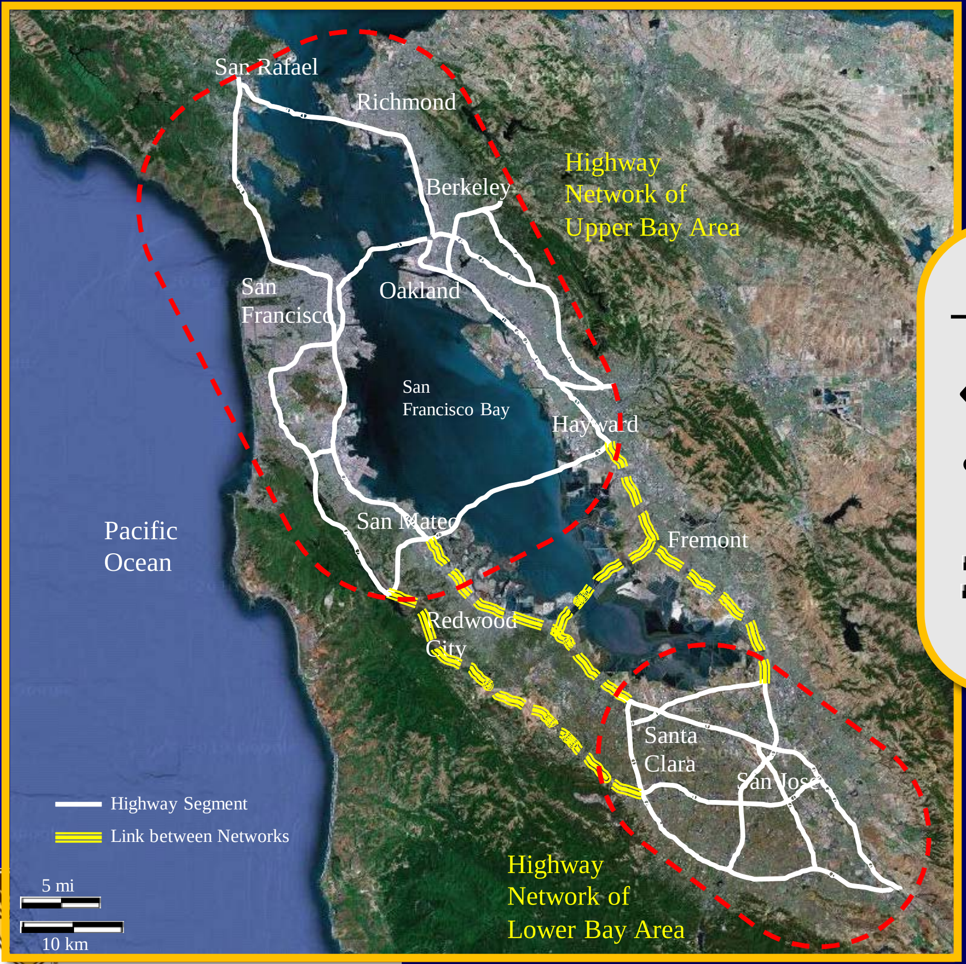
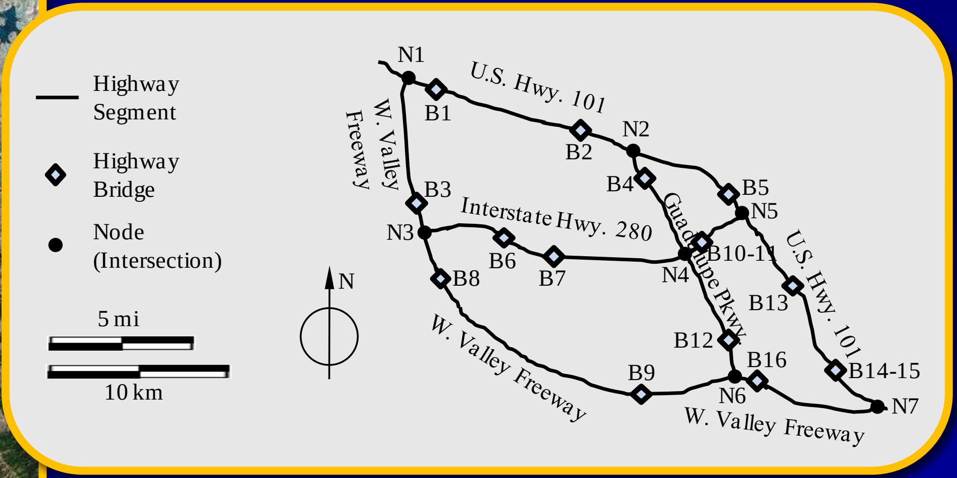
Applications

Bridge networks





Saydam *et al*. (2013a)

Applications

Other engineering systems

Ships

High Speed Vessel (HSV-2 *Swift*)

Sea Fighter (FSF – 1)

Wikipedia (2008)

Movable bridges

GenDisasters (2013)

Gokce *et al*. (2013)

Bridge – ship interaction

ICOSSAR 2013
11th International Conference on Structural Safety & Reliability

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

June 16-20, 2013

Sustainability of Bridge Networks under Earthquake and Flood-Induced Scour

You Dong, Dan M. Frangopol, and Duygu Saydam

Lehigh University
Bethlehem, PA, USA

LEHIGH UNIVERSITY

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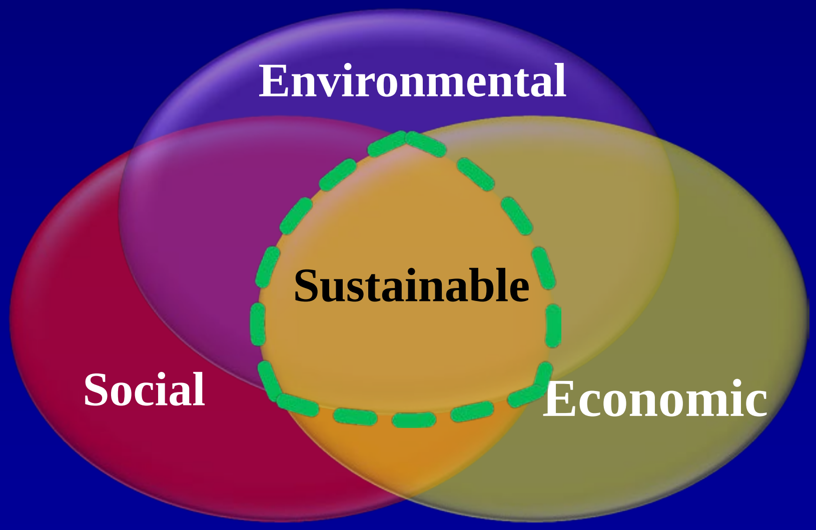
MOTIVATION

