



OPTIMIZING INFRASTRUCTURE INVESTMENTS FOR THE 21ST CENTURY

| OCTOBER 2009 |



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**OPTIMIZING INFRASTRUCTURE INVESTMENTS
FOR THE 21ST CENTURY**

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America annually invests hundreds of billions of dollars in infrastructure, but as a fraction of GNP, America is one of the lowest among developed nations. The Obama Administration has signaled increasing infrastructure investment as a high priority with the recent passage of the American Recovery and Reinvestment Act of 2009. Rationally allocating such funds is constrained by long-standing, ingrained practices such as “earmarks” for special projects, “trust-fund” single-purpose financing of some infrastructures (e.g., roads) and the absence of such funds for others (e.g., drinking water), formulaic allocation of block grants, and the absence of a central clearing point or standard metrics for essential comparisons. Regardless of which policy and institutional reforms emerge, decisions about priorities and resource allocation to specific investment projects cannot be made in the absence of a consistent, risk-based, transparent, quantitative methodology that permits direct comparison of the value, costs, risks, and resilience among investment opportunities.

ASME Innovative Technologies Institute, LLC, convened an expert Working Group on Infrastructure Investment to conduct a pre-design study to determine the feasibility and principal directions for developing the needed investment selection methodology. This report specifies design criteria and an analytic portfolio optimization approach built upon investment valuation of interdependent infrastructure assets. It provides the organizing paradigm for developing a concrete methodology to set priorities and select an optimal collection of infrastructure investments, a process for refining and validating it and a strategy for encouraging its adoption and application. It suggests aligning the effort with a coalition of the National Research Council, several professional societies and other groups seeking to enhance the amount and rationality of funding for infrastructure for the 21st Century.

This is not the end of this project, but a mid-point assessment. Ultimately, this project will lead to a comprehensive methodology complete with implementation strategy for optimal allocation of resources to enhance infrastructure value, reduce risks and enhance resilience of the nation’s vital but aging infrastructures.



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1 | EXECUTIVE SUMMARY



THE CHALLENGE It has taken tragedy to bring public and political attention to the deterioration of America's critical infrastructure and the crying need for new systems for the 21st century. Hurricane Katrina (1800 deaths; \$150 billion in economic losses), Minneapolis's I-35 bridge collapse (killing 13; disrupting the local economy for a year) and the Northeast Blackout of 2003 (denied power to one-seventh of the U.S. population and one-third of all Canadians; with a loss of at least 11 lives and more than \$6 billion) represent catastrophes that must be avoided in the future.

Too little invested Federal, state and local capital outlays for infrastructure as a percentage of Gross National Product (GNP) have declined steadily since 1959. The U.S. currently ranks 15th among members of the Organisation for Economic Co-operation and Development (OECD) (plus India and China) in investment per dollar of GNP. The Obama Administration's American Recovery and Reinvestment Act of 2009 (ARRA) will add a meaningful increment to the recent level of federal investment, but even with the stimulus, significantly greater amounts will be required to meet the requirements of the 21st century.

Poorly allocated In addition to spending too little, however, the nation is investing too much on the wrong assets, exacerbating the underinvestment. The nation is simply poorly prepared to prioritize and select investment options in a way that optimizes the benefits of the outlays of taxpayer and ratepayer monies. Myriad bureaucratic and political schemes have evolved for distributing appropriated funds, bond proceeds and capital budgets that individually and collectively fall well short of rational allocation of public resources. The result is a massive opportunity loss as tens of billions of dollars are potentially diverted or misspent.



THE "CLIENTS" FOR A SOLUTION One of the central impediments to optimal investment in infrastructure is the "stovepiped" nature of the U.S. system for allocating infrastructure investment: from Congressional authorizing and appropriating committees through to the local spade point, infrastructures are never examined as the holistic, interdependent systems that they are.

Trade-offs across stovepipes can only be made by the "general executives," CEOs in industry, governors and mayors, and, of course, the President through their capital budgeting staffs and, by extension through the application/allocation process, the capital improvements planners who propose infrastructure investments. The "infrastructure bank" proposals being considered by Congress and the emerging regional public-private resilience partnerships could potentially add other cross-cutting infrastructure investment perspective. These considerations target the "general executives" as primary clients for the process.

PROJECT OBJECTIVE AND SCOPE ASME Innovative Technologies Institute convened a distinguished Working Group on Infrastructure Investment to design and assess the feasibility of a methodology to address the investment decision-making aspect of the challenge.

The initial scope specified a risk/resilience management process for aging infrastructure. Early in the project, however, this scope was recognized as being too narrow. Examining aging infrastructure alone could result in re-building the 20th century infrastructure instead of providing for the needs of the 21st century. Accordingly, the scope was broadened to designing and determining the feasibility of an *objective, transparent methodology for valuing and selecting investments in both new and renewed infrastructure that would rationalize and optimize the infrastructure portfolio*. To support decision-making at the general executive levels, the methodology must apply to and permit direct comparisons among virtually any infrastructure facility or system, permitting holistic optimization.



A FEASIBLE, TRANSPARENT SOLUTION

Feasibility of the methodology is demonstrated by defining a series of *essential design specifications* and outlining a comprehensive analytic process that integrates *existing techniques* – requiring no major methodological discovery or invention – into a holistic, transparent, objective and defensible approach that meets all the specifications.

Financial vs. infrastructure portfolio optimization

The methodology is defined by analogy to financial portfolio optimization. *Table 1* below shows the conventional financial portfolio approach, the approach adapted for infrastructure investments and the analytic tools required. Financial portfolio optimization must be adjusted for application to real (non-financial) critical infrastructures, e.g.:

- Assuring objectivity and direct comparability of investment options regardless of type, by establishing a common set of definitions, metrics, scenarios, analyses and selection/optimization processes;
- Defining infrastructure value more broadly than most financial portfolios, as a multi-attribute objective that includes not only cost-effective provision of needed infrastructure services, but also the investments' contribution to other major challenges facing the nation, i.e., global competitiveness, energy independence, sustainability, safety and resilience to disruptions, and national security;
- Conducting the analysis from the respective perspectives of *both* the infrastructure *owner* and the *public* to identify when the business case alone justifies the investment and when major issues of externalities and public goods call for greater participation by public agencies;
- Including risk and resilience analysis as an integral part of the assessment, thereby addressing the issue of aging infrastructure as well as encouraging security-by-design and resilience-by-design at the most cost-effective stages of infrastructure life-cycle, initial design of new facilities or re-design of existing facilities;
- Keeping the general approach relatively simple, direct and credible enough to be applied by engineering, analytic and planning staffs and the decision-makers they support – whether private sector or state and local government infrastructure owners – with a minimum of outside expertise or training, using data that are readily available.

