Maintenance Management of Infrastructure Networks: Issues and Modeling Approach

Network Optimization for Pavements

Pontis System for Bridge Networks

Integrated Infrastructure System for Beijing

Common Issues

- All systems address networks of infrastructures
- Deteriorations are probabilistic
- Maintenance optimizations are dynamic
- Political and operational issues are important

Main Differences

- Decision problems
- Formulations
- Network to project relationships
- State space definitions and measurements
- Uncertainties and their quantification
- Defining units
- Funding processes and regulatory oversight

Arizona Pavement Management

ADOT's Highway Division

ADOT:

- 2200 miles interstate
- 5200 miles non-interstate
- 2400 of 3700 ADOT employees
- 7 autonomous districts

Cost:

- $2 billion dollars to construct
- $6 billion dollars in 1982
- 83% of ADOT's $221 million budget

Need for Pavement Management System

- Shift of emphasis to preservation
- Aging of highways
- Increase in preservation costs
- Federal regulations
- Decentralized estimates of Needs
- Uncertainty in future budget

Cost Increases

- 40% of maintenance costs was for materials
- Asphalt cost increased $88 to $270 in 5 years
- Budget increased: $25 to $52 million in 3 years
- Arizona legislature refused extra budget
- FHWA requirements consumed state budget

Formulation Issues

1. Centralization of the decision process
2. Incorporation of the uncertainties
3. Dynamic decision process
4. Maximization of benefits vs. minimization of costs
5. Steady-state versus short-term
6. Network to project relationship
7. How to define the condition states for Markov process
8. How to solve the budget-constrained problem

Condition States

Roughness	3 levels
Cracking	3 levels
Cracking during previous year	3 levels
Index to first crack	5 levels

135 states ⇨ 120 feasible states

Maximization of Benefits

Let: M = state space

A_i = set of feasible actions associated with state i

$P_{ij}(a)$ = one period transition probability

$f(i,a)$ = benefit associated with (i,a)

α = discount factor

$$V\pi(i) = E_\pi\left(\sum_t \alpha\, f(X_t, a_t) \mid X_o = i\right) \qquad i \in M$$

$$V(i) = \max_\pi V_\pi(i)$$

Then,

$$V(i) = \max_a \left[\left(f(i,a) + \alpha \sum_{j \in M} P_{ij}(a) V(j)\right) \right]$$

It is known that the LP defined by

minimize $$z = \sum_{j=1}^{M} \delta_j \, y_j$$

subject to:

$$y_i - \alpha \sum_{j=1}^{M} P_{ij}(a)\, y_j \geq f(i,a)$$

gives optimal solution:

$$(y_1^*, y_2^*, \ldots y_M^*) = [V(1), V(2), \ldots V(M)]$$

Dual of Benefit Maximization Problem

maximize $$\sum_{i,a} f(i,a)\, w_{ia}$$

subject to:

$$\sum_{a} w_{ja} - \alpha \sum_{i,a} p_{ij}(a)\, w_{ia} = \delta_j \qquad j \in M$$

$$w_{ia} \geq 0 \qquad \text{for all } i,a$$

- Constraint holds as equalities as y_i are unrestricted in sign

- By complementary slackness principle, w_{ia} is positive only if action a is optimal for state i

We can show that

w_{ia} = steady state probability of being in state i and taking action a

if $$\sum_{j=1}^{M} \delta_j = 1-\alpha$$

and $$\sum_{i,a} w_{ia} = 1$$

Budget constraint: $$\sum_{i,a} w_{ia} c(i,a) n_i \leq B$$

B = average annual maintenance budget

n_i = number of miles in state i

Problems with Benefit Maximization

1. Subjective tradeoffs between road types

2. Subjective tradeoffs between conditions

3. Unknown effect of standards on budgets

4. Computational issues

Minimum Cost Formulation
Long-term Model

For any policy let w_{ia} denote the limiting probability that the road will be in the state *i* and action *a* will be chosen when the policy is followed.

$$w_{ia} = \lim P\,[X_n = i, a_n = a\,]$$

The vector $w = (w_{ia})$ must satisfy (1), (2), (3)

The reverse is also true.

Minimum Cost Formulation
Long-term Model

minimize $$\sum_{i} \sum_{a} w_{ia} c(i,a)$$

subject to $$w_{ia} \geq 0 \qquad (1)$$

$$\sum_{i} \sum_{a} w_{ia} = 1 \qquad (2)$$

$$\sum_a w_{ja} = \sum_i \sum_a w_{ia} p_{ij}(a) \qquad \text{for all } j \qquad (3)$$

$$\sum_a w_{ia} \geq \varepsilon_i \qquad \text{if } i \text{ desirable}$$

$$\sum_a w_{ia} \leq \gamma_i \qquad \text{if } i \text{ undesirable}$$

Short-Term Model

T = time to achieve steady state

q_i^n = proportion of roads in state i in period n

q_i^1 is known

C = steady-state average cost

$$\text{minimize} \quad \sum_{k=1}^{T} \sum_{i} \sum_{a} \alpha^k w^k_{ia} c(i,a)$$

subject to:

$$w^k_{ia} \geq 0 \qquad \text{for all } i,a,k = 1,2,\ldots,T,$$

$$\sum_i \sum_a w^k_{ia} = 1 \qquad \text{for all } k = 1,2,\ldots,T,$$

$$\sum_a w^1_{ia} = q_i^1 \qquad \text{for all } i,$$

$$\sum_a w^k_{ja} = \sum_i \sum_a w^{k-1}_{ia} p_{ij}(a)$$

for all j and k= 1, 2,…,T.

Attain steady state in T periods (with tolerance)

$$\sum_a w^T_{ja} \geq \sum_a w^*_{ja}(1-\Phi) \qquad \text{for all } j$$

$$\sum_a w^T_{ja} \leq \sum_a w^*_{ja}(1+\Phi) \qquad \text{for all } j$$

$$\sum_i \sum_a w^T_{ja} c(i,a) \leq C(1+\Psi).$$

Performance standards:

$$\sum_a w^k_{ia} \geq \varepsilon'_i$$

if i is acceptable, k=2,…,T-1,

$$\sum_a w^k_{ia} \leq \gamma'_i$$

if i is unacceptable, k=2,…,T-1.