Infrastructure systems are critical for the economy and society. The **probabilistic time-variant risk** assessment under **multiple hazards** is a relatively new research area.

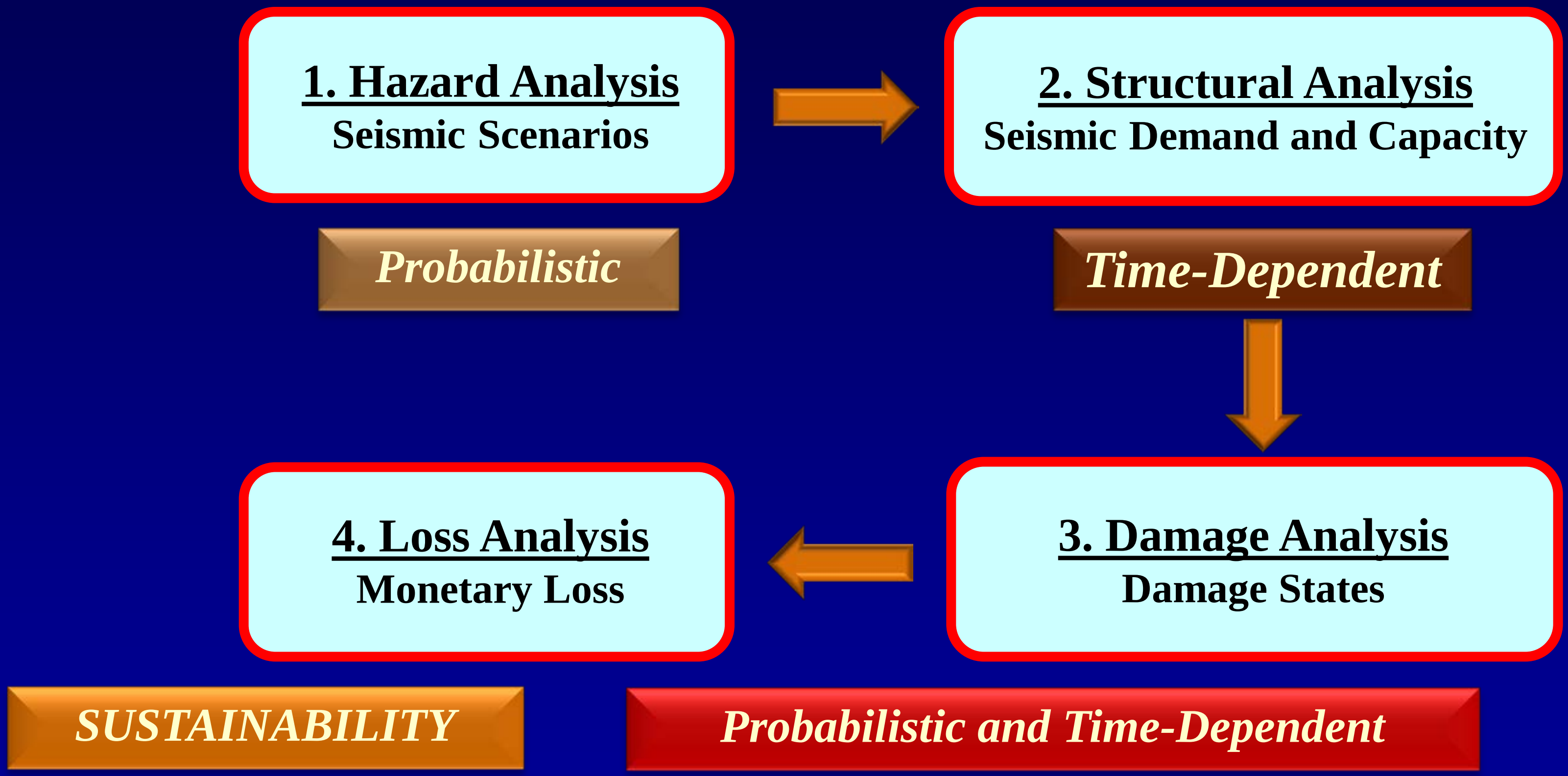
The sustainability aims to improve the quality of life for **present and future** generations. There is the need for well established methods for quantifying the **metrics of sustainability**.