Table 1. Summary of the Financial vs. Infrastructure Portfolio Optimization Processes

Process for Financial Assets	Process for Infrastructure Assets	Required Tools
<p>1. Develop strategic goals and plan. Define:</p> <ul style="list-style-type: none"> a. Strategic and operational objectives & their relative priorities; b. Constraints, e.g., budget total, geographic “balance,” product lines, etc. c. Valuation metrics to measure objectives and constraints. 	<p>1. <i>Same.</i></p>	<p>Analytic Hierarchy Process (AHP)</p>
<p>2. Value <i>existing</i> portfolio relatives to strategic and operational objectives – gap analysis of value, risk: existing dependencies – from owner’s perspective</p>	<p>2. <i>Same</i>, except from <i>both</i> owner’s and public’s perspectives “dual perspective,” below.</p>	<p>Regional Input-Output Model OR Regional Systems/Economics Model</p>
<p>3. Assess new financial investment opportunities individually – full value, risk, performance relative to objectives</p>	<p>3. <i>Same</i>, but dual perspective with full multi-attribute value, risk, resilience, etc. – public <i>and</i> owner</p>	<p>Engineering-Economics Model</p>
<p>4. Estimate correlations among existing & new assets or with market as whole (covariance or “beta”)</p>	<p>4. <i>Same</i>, but estimate physical interdependencies among existing & new assets – unintended consequences, cascades & systemic failures</p>	<p>Regional Input-Output Model OR Regional Systems/Economics Model</p>
<p>5. Optimize investment portfolio – efficient frontier; <i>maximize</i> value at acceptable risk level, within budget & other private constraints (performance, “balance,” lines of business, etc.)</p>	<p>5. <i>Same</i>, but set aside investments private investors will make; then <i>maximize</i> multi-attribute value at acceptable risk level, within budget & other constraints (distributional balance, equity, etc.)</p>	<p>Portfolio Optimizer, either integrated with AHP OR Specially adapted to examine virtually all investment combinations</p>
<p>6. Examine constrained, optimal portfolios – owner’s perspective only – Select portfolio, invest, manage & evaluate performance for next iteration.</p>	<p>6. <i>Same</i>, but examine constrained optimal portfolios – public’s perspective only – Select portfolio, invest, manage & evaluate performance for next iteration.</p>	<p>Sensitivity analysis using any or all of the above tools</p>

Decision-maker flexibility The approach is not a “black box” that churns out definitive, inflexible “right” solutions. It recognizes that decision-makers operate amidst a variety of very real and changing constraints. Flexibility is provided to the general executive decision-maker in several ways, including:

- Establishing the goals, objectives, criteria and their relative priorities – highest level policy decisions – as the definition of value in the initial step;
- Setting overall budget levels and basic “pools” within the budget for specific purposes;
- Setting minimum levels of outlay for any proposed project or project type;
- Defining logical relationships among the candidate projects – e.g., if A is selected, B must (or must not) be selected;
- Including “distributional” constraints, e.g., a minimum levels to certain areas, jurisdictions or type of project; and
- Making final adjustments in the selection among investment options within the selected portfolio to assure support needed for acceptance of the overall program.

This flexibility does not detract from the method’s objectivity or usefulness, but enhances it by making compatible with the processes in which it must be embedded. These capabilities make it truly useful to decision-makers, enabling the coalitions necessary to assure passage while optimizing within the constraints makes it the best of all practical and feasible solutions.

OUTCOMES Introduction of a methodology that supports rational infrastructure decision-making will bring discipline to the jumble of processes by which America now makes these vital investments. It will reject “bridges to nowhere” early in the process, exposing self-serving proposals and highlight those that are sound. It will elevate emerging values of safety, security, resilience, sustainability and social equity to their rightful position as decision criteria.

In the near term The quality and consistency of infrastructure investment proposals, plans and capital budgets will rise. The reality of interdependencies and the logic connecting investment to the social benefits will be clearly defined, options will be compared, and strategic portfolios will be defined on regional and national scales.

Over the longer term The outcomes will be measured by the quality and reliability of infrastructure services provided, the spread of new infrastructure services to a growing population, reduction in the number and duration of service denials, and reduction of unit costs of the service as new, more efficient assets replace worn and obsolete ones.

The primary outcome Use of this new approach will be a marked increase in the true value of investment in new and renewal infrastructures. Regional economies will expand in sustainable, equitable ways; safety, security and resilience relative to man-made and natural events will be materially enhanced; cascading infrastructure failures will be less likely, less frequent and less widespread; and fewer “wrong” projects will absorb scarce resources. The results would vastly increase the efficiency and global competitiveness of American industry and contribute to the quality of life of all our citizens.

In brief, such an approach would bring “*more bridge for the buck, more dam for the dollar, more levee for the levy.*” It would delineate the difference between investing hundreds of billions of taxpayer and ratepayer dollars well and spending them poorly, between a significantly higher quality American infrastructure base and risking economic and social stagnation over the rest of the present century.

NEXT STEPS The opportunity to capture the benefits of enhanced infrastructure investment could quickly pass, giving rise to wasted investments, unnecessary projects and unmet needs. This report suggests a two-pronged approach for realizing these benefits:



Intellectual advocacy The first line of development is to join the coalition being developed by the Board on Infrastructure and the Constructed Environment of the National Research Council/National Academies of Science, several professional societies (including ASME), and other groups concerned about America’s infrastructure crisis. This coalition will conduct meetings and studies to advance the understanding of the nation’s infrastructure needs and to educate both the public and those in positions to begin to meet these needs.

R&D and demonstration The second line is to conduct a program of research and development (sketched in the final section of the report) to refine, detail and integrate the defined tools, pilot-testing, then demonstrating them in one or more regions, and transferring the demonstrated methodology as an essential part of any program of reform of the infrastructure investment process.

TIME IS OF THE ESSENCE Significant investments are being made and more hundreds of billions of dollars will continue to be spent, regardless of the caliber of supporting analysis or the wasted opportunities to optimize these massive investments. For the United States to capture the full benefit of these outlays, the approach advocated in this report must be completed quickly and correctly – the first time – or the opportunity will be lost. If the challenge is met, the decision-support methodology described here will transform the critical infrastructure base of the American economy for decades to come.



2 | THE CHALLENGE AND THE OPPORTUNITY

2.1 Definition of Critical Infrastructure

Executive Order 13010, signed by President Clinton in 1996, defined critical infrastructures as “so vital that their incapacity or destruction would have debilitating impact on the defense or economic security of the United States” and included “telecommunications, electrical power systems, gas and oil storage and transportation, banking and finance, transportation, water supply systems, emergency services and continuity of government.”