Benefits in Arizona

- Saved $14 million
  ($32 Vs. $46 million in first year)
- Saved over $100 million in next 5 years
- Focal point of centralized decision process
- Coordinated data gathering and management
- Made budget requests defensible

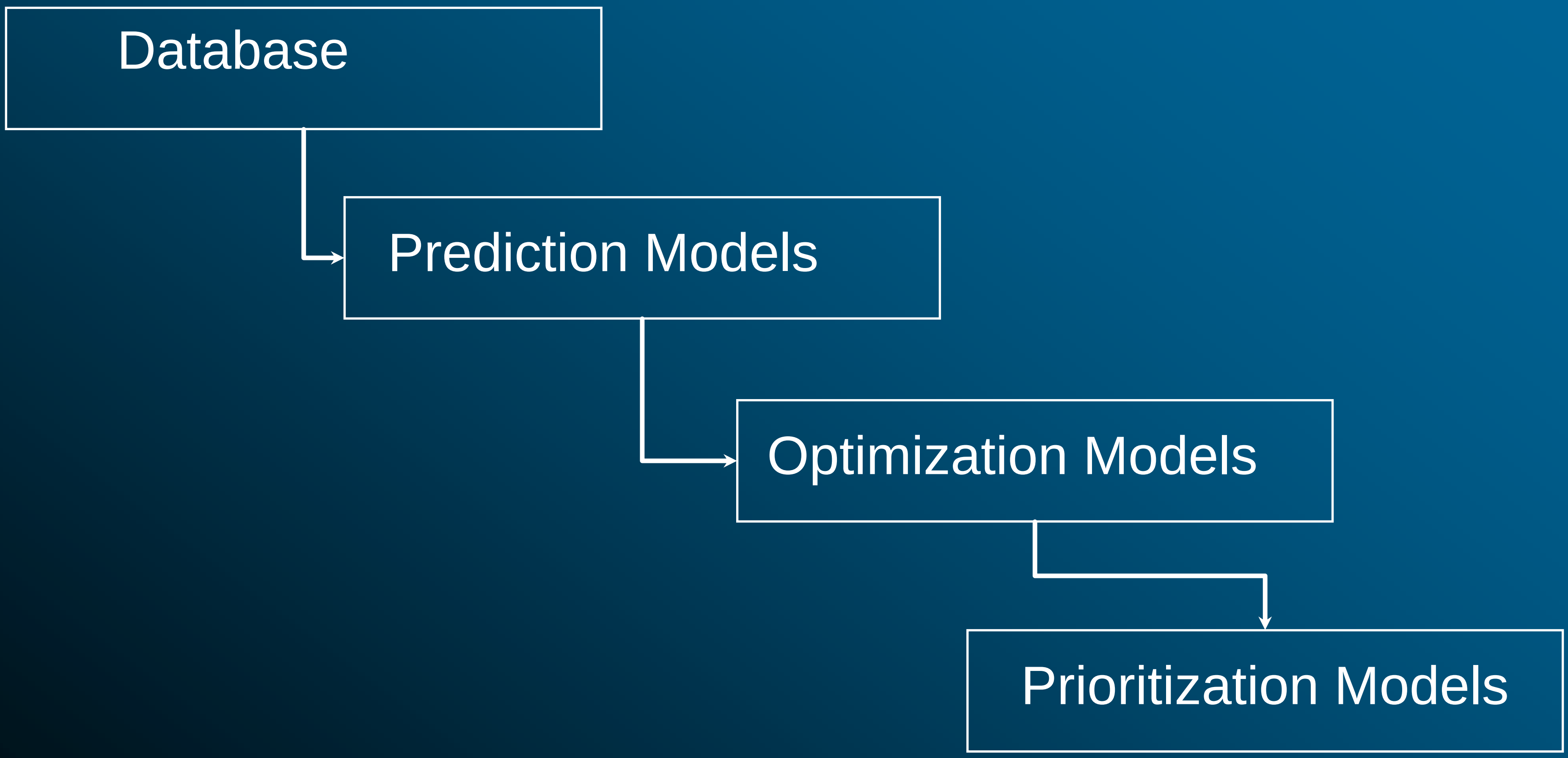
IMPACTS

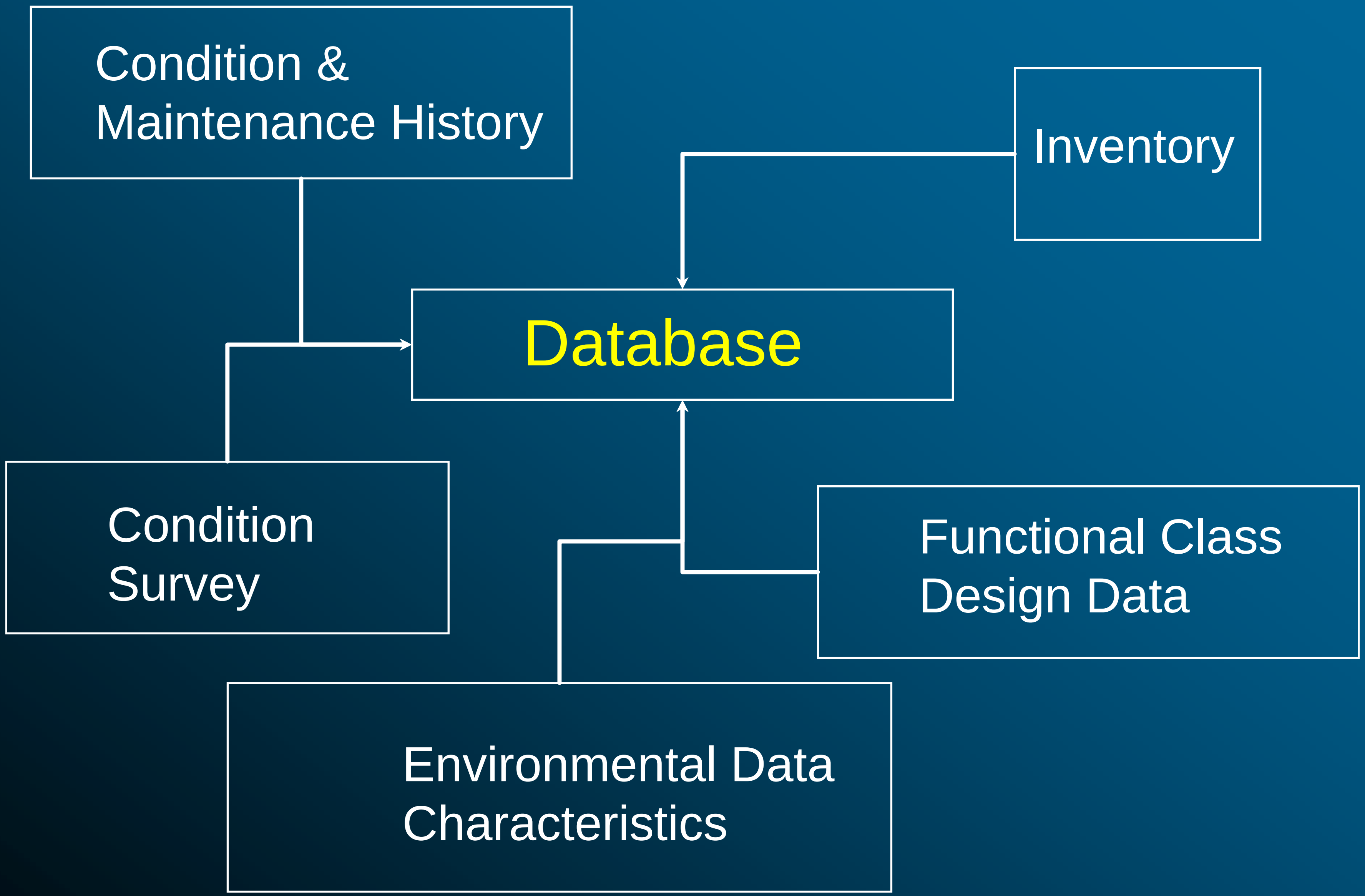
Some countries and states using the model:

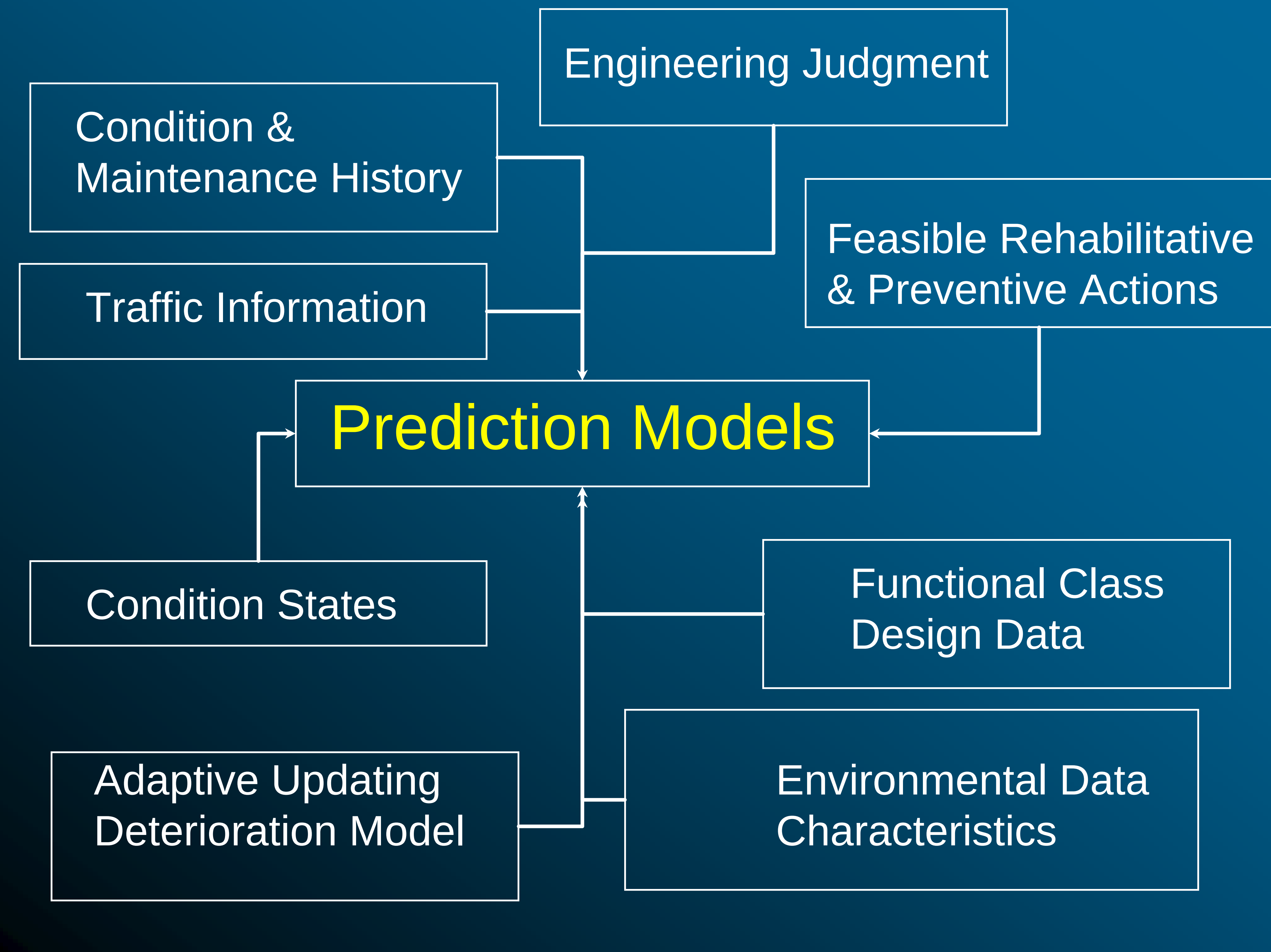
- Arizona
- Kansas
- Alaska
- Colorado
- California