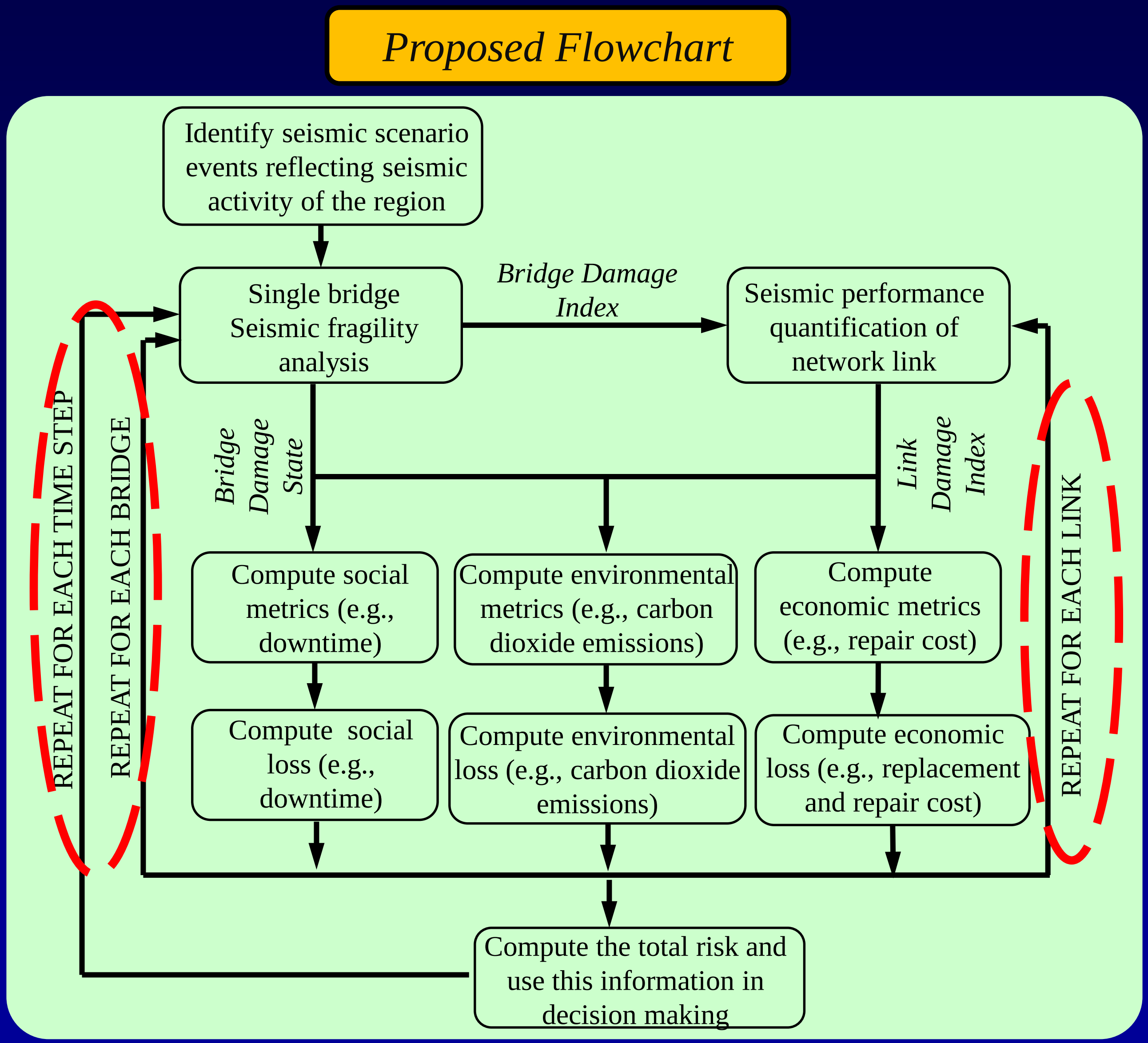
Adams, 2006

METHODOLOGY

- *Flowchart for Hazard Risk Assessment*



METHODOLOGY



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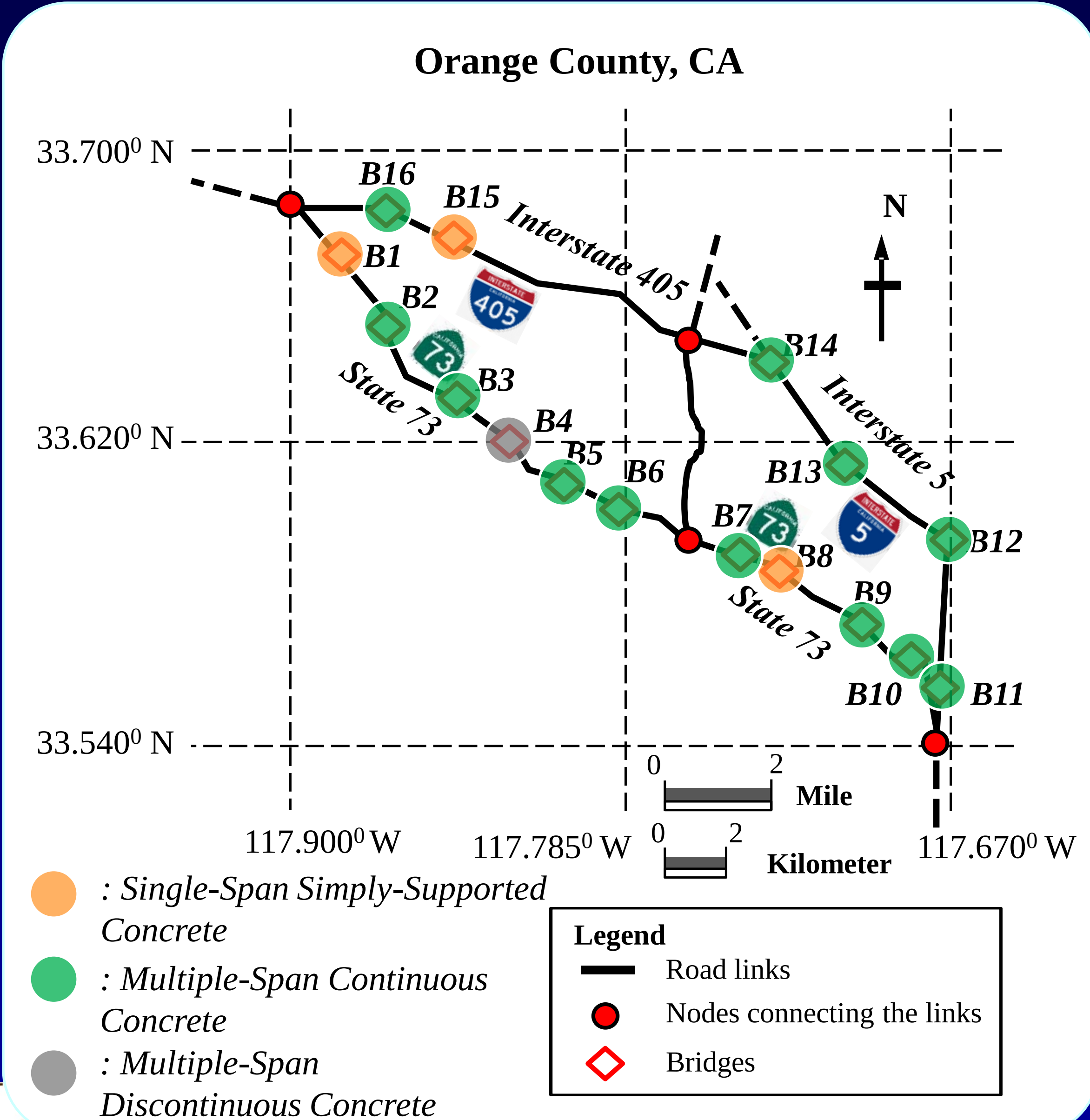
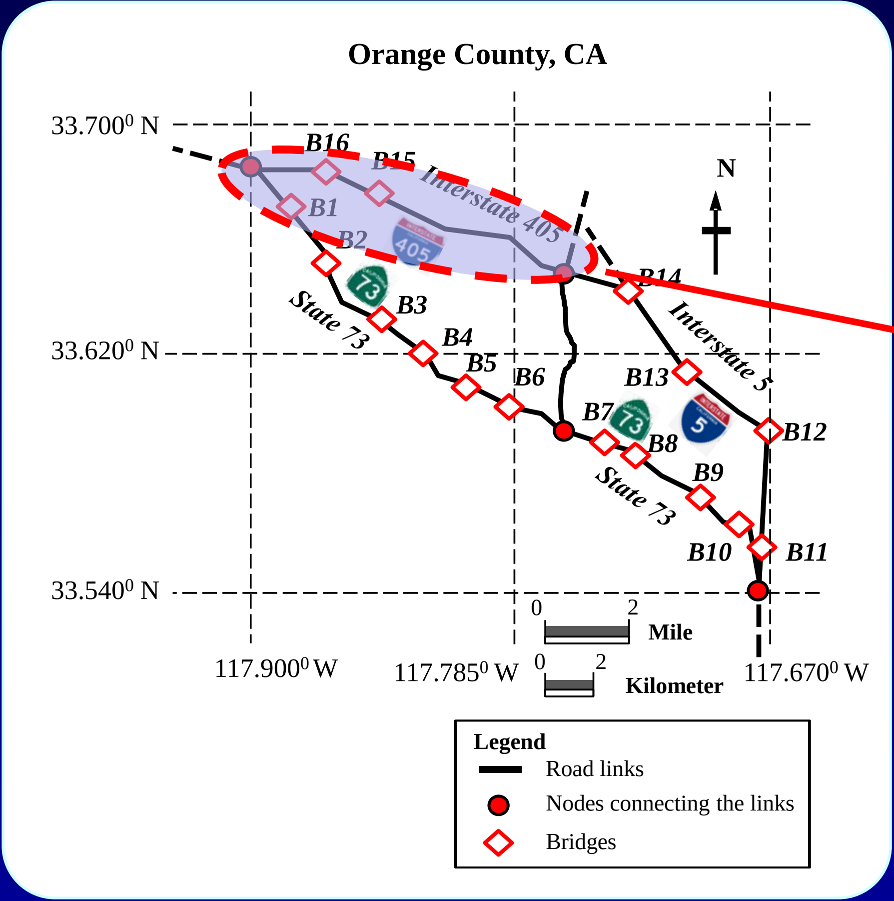
ILLUSTRATIVE EXAMPLE



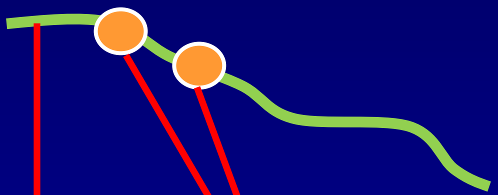
Bridge highway segments

4 nodes and 16 bridges

ILLUSTRATIVE EXAMPLE



The seismic performance of the link (***LDI***) depends on the damage states of the bridges in the links.