The U.S. Department of Homeland Security (DHS) in the National Infrastructure Protection Plan has expanded the concept to include “key resources” and added food and agriculture, health and healthcare, defense industrial base, information technology, chemical manufacturing, postal and shipping, dams (including locks and levees), government facilities, commercial facilities, critical manufacturing and national monuments and icons.¹

The Board on Infrastructure and the Constructed Environment (BICE) has argued that five “lifeline” infrastructures are the most critical because all the others depend on them for survival. These are power, telecommunications, transportation, water and wastewater systems.² This report focuses on these five, agreeing with the BICE, but expecting that the results will ultimately apply to many of the 18 sectors identified by DHS.

2.2 Consequences of Aging Infrastructures

The infrastructures of the United States provide the lifelines on which our communities and our economy depend. Many of these, however, are aging in place, imposing risks of fatalities, serious injuries and massive economic disruptions on all Americans. For example:

Highways – The vast bulk of our major highways were built in the 1950s and 1960s and have been maintained largely at the level of hot-patching even as the number of vehicles has increased enormously. (New highway construction, however, has continued.) Between 1970 and 2002, passenger travel doubled, with projected growth of another 67% by 2022. The Federal Highway Administration (FHWA) currently considers one-third of the nation’s roads to be “poor,” “mediocre” or “fair” – all three categories requiring investment. The American Automobile Association estimates that as many as 12,000 lives (of a total of 44,000) could be saved annually if highways were improved by adding lighting and guardrails and straightening dangerous curves. The Road Information Program estimated losses as much as \$220 billion a year, which includes car repairs (\$65B), congestion (\$78B) and accidents (\$77B) – the equivalent of nearly two percentage points of the national economy.

THE INFRASTRUCTURES
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¹U.S. Department of Homeland Security, National Infrastructure Protection Plan, http://www.dhs.gov/xlibrary/assets/NIPP_Plan.pdf (accessed June 2009).

²Board on Infrastructure and the Constructed Environment (BICE), Division on Engineering and Physical Sciences, National Research Council of the National Academies, “Sustainable Critical Infrastructure Systems—a Framework for Meeting 21st Century Imperatives,” (Washington, DC: The National Academies Press, 2009).

Bridges – The age of famous bridges is illuminating: New York’s Brooklyn Bridge is over 120 years old and its George Washington Bridge is 75+ years; St. Louis’s Eads Bridge is 130+; San Francisco’s Bay Bridge and Louisiana’s Huey P. Long Bridge are both 70+. The FHWA rates 13.1% of America’s highway bridges “structurally deficient” and an additional 13.6% as “functionally obsolete.” Most remain open to traffic. One of these was the I-35 bridge in Minnesota that collapsed, killing 13 people in 2007. Others were the I-95 Mianus River Bridge in Greenwich, Connecticut, where three died in 1982, and the New York Thruway Bridge near Amsterdam, N.Y., where ten perished in 1987. More than 1,500 bridges failed between 1966 and 2005, 60% due to soil erosion around the bridge supports, a potential weakness seldom checked in inspections.

Dams and Levees – Hoover Dam is 74 years old; the Wilson Dam, 84; the Grand Coulee Dam, 66; and all of the dams over the Tennessee River are more than 60 years old. The number of “high hazard” dams, whose failure would endanger human life, has increased from 9,281 in 1998 to 10,213 in 2007. In the past two years, more than 67 dam incidents, including 29 dam failures, were reported to the National Performance of Dams program. States report more than 3,500 “unsafe” dams with conditions that could cause them to fail. Seepage has been noted under the 55-year-old Wolf Creek Dam, forcing its water level to be lowered to avoid devastating failure of the dam holding the largest man-made reservoir east of the Mississippi and the flooding of Nashville and neighboring communities. Precautions came too late for the levees protecting New Orleans after Hurricane Katrina in 2005, killing almost 1,800 and making thousands refugees, many still far from returning to their homes.

Electric Power – Modern life depends on electricity. The transmission of electric power is largely based on technologies installed more than 50 years ago. From 1988 to 1998, U.S. electricity demand rose by nearly 30% while the transmission network’s capacity grew by only 15%. The Electric Power Research Institute (EPRI) anticipated that the disparity would further increase during the period 1999–2009 and projected demand to grow by 20% and system capacity to increase by just 3.5%. The Northeast Blackout of 2003, caused by human error and transmission lines contacting improperly trimmed trees, resulted in the shutdown of more than 100 power plants, denied power to 40 million Americans (one-seventh of the national population) and ten million Canadians (one-third of its national population), with a cost of more than six billion dollars. Water and wastewater plants were idled, transportation by all modes slowed to a stop, communications and industry were largely stopped and at least eleven fatalities were reported. In a CNN interview about the Blackout, Governor Bill Richardson of New Mexico, former U.S. Secretary of Energy, described the U.S. as “a major superpower with a third-world electrical grid.”³ In the 1960s and before, blackouts lasting more than a few hours were rare but by the mid-1990s, their frequency rose to yearly or greater. An EPRI survey of industry which tracked the cost of blackouts over this time indicated a rise from insignificant levels to \$100 billion/year. The White House’s National Energy Policy of 2001 suggests that the nation will need 1,300 to 1,900 new power plants in the next two decades, but this ignores the investments needed in transmission and distribution.

Water and Wastewater – Many cities, especially in the east and northwest, have water systems containing components more than 100 years old, including asbestos-cement pipes, lead pipes, even wooden pipes and storage tanks. New York City’s fresh water is transmitted through two tunnels built in 1917 and 1936 (a third will be completed by 2020 if the schedule holds). A survey by EPA found that in systems

³David Firestone, “Power Failure Reveals a Creaky System, Energy Experts Believe,” The New York Times, <http://www.nytimes.com/2003/08/15/nyregion/15GRID.html> (accessed June 2009).

that serve more than 100,000 people, about 30% of the pipes are between 40 and 80 years old and about 10% of the pipes are more than 80 years old. Some systems treat as much as 100% more water than is consumed due to high rates of leakage from old transmission and distribution pipes. The U.S. Conference of Mayors reports that more than half of a 330-city survey suffer annual or more frequent water main breaks – some as many as 50 or more per year.⁴ During the 2003 Northeast Blackout, emergency generators in New York City failed and some 30 million gallons of raw sewage were dumped into the East River. In New York and many other cities, raw sewage mixes into waterways with every significant rainstorm. Sanitary sewer overflows caused by blocked or broken pipes result in the release of as much as 10 billion gallons of raw sewage annually, according to the EPA. During blackouts, pressure drops in water mains, impeding the cooling of high-rise buildings, severely limiting the ability to control fires, and risking introduction of contaminants into drinking water.

THE CONSEQUENCES OF
AGING INFRASTRUCTURE
ARE DIRE

—
OPTIMALLY INVESTING
IN NEW, RENEWAL AND
REPLACEMENT
INFRASTRUCTURE IS A
PRIORITY.