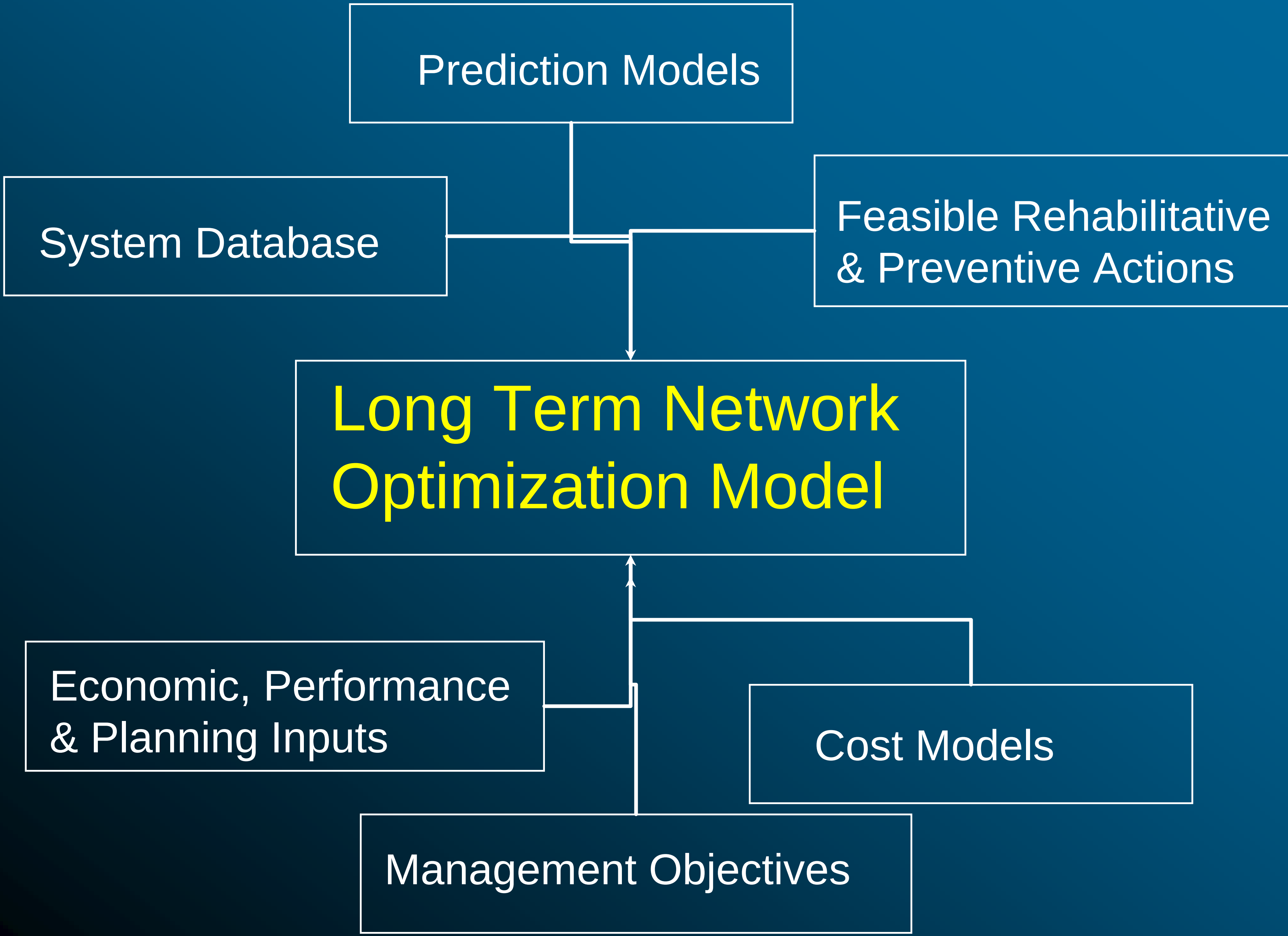
- Holland
- Finland
- Portugal
- Hungary
- Australia (NSW)
- Saudi Arabia
- Greece