$$LDI(t) = \sqrt{\sum_{j=1}^{n} (BDI_j(t))^2}$$

HAZARD ANALYSIS

Hazard analysis

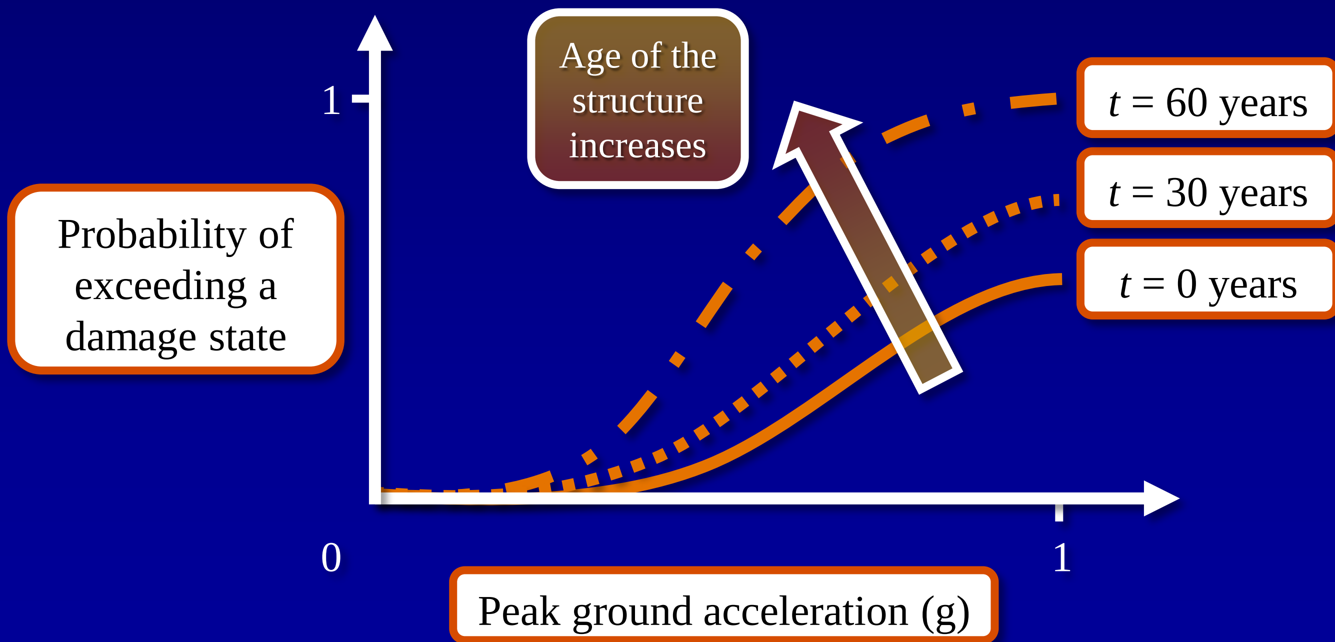
Example:
seismic hazard

Probability of occurrence

Poisson process

Effect on structural vulnerability

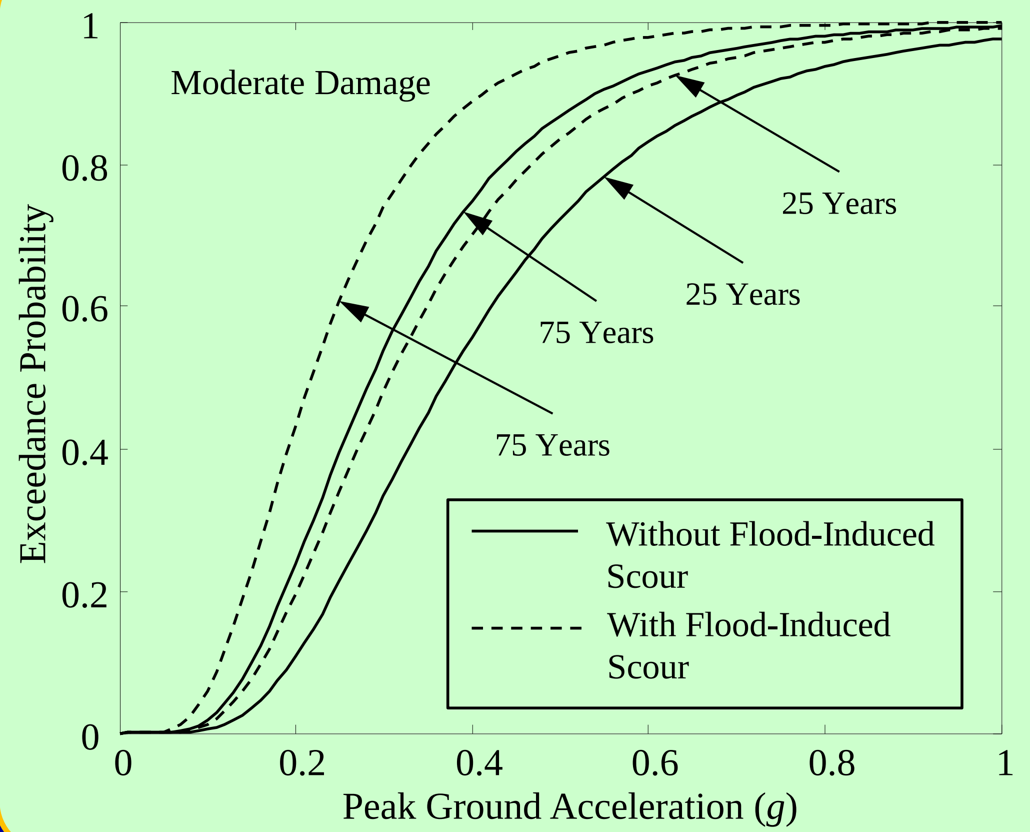
Fragility analysis



ILLUSTRATIVE EXAMPLE

Type B Bridge: Fragility Curve

Time Effects+ Flood-Induced Scour



The conditional probability of exceeding moderate damage state

t

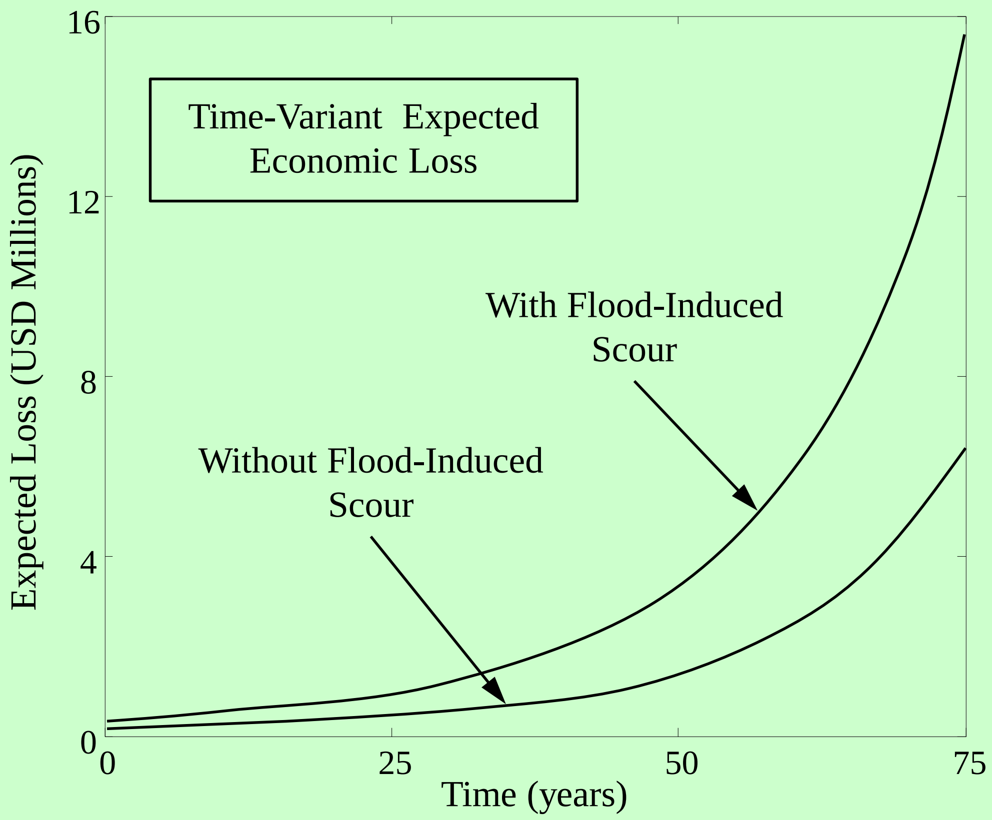
$$m_i(t) = m_{i0} \cdot (1 - \gamma_1 \cdot t - \gamma_2 \cdot Z_{Scour})$$