The consequences of aging infrastructure are dire and add to the congestion costs of inadequate infrastructure capacity in parts of the country undergoing economic or population growth. Optimally investing in new, renewal and replacement infrastructure is a priority.

2.3 Recent and Near-Term Infrastructure Investment Rates

Hurricane Katrina and the collapse of Minneapolis's I-35 bridge have stimulated public awareness of the necessity for accelerated programs of new investment, replacement, rehabilitation and renewal. Most Americans are unaware of the magnitude or trends in American investment in infrastructure. In the sources cited below, the definition of investments included in “infrastructure” varies widely. Where possible, the text or figure labels will make clear what is included.

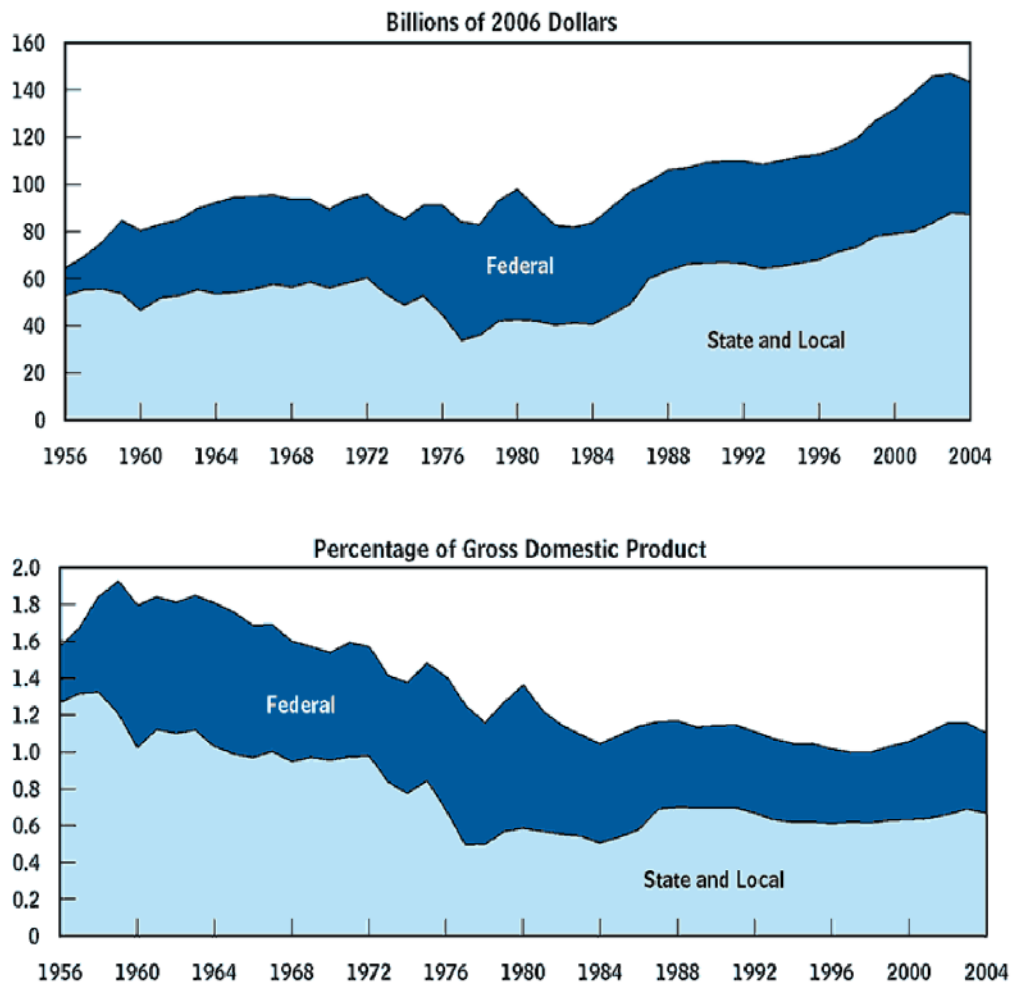
Most public infrastructure investment is focused on transportation and water, while most private sector infrastructure is focused on energy and telecommunications. Public investment in infrastructure has grown steadily since World War II (Figure 1A), but, as a portion of Gross Domestic Product, has declined more or less steadily since the late 1950s (Figure 1B).

Relative to its international competitors, the U.S. ranks 13th in infrastructure investment among OECD nations (Figure 2A). Both China and India, not OECD members, also rank higher than the U.S. This is not a recent trend. U.S. infrastructure investment has been well below the average of the leading 17 countries in every decade since at least the 1970s (Figures 2B and 2C).

In a more detailed look, capital investment by public and private sectors in selected infrastructures in 2004, the last year of complete data, totaled more than \$300 billion (Table 2), split about evenly between the public (mostly in transportation and water/wastewater) and the private sector (mostly in

⁴Richard Anderson, “National City Water Survey 2007: The Status of Asset Management Programs in Public Water and Sewer Infrastructure in America’s Major Cities,” The U.S. Conference of Mayors, September 2007, http://usmayors.org/pressreleases/documents/watersurvey_report_0907.pdf (accessed October 2009).

Figure 1. Public Capital Spending on Transportation and Water Infrastructure, 1956 to 2004
 (Source: CBO, 2008)