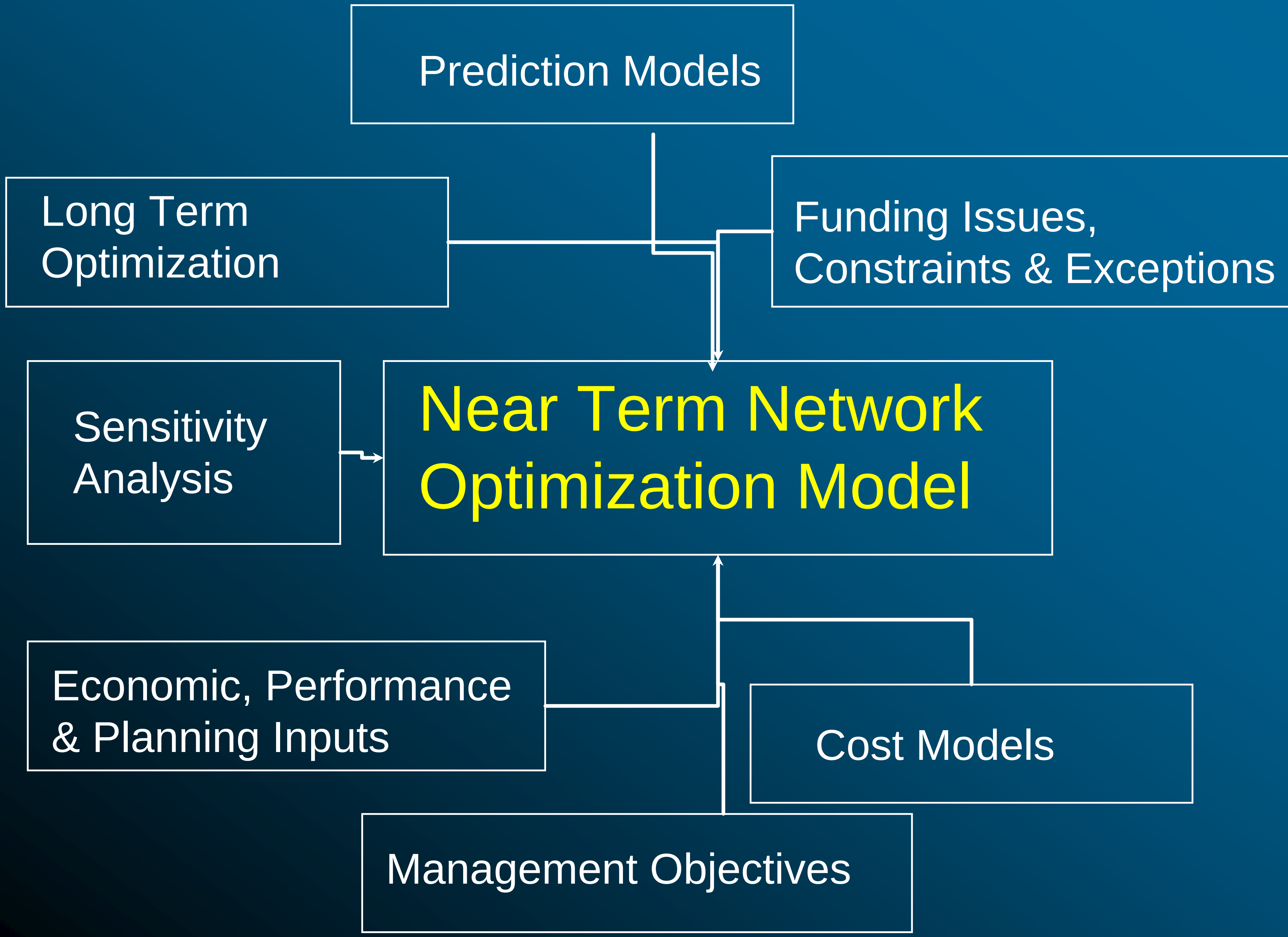
Expanded Portuguese System Framework

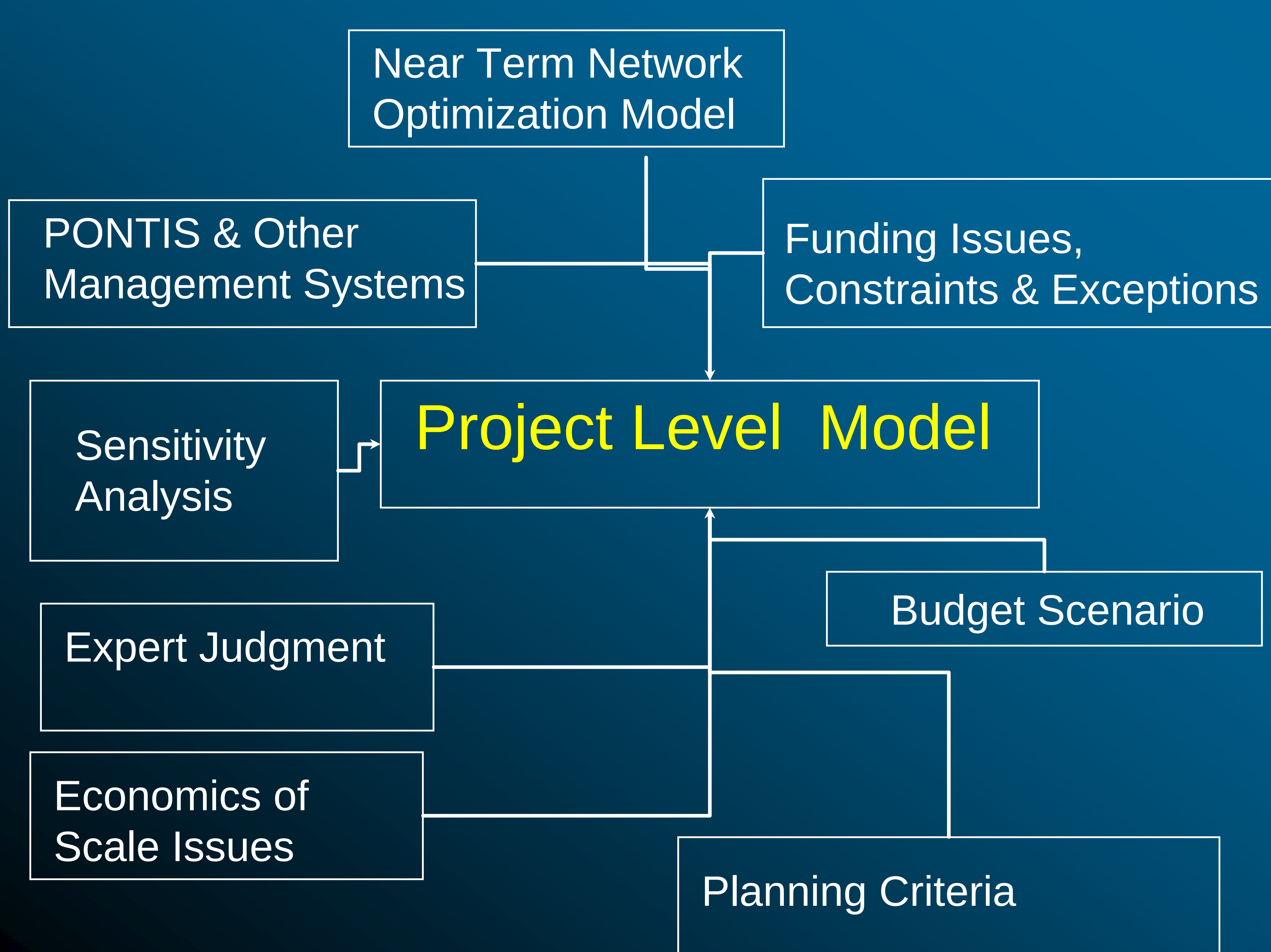



Condition & Maintenance History
Inventory
Database
Condition Survey
Functional Class Design Data
Environmental Data Characteristics