0.87 at *t* = 75 years without scour. This value is 0.95 at *t* =75 years with flood-induced scour.

The findings highlight importance of considering effects of aging and flood-induced scour on the seismic vulnerability of bridges.

ILLUSTRATIVE EXAMPLE

Expected Annual Economic Loss
Bridge Network



The expected economic loss increases with time and reaches the maximum value at the end of the time-interval under investigation.

The difference between the cases with and without flood-induced scour increases with time.

CONCLUSIONS

1. **Effective and practical methods** for capturing system performance including **redundancy and robustness in a time-dependent context** will continue to present an important challenge.

2. Development of prediction models for the structural performance assessment and prediction with **higher accuracy** will **improve the results** of any optimization process. **Incorporation of SHM** in this process is a field in its infancy.

3. **Improvements** in probabilistic and physical models for evaluating and comparing the risks and benefits associated with various alternatives for **maintaining or upgrading the reliability of existing structures** are needed.

FUTURE CHALLENGES

Acquire reliable data and develop advanced computational tools in order to :

- PROVIDE BETTER KNOWLEDGE ON DEGRADATION AND PERFORMANCE OF CIVIL AND MARINE INFRASTRUCTURE SYSTEMS
- SUPPORT BETTER DESIGN METHODS AND PERFORMANCE PREDICTIVE MODELS
- SUPPORT ADVANCED MANAGEMENT DECISION-MAKING TOOLS

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ASCE
AMERICAN SOCIETY OF CIVIL ENGINEERS

SEI
Structural Engineering Institute

SEI-ASCE Technical Council on Life-Cycle Performance, Safety, Reliability and Risk of Structural Systems

Founded 2008

http://content.seinstitute.org/committees/strucsafety.html

TECHNICAL COUNCIL ON LIFE-CYCLE PERFORMANCE, SAFETY, RELIABILITY AND RISK OF STRUCTURAL SYSTEMS

(Created on October 1, 2008; replaces the former Technical Administrative Committee on Structural Safety and Reliability)

Chair: Dan Frangopol
Vice Chair: Bruce Ellingwood

Purpose:

To provide a forum for reviewing, developing, and promoting the principles and methods of life-cycle performance, safety, reliability, and risk of structural systems in the analysis, design, construction, assessment, inspection, maintenance, operation, monitoring, repair, rehabilitation, and optimal management of civil infrastructure systems under uncertainty .

Task Group 1: Life-Cycle Performance of Structural Systems Under Uncertainty
Chair: Fabio Biondini

Purpose:

To promote the study, research, and applications of scientific principles of safety and reliability in the assessment, prediction, and optimal management of life-cycle performance of structural systems under uncertainty.

Task Group 2: Reliability-Based Structural System Performance Indicators
Chair: Michel Ghosn

Purpose:

To promote the study, research, and applications of reliability-based system performance indicators including structural system reliability, robustness, and redundancy.

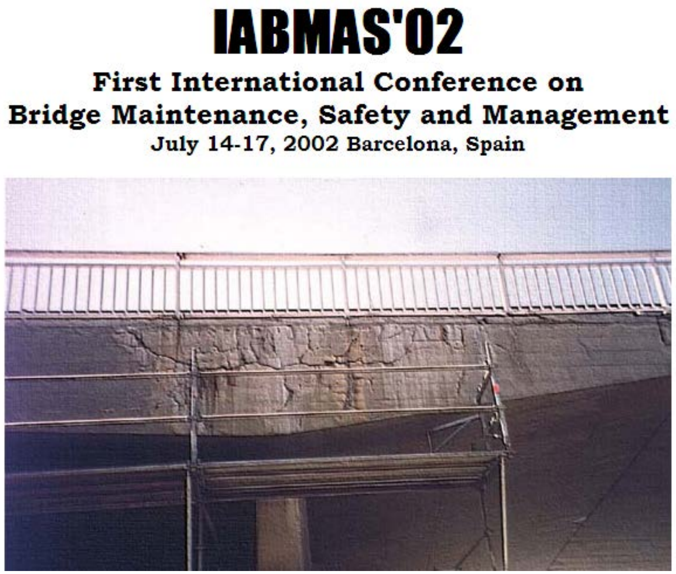
Task Group 3: Risk Assessment of Structural Infrastructure Facilities and Risk-Based Decision Making
Chair: Bruce Ellingwood