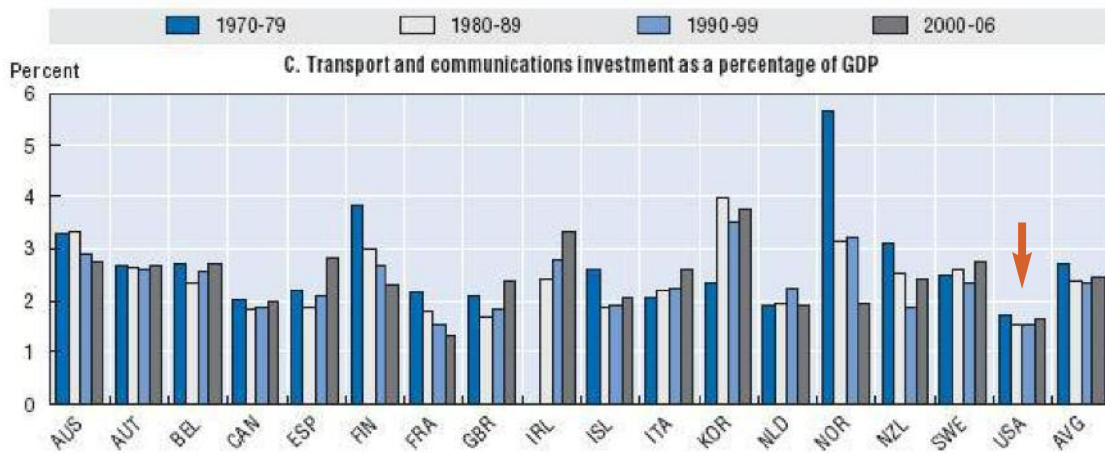
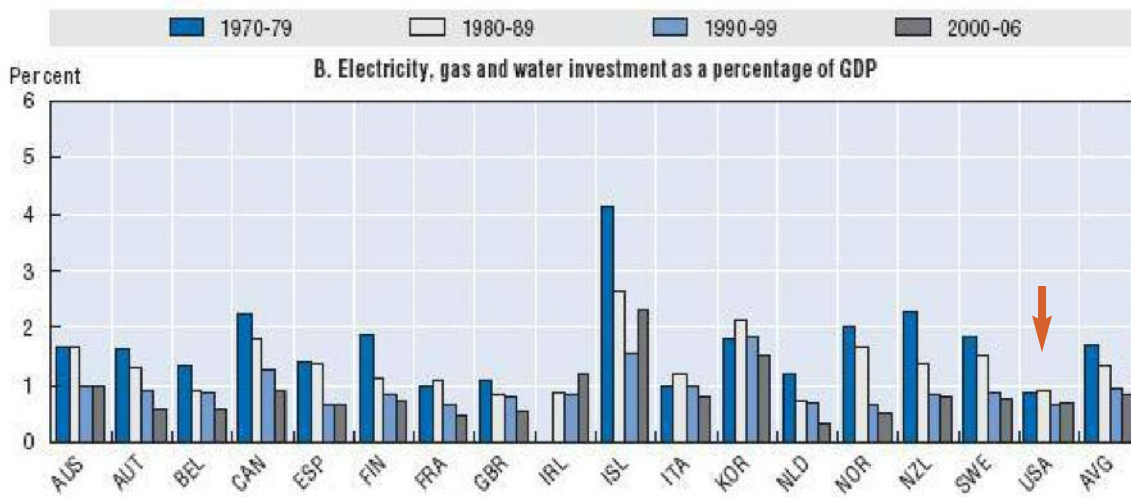
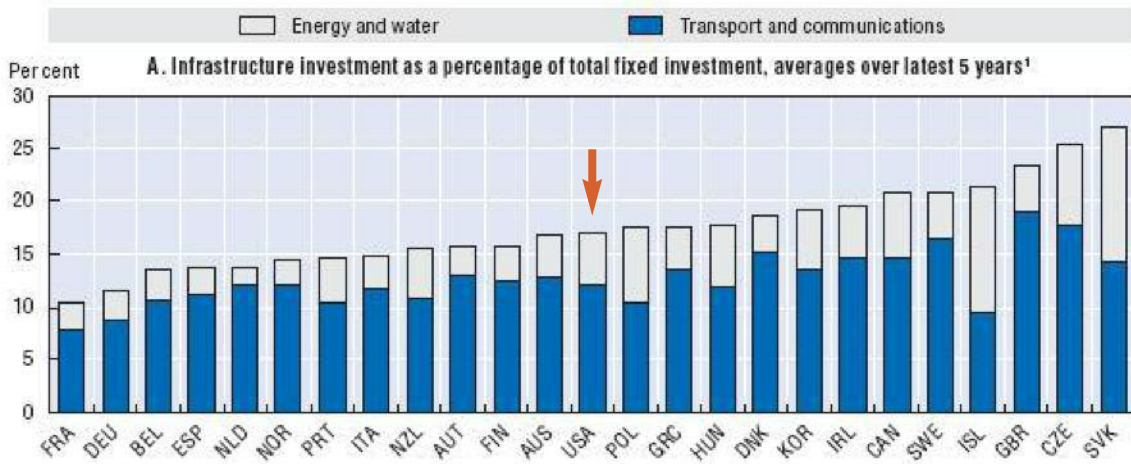


energy and telecommunications). The Federal portion, \$60.8 billion in 2004, actually declined by three percent from 2004 to 2007, but the American Recovery and Reinvestment Act of 2009 provides an increment totaling \$105.8 billion (of a total stimulus of \$787 billion⁵), by this project's definition of key infrastructures, a significant addition over the next few years. Several press accounts cited infrastructure amounts of slightly more than \$80 billion, but these appear to have ignored elements that this project includes. The Congressional Budget Office, using this apparently more restricted definition, estimates outlays in Fiscal Year 2009 of about \$9 billion (or 15%) and which rises rapid to about \$22 billion (37%) in Fiscal Year 2010 and \$24 billion (41%) in Fiscal Year 2011, declining gradually through Fiscal Year 2018 (Figure 3).⁶

⁵For details see www.recovery.gov.

⁶Congressional Budget Office, Director's Blog, Thursday, April 30, 2009, <http://cboblog.cbo.gov/?cat=20> (accessed July 2009).

Figure 2. U.S. Infrastructure Relative to Other OECD Nations
 (Source: OECD, Going for Growth 2009)



2.4 The Costs of Renewal or Replacement

In brief, vast sums of money are being and will be invested. The American Society of Civil Engineers (ASCE), however, has judged that it will not be nearly enough, estimating that \$2.2 trillion dollars will be required to restore U.S. infrastructure to a sound level.⁷ Some examples illustrate this pressing need:

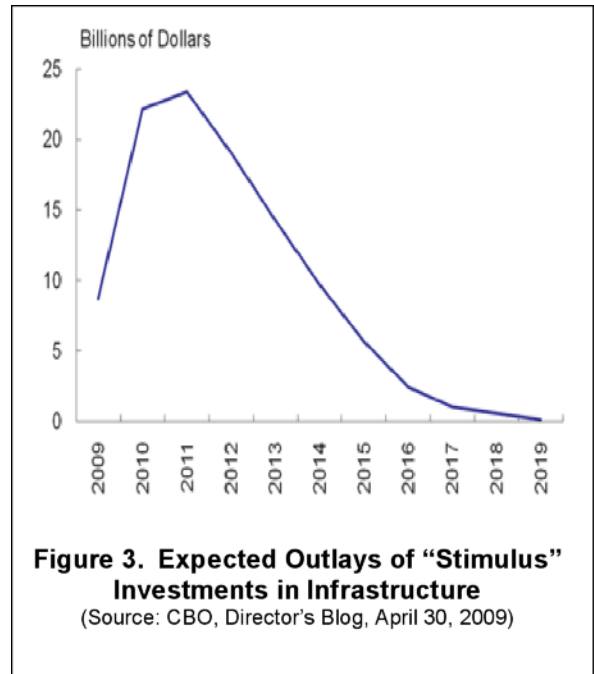
Highways – The American Association of State Highway and Transportation Officials, Federal Highway Administration and ASCE all point to the need for massive increases in capital outlays by all levels of government to reach the cost-to-maintain level, and roughly double that to reach the cost-to-improve level. ASCE is calling for \$186 billion annually, which compared to current actual outlays, is well below even maintenance level.