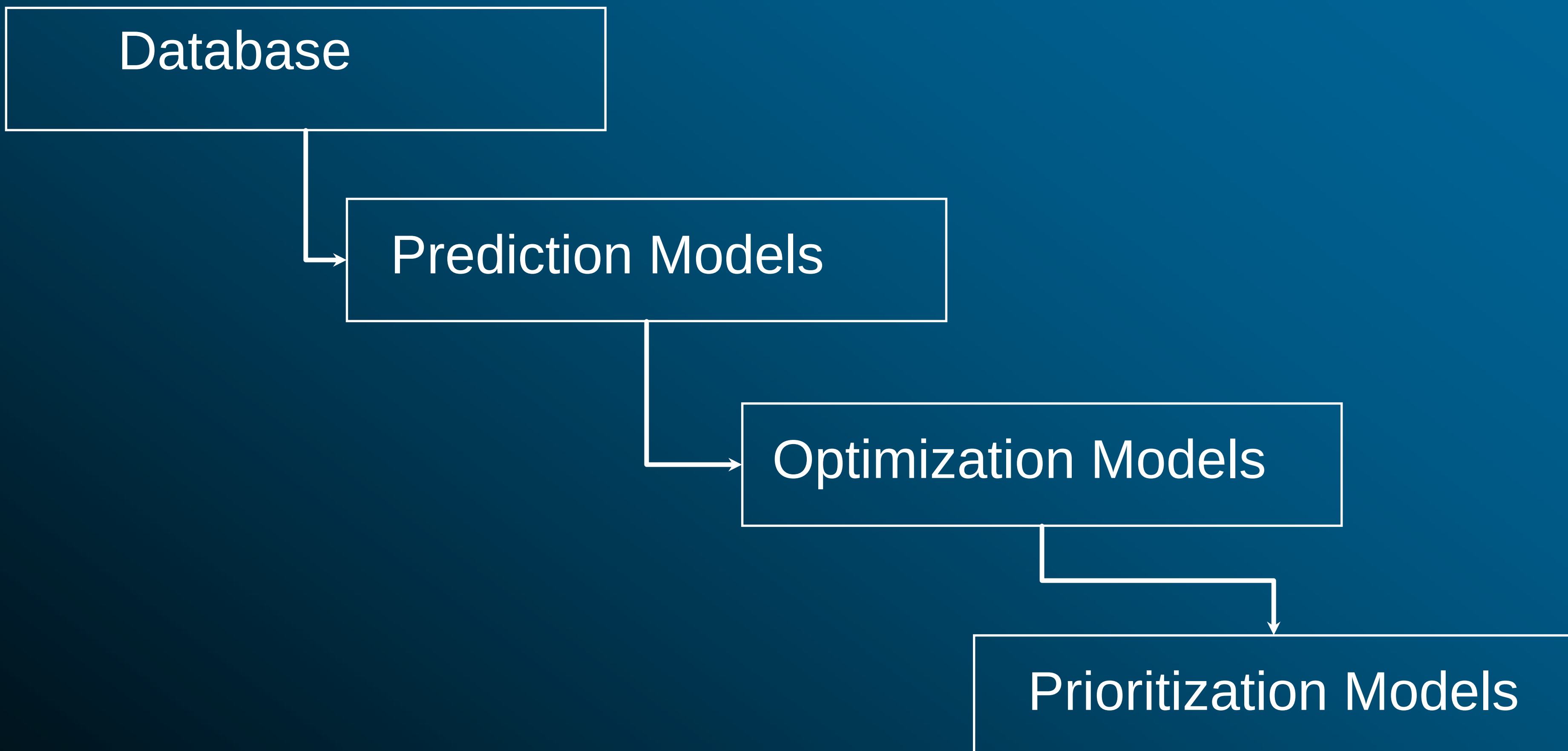

Engineering Judgment
Condition & Maintenance History
Feasible Rehabilitative & Preventive Actions
Traffic Information
Prediction Models
Condition States
Functional Class Design Data
Adaptive Updating Deterioration Model
Environmental Data Characteristics


Prediction Models
System Database
Feasible Rehabilitative
& Preventive Actions
Long Term Network
Optimization Model
Economic, Performance
& Planning Inputs
Cost Models
Management Objectives