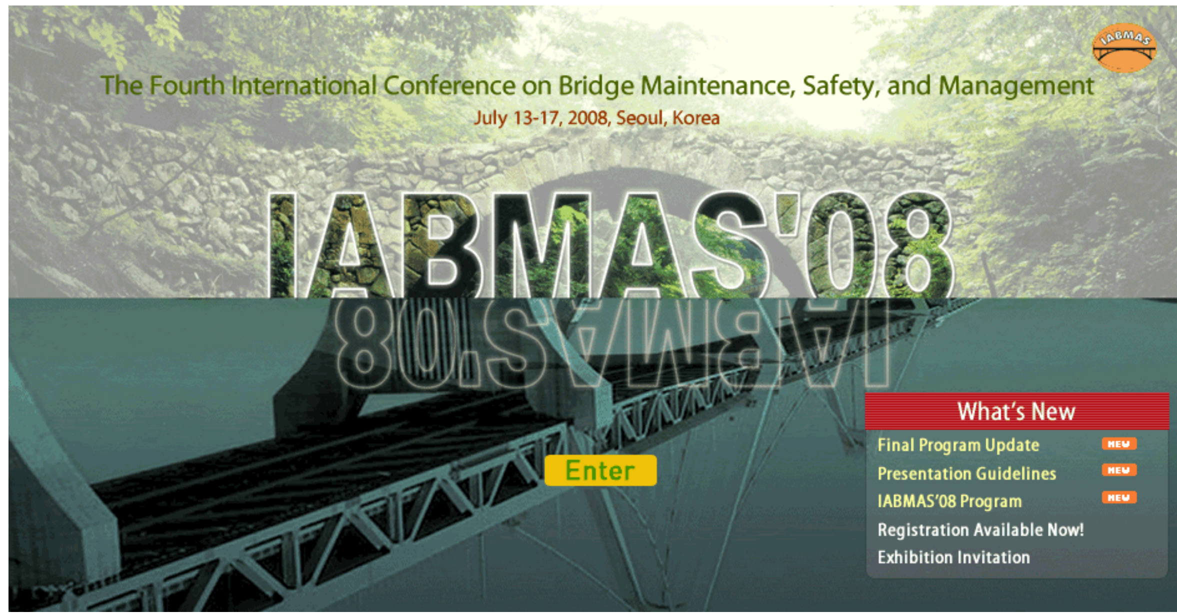
Purpose:

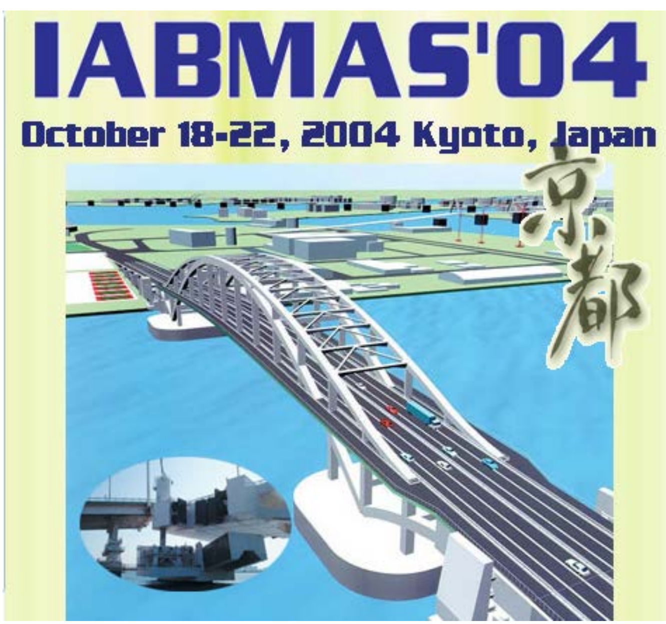
To promote the study, research and applications of scientific principles of risk assessment and risk-based decision making in structural engineering .

When filling out application to join Technical Council, please indicate which Task Group.