Bridges – ASCE estimates that it will cost \$17 billion per year over 20 years to eliminate bridge deficiencies compared to the \$10.5 billion currently being spent by all levels of government.

Dams and levees – ASCE estimates the cost of restoring American dams to safety is \$12.5 billion and another \$100 billion is needed to repair and rehabilitate U.S. levees.

Electrical Power – ASCE estimates that \$1.5 trillion in new investments will be needed by 2030.

Water and Wastewater – For drinking water, EPA estimates potential funding gaps as high as \$263 billion by 2019. For wastewater, EPA and ASCE estimate \$390 billion is needed over the next twenty years to replace existing wastewater infrastructure systems and to build new ones.



⁷American Society of Civil Engineers, “2009 Report Card for America’s Infrastructure,” http://www.infrastructurereportcard.org/sites/default/files/RC2009_full_report.pdf (accessed June 2009).

Table 2. Capital Spending on Infrastructure in 2004 and ARRA, by Category
(Billions of dollars; columns may not add due to rounding)

	Public ⁸		Total ⁸		Total	ARRA 2009 ⁹
	Federal	State	Public	Private	Public/Private ⁸	
Transportation						
Highways	30.2	36.5	66.7	n/a	66.7	27.5
Mass Transit	7.6	8.0	15.5	0	15.5	8.4
Railroads	0.7	0	0.7	6.4	7.1	9.3
Aviation	5.6	6.8	12.4	2.0	14.4	2.1
Water Transportation	0.7	1.7	2.4	0.1	2.5	0.2
Total Transportation	44.7	53.0	97.7	8.5	106.2	47.5
Water/Wastewater	2.6	25.4	28.0	n/a	28.0	7.4
Energy	1.7	7.7	9.4	69.0	78.4	36.8
Telecommunications	3.9	n/a	3.9	68.6	72.5	7.2
Pollution Control and Waste Disposal	0.8	1.8	2.6	3.6	6.2	0.8
Water & Natural Resources	7.1	4.3	11.3	n/a	11.3	6.1
Total, Non-Transportation	16.1	39.2	55.2	141.2	196.4	58.3
Total	60.8	92.2	152.7	149.7	302.6	105.8

⁸Peter R. Orszag, Director, Congressional Budget Office, "Investing in Infrastructure," Testimony before the Committee on finance, U.S. Senate, July 10, 2008, obtained from <http://www.cbo.gov/ftpdocs/95xx/MainText.1.2.shtml>, accessed on June 22, 2009. The original table included investments for schools (\$99.7 billion), prisons (\$2.9 billion) and postal facilities (\$0.9 billion), for a total of \$406.1 billion. These were deleted as not being parts of the infrastructures of interest in the present report. *The entries in the first five columns are in 2004 dollars.*

⁹Interpreted from U.S. Congress, House Committee on Appropriations, "Summary: American Recovery and Reinvestment – Conference Agreement," February 13, 2009. *The entries in this column are in 2009 dollars.*

2.5 Interdependencies among Infrastructures

Valuation of infrastructure investments is complicated by the dependencies and interdependencies among the constituent system elements of some infrastructures (e.g., the electricity system of power plants, substations, and transmission and distribution lines; the transportation system of ports, rail, barges, roads, highways, airports, bridges and tunnels; water storage dams and water supply).

Interdependencies also exist between infrastructures, such as:

- Cooling of power plants uses about 40% of the fresh water withdrawals, as much as all the nation's irrigation requirements;
- Water-related energy requirements are reported in California to account for 19% of all power generated in the state;
- The Northeast Blackout of 2003 and Hurricane Isabel of 2005 illustrated how loss of electricity can cause loss or diminution of communications, water and sanitation services, automotive fuel pumping, rail transportation, traffic control, food distribution, building cooling, fire protection, hospital services and numerous other life-essential services – even power generation itself where cooling water relies on electrically powered pumps;
- The failure of one infrastructure in New Orleans, the levee system, caused the near total collapse of all the infrastructures – indeed, of basic human viability – following Hurricane Katrina.

Such interdependencies can and do result in “cascading failures.” These interdependencies make it difficult for decision-makers in the responsible institutions and organizations to consider all the consequences as they decide where to allocate their severely limited funds

**SUCH INTERDEPENDENCIES
CAN AND DO RESULT IN
“CASCADING FAILURES.”**

for infrastructure replacement and restoration. Often, whole metropolitan areas or even multi-state regions can be impacted by a single failure, such as a poorly trimmed tree in the wrong place. The interactions among infrastructures necessitate a “system-of-systems” analytic approach in which the assets and networks of each infrastructure are assessed in the context of their consequences on all the impacted infrastructures and communities.

2.6 Infrastructure Investment Decision-Making

Infrastructure investment is a major societal challenge but the United States is currently ill-equipped to make the needed priority and resource allocation decisions. Rationally allocating such funds is complicated by long-standing, ingrained practices – “earmarks” and “pork-barrel” funding for special projects (some necessary, others perhaps less so); “trust-fund” single-purpose financing of some infrastructures (e.g., roads) and the absence of such funds for others (e.g., drinking water); formulaic allocation of block grants based on criteria at best loosely related to infrastructure requirements on the ground. Congressional committees and subcommittees authorize and appropriate funds that flow directly to specialized Federal agencies and from there, often to state and local specialized agencies, creating “stove-pipes” from funds source to sink, from concept to spade tip, without any challenge of comparative assessment of the

benefits and costs of the investments. The absence of a central clearing point or set of standard metrics makes essential comparisons for rational optimization impossible.

Powerful vested interests have a stake in maintaining the current jumble of allocation schemes because they are in the position to exercise power, take credit, and/or receive funding. Starting with Congressional earmarks and horse-trading, through trust funds and federal agency formula grants, clear through to state and local elected and appointed officials' final decisions, there is little or no comprehensive, comparative analysis of value, sustainability, risk or resilience of potential infrastructure projects. Availability of a competent, standardized technology for valuing and prioritizing infrastructure investments would permit the adaptation of existing processes to provide a more rational analytic underpinning and more nearly optimal allocation of investment funds.

Further, there are few incentives for the needed design and advocacy to be undertaken. Infrastructures are, almost by definition, networked and highly interdependent, so an improved valuation and selection method requires contributions from diverse disciplines and industries that seldom collaborate, making it unlikely that the needed research will be undertaken without Federal support.

To date, the combination of political and functional barriers has resulted in there being no comprehensive, comparative method for rationally undertaking these critically important decisions. Politically robust forces benefit materially from the current jumble of allocation processes and the requirements for constructing new, more competent methods cover too broad and diverse a set of disciplines to be feasible in the absence of a concentrated Federal effort. The opportunity cost of continuing with the present system will be enormous as the nation rushes to make investments that will entail jobs, while potentially wasting tens or hundreds of billions of dollars.