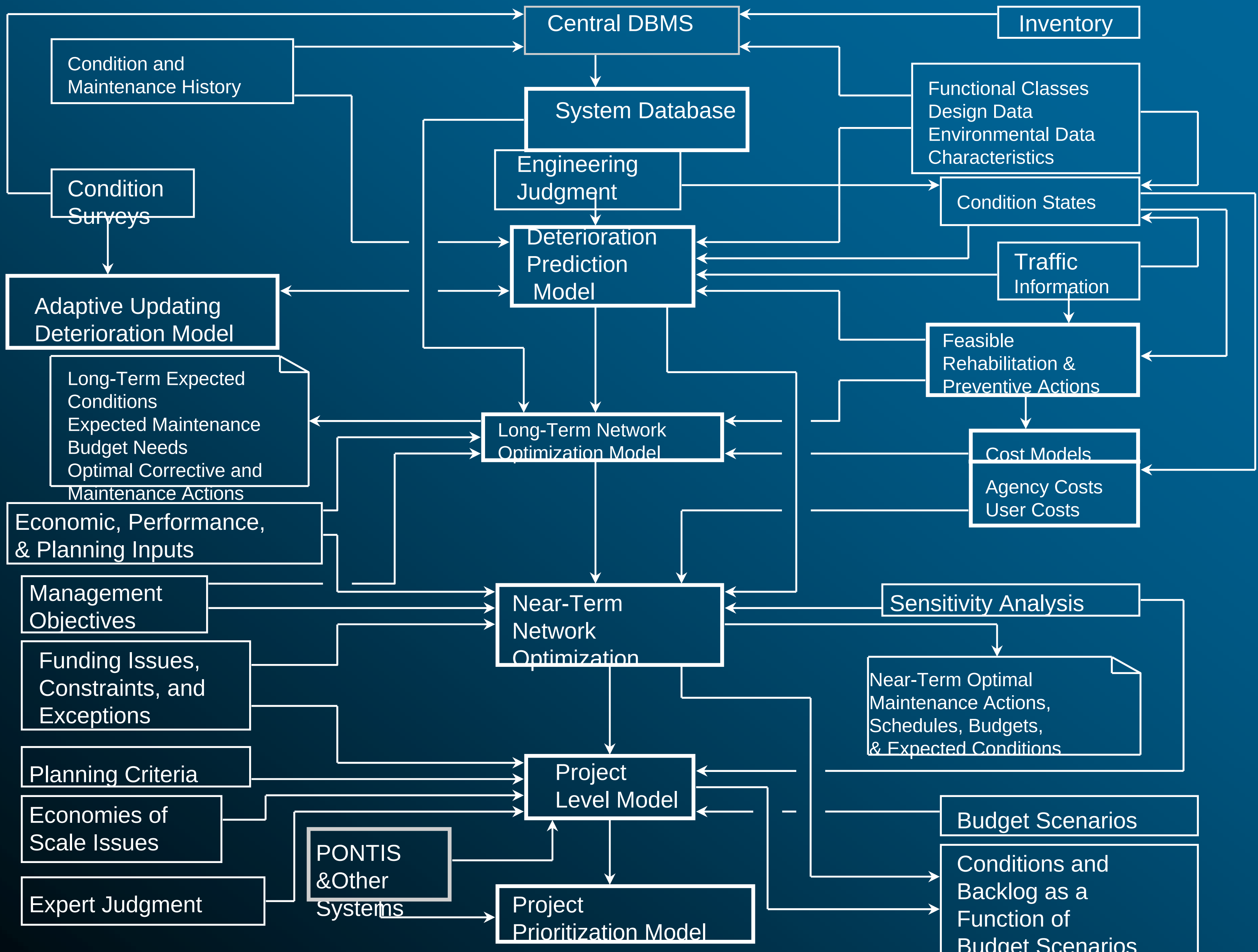

Prediction Models
Long Term Optimization
Funding Issues, Constraints & Exceptions
Sensitivity Analysis
Near Term Network Optimization Model
Economic, Performance & Planning Inputs
Cost Models
Management Objectives


Near Term Network Optimization Model
PONTIS & Other Management Systems
Funding Issues, Constraints & Exceptions
Sensitivity Analysis
Project Level Model
Budget Scenario
Expert Judgment
Economics of Scale Issues
Planning Criteria

Expanded Portuguese System Framework



Expanded Portuguese System Framework



PONTIS: A System for Maintenance Optimization and Improvement of U.S. Bridge Networks

- Clients:
  - Federal Highway Administration (FHWA)
  - State of California DOT
  - Adopted by Association of American State Highway Officials (AASHTO)
- Implemented in 48 states

PONTIS Technical Advisory Committee

- Principal Investigator: K. Golabi
  - Federal Highway Administration
  - Transportation Research Board
  - State of California
  - State of Minnesota
  - State of North Carolina
  - State of Tennessee
  - State of Vermont
  - State of Washington

U.S. Road Network

- 3.8 million miles
- 565,000 bridges
- 400,000 built before 1935

Funds

- $2.7 billion bridge budget
- No funds for routine maintenance
- Distributed according to subjective sufficiency rating

Issues In Bridge Management

- Widening gap between funds and eligibility
- FHWA subjective rating
- Inequities of fund distribution
- Maintenance sacrificed to major rehabilitation

Main Objectives

- Equitable allocation of resources
- Optimal maintenance and improvement
- Network-wide optimization
- Consider agency and users' costs
- Minimize costly repairs and replacements
- Coordinate maintenance and improvement optimization

Distinguishing Features

- Large replacement costs
- Large risks and visibility
- More complex problem than pavements
- Lack of meaningful deterioration data
- Many types and designs and materials
- Not meaningful to define “bridge unit”

Distinguishing Features (cont'd)

- Various different deterioration rates for components
- Possibly different environments in same bridge
- Improvement activities vs. maintenance (MR & R)
- All action on each bridge at same time
- U.S. funding situation is complex
- Improvement is different from MR & R

Maintenance vs. Improvement

- Maintenance
  - Response to deterioration
    - Patching
    - Repairs
    - Rehabilitation
- Improvement
  - Response to user needs
    - Replacement
    - Widening
    - Raising

Key Modeling Ideas

- Abandon FHWA rating method
- Separate Improvement from MR & R
- Define set of elements from which all bridges in U.S can be built
- Require more detailed information on all elements

- Maintenance optimization by considering "network of bridge elements" and then combine results
- Coordinated maintenance and improvement optimization
- Independence of MR & R optimization from number of bridges
- Predictive models that start with engineering judgement and learn from data

MR & R Optimization Models

- Optimal MR & R: Markov DM (Primal LP)
- Steady-state conditions: Markov DM (Dual LP)
- Prioritization of MR & R: simplified integer program
  - -benefits: cost saving of now vs. next year
  - -cost: agency cost

Improvement Optimization

Deficiencies addressed:

- Load carrying capacity
- Clear deck width
- Vertical clearance
- User specified actions
- Cost from simple unit cost model
- Benefit is cost saving of now vs. next year

Improvement Model

- Notations
  - b_{na}: Total discounted benefits for the nth bridge when action *a* is taken
  - a_r: Replacement action
  - a_w: Widening action
  - a_v: Vertical clearance correction
  - I_{na}: 0~1 variable denoting whether a bridge n would be chosen for action *a* (Ina=1 if action *a* is chosen)
  - c_{na}: Cost of taking action *a* for bridge n
  - B_f: Federal budget for improvement
  - B_s: State budget for improvement
  - f_{na}: The proportion of the cost of improvement a on bridge n paid from federal budget