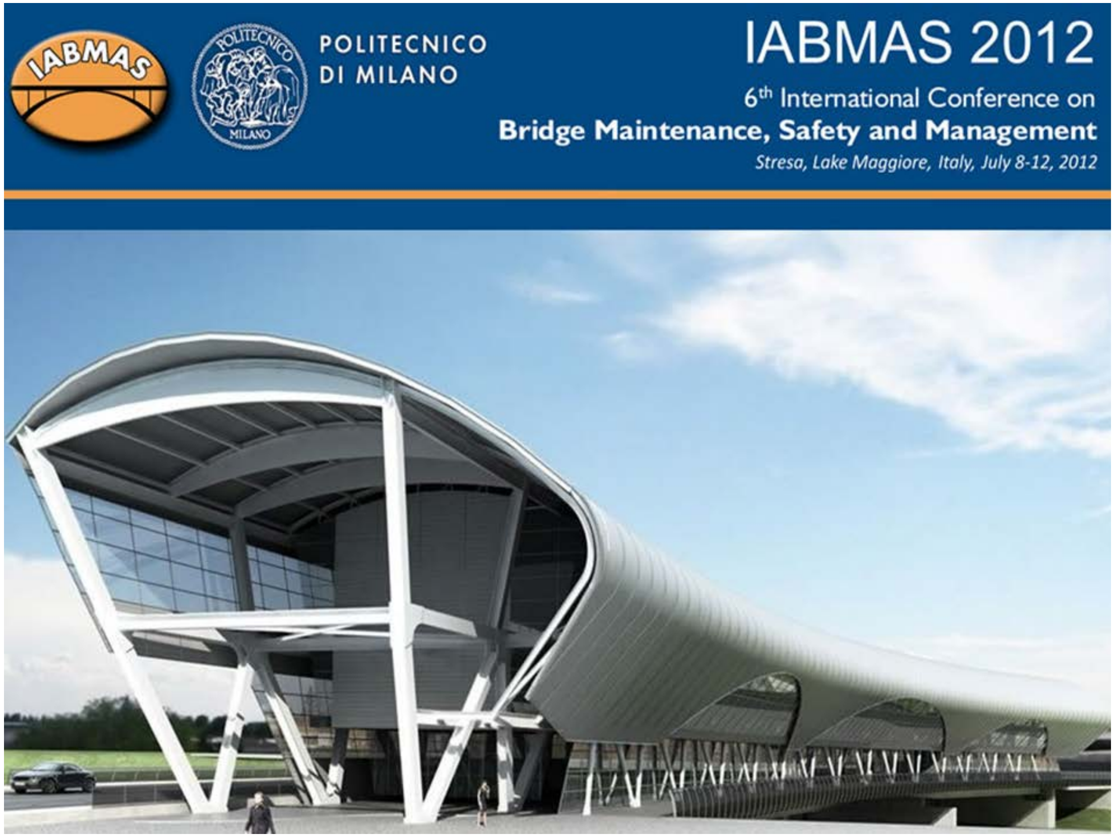
IABMAS Conferences



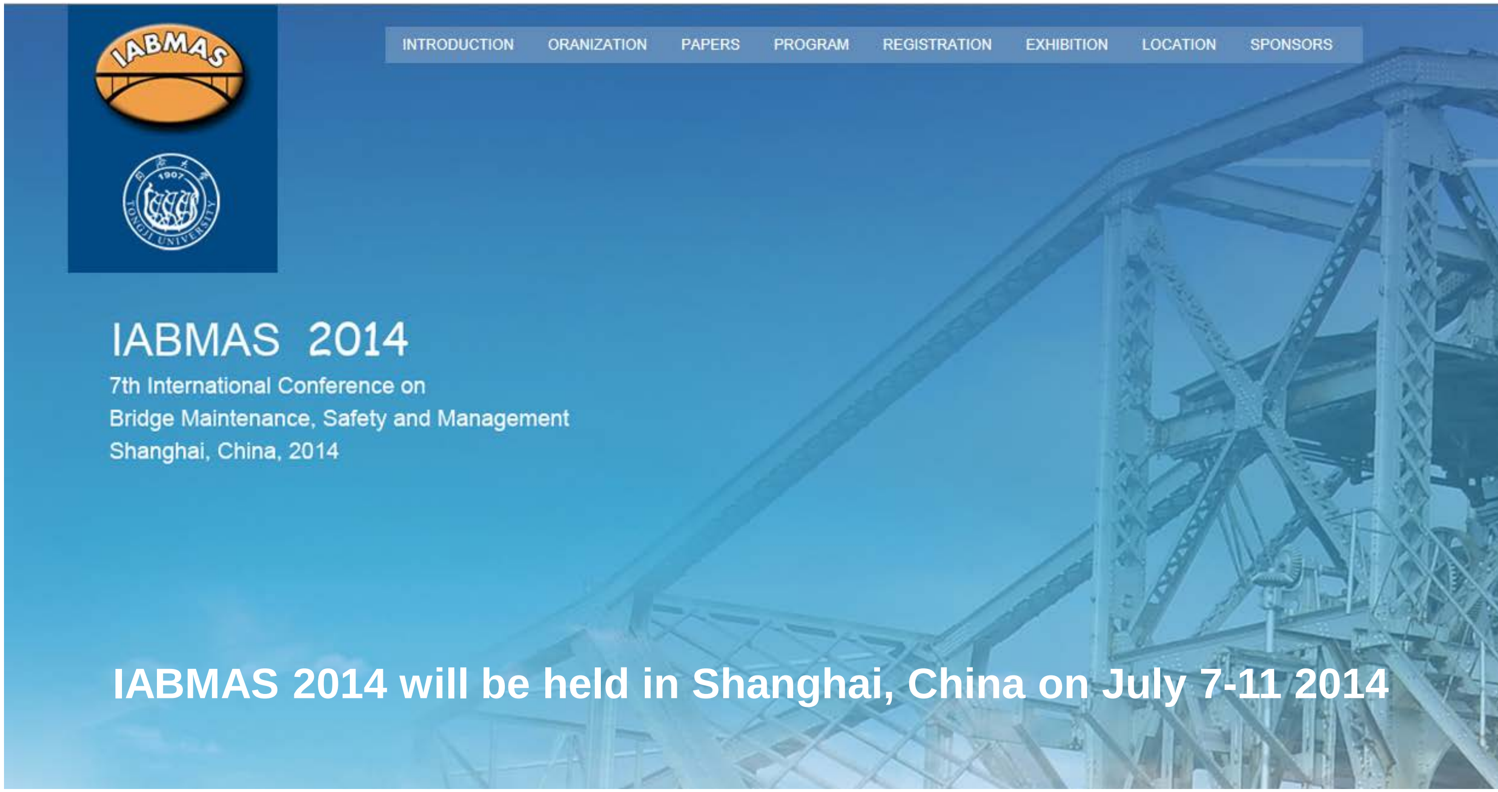




Report of IABMAS2012



IABMAS 2014



IABMAS 2014 will be held in Shanghai, China on July 7-11 2014

IABMAS 2016

IABMAS BRAZIL

INTERNATIONAL ASSOCIATION FOR BRIDGE MAINTENANCE AND SAFETY

IABMAS 2016
Iguazu Falls
Paraná, Brazil

June 26 – 30, 2016

National Groups of IABMAS

Portuguese Association for Bridge Maintenance and Safety www.ascp.pt

China Group of IABMAS www.iabmas-cg.org

INTERNATIONAL ASSOCIATION FOR BRIDGE MAINTENANCE AND SAFETY

ITALY

IABMAS Italian Group

Foundation Meeting

Regina Palace Hotel, Azalea Room

Stresa, Lake Maggiore, Italy | *July 9th, 2012*

IALCCE 2014

Fourth International Symposium on Life-Cycle Civil Engineering

www.ialcce2014.org

International Association for Life-Cycle Civil Engineering

Department of Civil and Environmental Engineering, Waseda University

November 16-19, 2014

RIHGA Royal Hotel and Waseda University, Tokyo, Japan

Symposium Chairs:

Hitoshi Furuta, Kansai Unviersity, Osaka, Japan
Dan M. Frangopol, Lehigh University, Bethlehem, PA, USA
Mitsuyoshi Akiyama, Waseda University, Tokyo, Japan

THANK YOU