**“WE ARE BOTH UNDER-
INVESTING IN INFRASTRUCTURE
AND INVESTING IN THE WRONG
PROJECTS: NEW INVESTMENTS ARE
CRITICALLY NEEDED, BUT WE LACK
THE POLICY STRUCTURES TO MAKE
THE CORRECT CHOICES AND
INVESTMENTS.” – CSIS, 2006**

According to a distinguished bipartisan commission convened by the Center for Strategic and International Studies (CSIS) that included two sitting Senators, two former Senators, three sitting governors and a number of former cabinet members and ambassadors, “America’s economic well-being and physical security depend on safe and reliable ... infrastructure ... But we are both under-investing in infrastructure and investing in the wrong projects: new investments are critically needed, but we lack the policy structures to make the correct choices and investments... A

centralized infrastructure project approval process would force all infrastructure modes to be evaluated using common methods and parameters” (emphasis in original).¹⁰ The commission was not specific as to a particular set of “common methods and parameters.” Establishment of objective, transparent methods that use “common methods and parameters” that yield directly comparable estimates of benefits

¹⁰Center for Strategic and International Studies Commission on Public Infrastructure, *Guiding Principles for Strengthening America’s Infrastructure*, 2006.

and costs of alternative investments is the sine qua non of rational allocation of limited resources.

Rehabilitating or renewing aging infrastructures often yields little near-term revenue or profit to companies and seldom reflects great credit on public officials faced with competing, more visible demands. Strong incentives encourage deferral of these investments. Accordingly, investment in older infrastructures lags behind the rate of deterioration. Conversely, most new infrastructure development conspicuously adds local employment, so tends to highlight politicians who can take credit, accounting for much of the “earmarking” for favored projects. Ribbon cutting for new, highly visible facilities attracts far more media attention than rehabilitating or upgrading existing structures.

The diversity among the infrastructures and the complexity of the interdependencies among them encourage decision-makers to evaluate their investment options from their own very limited perspective, even though the full consequences may have very far-reaching effects. Each infrastructure sector and each operator may use any perspective, methodology, metrics or level of rigor it chooses, within only broad guidelines, often prescribed by the oversight or funding authority. Numerous criteria and metrics for valuing benefits and costs are used, and usually, no attempt is made at optimizing the allocation of the resource base for aging infrastructures. Across all infrastructures, local to national in scale, this results in an absolute inability to compare one project’s benefits or costs to competing project opportunities. At best, resource allocation decisions can be “sub-optimized” as each oversight or funding authority, functional agency, utility operator or company makes its choices by its own criteria within its own “stove-pipe.” The overall national infrastructure portfolio cannot be optimized in any sense, so scarce resources are expended for less benefit than a more comprehensive approach could accomplish.

2.7 Calls for Solutions

Both the private sector and Federal, state and local governments have noted the need for prompt, prudent action. The National Infrastructure Development Bank Act of 2009 (H.R. 2521) has been re-introduced in the 111th Congress. Similar legislation passed the Senate in the 110th Congress. This legislation’s purpose is to “facilitate efficient investments and financing of infrastructure projects and new job creation.”¹¹ Among its provisions is: “(A) IN GENERAL- The Bank shall conduct an analysis that takes into account the economic, environmental, social benefits, and costs of each project under consideration for financial assistance under this Act, prioritizing projects that contribute to economic growth, lead to job creation, and are of regional or national significance” (Section 10). The bill goes on to establish specific criteria for project proposals in transportation, environmental protection, energy, and telecommunications, all or several of which have in common such things as job creation, inequality and poverty reduction, reduction of carbon emissions, and the application of new technologies.

The distinguished, bipartisan CSIS commission, quoted above, set in motion the formation of Building America’s Future (BAF), co-chaired by Governors Schwarzenegger (R-CA) and Rendell (D-PA) and Mayor Bloomberg (Independent – New York City). BAF is seeking a new vision to strengthen our nation’s infrastructure while promoting job creation, economic growth and sustainability. Elected officials from all over the country at all levels of government are beginning to understand the importance of this vital national endeavor. BAF stresses the need for a cogent national policy on infrastructure that focuses on revitalization, economic competitiveness, and reduced dependency on foreign oil.¹²

¹¹National Infrastructure Development Bank Act of 2009, <http://www.govtrack.us/congress/billtext.xpd?bill=h111-2521>, (accessed June 2009).

¹²Building America’s Future, <http://www.investininfrastructure.org/about>, (accessed June 2009).

The movement is growing. The Urban Land Institute (ULI), along with Ernst & Young, recently published a report calling for action on this pressing national need. While supporting many of the same recommendations as BAF, ULI recommended that “the White House should consider setting national goals and managing objectives through a high-level infrastructure czar and/or commission.”¹³ The current spending stimulus and resource allocations only address “a small fraction of what will be needed over the next two decades.”¹⁴ In a separate study, Ernst and Young concluded that “impact of aging or inadequate infrastructure” ranked third among risks for commercial real estate, after only the “credit crunch” and “global economic and market conditions,” and higher than such threats as the “global war for talent” and climate change.¹⁵ With credit crunches and revenue shortfalls at state and local levels, a rational infrastructure investment plan will need to be implemented for any legitimate long-term improvements and benefits.

These voices are not alone. Infrastructure investment is likewise a critical concern for organizations such as America 2050¹⁶ and the National Governors Association.¹⁷ As Judith Rodin, President of the Rockefeller Foundation commented:

*We can build 21st century infrastructure and create jobs in the process. We can mitigate the climate change we're causing, and develop clean, reliable, renewable, sustainable energy supplies. We can build stronger resilience so people aren't left vulnerable to the wrath of a world that we know will continue warming no matter how many Hummers are traded in for Priuses. And so we must. We must do all these things in a way that widens the circle of opportunity.*¹⁸

Title IX of the 9/11 Commission Recommendations Act requires establishment of a system of national standards, accreditation and certification to encourage business continuity (in infrastructure, another name for resilience). The Alfred P. Sloan Foundation has mounted a major program to encourage continuity and resilience. The American Society for Industrial Security, the International Standards Organization, the American National Standards Institute Homeland Security Standards Panel, and other groups are working to establish an environment in which security, continuity, resilience and risk management are commonplace. Independent advisory panels to the President and to the Secretary of Homeland Security in the last administration endorsed resilience as a national objective, an initiative also advanced by Business Executives for National Security.