Improvement Model

$$Max \; . \sum_{n} \sum_{a} I_{na} b_{na}$$

$$s.t.$$

$$\sum_{n} \sum_{a} I_{na} c_{na} f_{na} \leq B_{f}$$

$$\sum_{n} \sum_{a} I_{na} c_{na} (1 - f_{na}) \leq B_{s}$$

$$I_{na_r} + I_{na_w} \leq 1$$

$$I_{na_r} + I_{na_v} \leq 1$$

$$I_{na_w} - I_{n'a_w} = 0$$

$$I_{na} = 0,1$$

Project Programming Output Report

- Total Unconstrained Need

Type of Action	1991	1992	1993	1995	1997	1999
Long-term steady state MR & R needs	79023		79023		79023	
Backlog MR & R needs	11967					
Improvement needs	172000					
Replacement needs	40980					
Pre-programmed needs	64270					
Total needs	368240		79023		79023	

Project Programming Output Report

- Work Programmed

Type of Action	1991	1992	1993	1995	1997	1999
MR & R costs programmed	20670	11780	49245	49245	50374	62719
Improvements costs programmed	29000	9000	8000	8000	9000	7000
Replacement costs programmed	5900	8610	8610	26470	0	0
Pre-programmed costs programmed	64270	0	0	0	0	0
Total programmed costs	119840	29390	29390	81715	59374	59719

- Backlog

Type of Action	1991	1992	1993	1995	1997	1999
MR & R backlog	70320	58540	639290	737012	796032	814166
Improvement backlog	14300	134000	128000	121000	112000	105000
Replacement backlog	35080	26470	0	0	0	0
Pre-programmed backlog	0	0	0	0	0	0
Total backlog	248400	219010	767289	858012	908032	919165
User cost of improvement and replacement back log	260310	207310	128000	121000	112000	105000

Integration and Program Planning

- Integrates results of MR & R and IOM
- Simulates future conditions, needs and backlog as functions of
  - budget allocation
  - traffic growth
  - changes in levels-of-service standards
- Works with and without budget constraints

Representation of Conditions

- Each element is rated by dividing among states
- Example: Reinforced concrete box girder
  - 20% in state 1: no deterioration
  - 35% in state 2: minor cracks and spalls but no exposed rebar
  - 30% in state 3: some rebar corrosion but insignificant section loss
  - 15% in state 4: advanced deterioration

Example: Transition Probability Matrix

- Concrete box girders, no action (probability in %)

State in this year	State 2 years later			
	1	2	3	4
1. No deterioration	94	6	0	0
2. Minor cracks and spalls, No exposed bar	0	79	21	0
3. Rebar may be exposed, Insignificant section loss	0	0	55	45
4. Advanced deterioration	0	0	0	100

Environments

- Benign
  - Neither environmental factors nor operating practices are likely to significantly change the condition of the element over time or their effects have been mitigated by past non-maintenance actions or the presence of highly effective protective systems
- Low
  - Environmental factors and/or practices either do not adversely influence the condition of the element or their effects are substantially lessened by the application of effective protective systems

Environments (cont'n)

- Moderate
  - Any change in the condition of the element is likely to be quite normal as measured against those environmental factors and/or operation practices that are considered typical by the agency
- Severe
  - Environmental factors and/or operating practices contribute to the rapid decline in the condition of the element. Protective systems are not in place or are ineffective

Deficiencies Considered by Improvement Model

- Load-carrying capacity
- Clear deck width
- Vertical clearance

User Cost Model

$$U = A + O + T$$

A: Accident cost

O : Vehicle operating cost

T: Travel time cost

Summary of Approach

The basic approach to development of Pontis is built on several simple but new ideas:

1. Separate MR & R decisions from improvement decisions
2. Divide the network of bridges into a reasonable number of elements, the sum of which would describe all bridges in the network
3. For each element define a homogeneous unit and specify a set of possible conditions that the unit can be in.
4. For each condition state define an appropriate set of feasible actions

Summary of Approach (Cont'n)

5. Define "environment" in such a way that interactions among elements (if any) can be addressed
6. For each bridge specify the percentage of each element in each condition state
7. Find optimal MR & R policies for each unit, and then bring the policies together to find optimal MR & R actions for each bridge
8. Use a separate optimization procedure to find the optimal set of bridges that could be chosen for each MR & R budget (if necessary), and their priority orders

Summary of Approach (Cont'n)

9. Use functional deficiencies, or instances of failure to meet level-of-service standards, in order to find candidates for "improvement" actions
10. Use reduction of user costs as a basis of determining the benefits of carrying out improvements for each candidate bridge
11. Use an optimization procedure to find the optimal set of bridges that should be improved for each improvement budget (if necessary), and their priority orders

Summary of Approach (Cont’n)

12. Bring all actions specified for MR & R and improvement for a bridge together, calculate the total benefit of recommended actions on the bridge, and find its priority code
13. Integrate all actions and budget requirements to specify the current work plan
14. Simulate traffic growth and deterioration of components to estimate budget needs in the future, and for every budget scenario find the future backlog and network conditions

Impacts

- Adopted by 48 States
- Fundamentally changing all aspects of :
  - information gathering
  - information processing
  - MR & R decisions
  - Federal funding allocations

- Defensible 10-year need forecasts for legislature (California, Minnesota, Vermont)

- Cost savings and rational improvement

- Elimination of backlogs in California

- Adoption by other countries:
  - Finland
  - Portugal ?
  - Hungary

Integrated Infrastructure Management for City of Beijing

Problems

- Non uniform construction
- Deteriorating infrastructure
- Olympics pressure
- Lack of records
- Haphazard budget allocation
- Lack of coordination
- Unfamiliarity with standards

Advantages

- Motivation
- Central authority
- Little or no infighting
- Visibility

Networks

- Gas pipes
- Heating pipes
- Streets
- Water pipes
- Sewage
- Electrical lines

Modeling Issues

- Individual departments
- Sensitivity in coordination
- Central budget allocation
- Observed vs. estimated conditions
- Non uniformity of segments
- Segment definition

Modeling Approach

- 6 coordinated Markovian models
  - Similar to TUBIS
- Coordinated by Super-TUBIS type system
- Units defined by vectors of attributes
  - Unit size: a street block