**A CONSENSUS CLEARLY EXISTS
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INFRASTRUCTURE IS NEEDED AND
THAT SECURITY AND RESILIENCE
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CRITERIA.**

A consensus clearly exists¹⁹ that more investment in infrastructure is needed and that security and resilience should be among the design criteria. The Obama Administration has included in its economic stimulus package the largest incremental investment in infrastructure since the creation of the

¹³The Urban Land Institute and Ernst & Young, *Infrastructure 2009: Pivot Point*, (Washington DC, The Urban Land Institute, 2009), p. 6.

¹⁴*Op. cit.*, p. 7.

¹⁵Sibley Fleming, “E&Y Ranks Top 10 Business Risks for Commercial Real Estate,” National Real Estate Investor, April 8, 2009, Penton Media Inc., located at http://enews.penton.com/enews/nrel/newsline_/2009_04_08_04082009/view.html, accessed.

¹⁶America 2050, <http://www.america2050.org/infrastructure.html>, (accessed July 2009).

¹⁷Darren Springer and Greg Dierkers, National Governor's Association, *An Infrastructure Vision for the 21st Century: Strengthening our Infrastructure for a Sustainable Future*, (Washington DC, NGA, 2009).

¹⁸Judith Rodin, “Philanthropy's Role: Supporting a Bold, 21st Century Infrastructure, Agenda America 2050 Forum,” (speech, The Woodrow Wilson Center, Washington DC, Friday, May 9, 2008).

¹⁹Luntz Maslansky Strategic Research Analysis, “Building America's Future National Survey of Registered Voters,” January 5, 2009. Summary memo at <http://www.investininfrastructure.org/Websites/investininfrastructure/Images/LuntzWebsiteMemo.pdf>

interstate highway system under Dwight D. Eisenhower. The Administration's budget proposal adds still more funding and advances controversial new appropriations processes. These billions of dollars for roads, bridges, water systems, etc., are only the beginning if the nation is to restore its fraying infrastructure to the capability required for economic health and global competitiveness in the 21st century.

The National Research Council's (NRC) Board on Infrastructure and the Constructed Environment (BICE) has recently issued a report by distinguished infrastructure experts that addresses critical infrastructure requirements for the 21st century.²⁰ The report focuses on "lifeline" systems – those which provide water, wastewater, power, mobility and connectivity (communications) services – without which buildings, emergency response systems, dams, and other infrastructure cannot operate. Sustainability is broadly defined to mean systems that are able to meet the needs of current and future generations by being physically resilient, cost-effective, environmentally viable, and socially equitable.

Major findings of the report include:

- The United States does not have a vision or concept of or stated objectives for the future configuration, level of performance, or level of services that critical infrastructure systems should provide;
- The United States has not yet fully considered how critical infrastructure system renewal can be leveraged to help meet other national challenges, especially economic competitiveness, global climate change, national security, energy independence, and disaster resiliency;
- Power, transportation, water, and telecommunications are the basis for producing and delivering goods and services that are central to economic competitiveness, emergency response and recovery, and quality of life.

THE UNITED STATES DOES NOT HAVE A VISION OR CONCEPT OF OR STATED OBJECTIVES FOR THE FUTURE CONFIGURATION, LEVEL OF PERFORMANCE, OR LEVEL OF SERVICES THAT CRITICAL INFRASTRUCTURE SYSTEMS SHOULD PROVIDE.

Renewing and updating the nation's critical infrastructure systems to help meet 21st century imperatives is a radically different task from that of building new systems across undeveloped territory. A comprehensive and coordinated renewal effort must account for the network of existing (legacy) systems and a number of underlying issues:

- Their interdependencies;
- Who owns them;
- How they are financed; and
- The level of public support for investment.

²⁰*Op. cit.*

A number of recommendations are proposed in the report, urging America's decision-makers to:

- Think about critical infrastructure more holistically, in terms of the services that these systems provide—water, wastewater removal, power, mobility, and connectivity – and as part of a strategy for meeting other national imperatives;
- Seek new approaches, strategies, and ideas for providing and financing infrastructure-related services; and
- Employ new technologies and materials as an investment in the nation's future.

A solution framework is suggested to create an environment for developing short- and long-term solutions to complex issues involving a multitude of stakeholders. Such a framework can help establish public expectations about the reliability, resiliency, efficiency, and cost of critical infrastructure systems and can guide action toward solutions that are physically resilient, socially equitable, cost-effective, and environmentally sustainable.

The essential components of the needed framework can be summarized as follows, to quote:

- *A broad and compelling vision* that will inspire individuals and organizations to pull together to help meet 21st century imperatives by renewing the nation's critical infrastructure systems. Such a vision would focus on a future of economic competitiveness, energy independence, environmental sustainability, and quality of life, not a legacy of concrete, steel, and cables.
- *A focus on providing the essential services involving water and wastewater, power, mobility, and connectivity*—in contrast to upgrading individual physical facilities—to foster innovative thinking and solutions.
- *Recognition of the interdependencies* among critical infrastructure systems to enable the achievement of multiple objectives and to avoid narrowly focused solutions that may well have serious, unintended consequences.
- *Collaborative, systems-based approaches* to leverage available resources and provide for cost-effective solutions across institutional and jurisdictional boundaries.
- *Performance measures* to provide for greater transparency in decision making by quantifying the links among infrastructure investments, the availability of essential services, and other national imperatives.²¹

Across all these groups, the clear message is that money is not the only requirement for turning American infrastructure around.

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INFRASTRUCTURE AND MISSING A HUGE
OPPORTUNITY TO GET IT RIGHT.

²¹BICE, *op. cit.*, p. S-4.

A major systemic shortcoming exists in the way we decide on infrastructure investments. But no industry group, professional society, research organization, blue ribbon panel, or coalition has developed a methodology for consistent, rational infrastructure investment valuation and selection. *The United States is currently ill-equipped to make the needed priority and resource allocation decisions, so we risk spending trillions of dollars over the coming decades on the wrong decisions, buying the wrong infrastructure and missing a huge opportunity to get it right.*

THE METHODOLOGY SHOULD FOCUS SQUARELY THE CONSEQUENCES OF INACTION VERSUS THOSE OF INVESTING IN ALTERNATIVE SOLUTIONS.

The U.S. Department of Homeland Security has established a National Infrastructure Simulation and Analysis Center (NISAC) at Sandia National Laboratories, funded in the tens of millions of dollars annually to model infrastructures, with an emphasis on interdependencies. Its models have been used to respond to high-level requests for analysis, but have not been made available to

infrastructure decision-makers outside the program. One of the NISAC models, the Critical Infrastructure Protection/Decision Support System (CIP/DSS), is chartered to build a capability that sounds much like the one advocated below. The managers of CIP/DSS, however, have determined to build a model that requires a super-computer to run and massive quantities of sensitive data that would be unavailable for outside use – all factors that make it ill-suited to meet the practical needs of decision-makers at the national, state and local levels.

Time is of the essence. Unless the necessary methodology is developed and disseminated quickly, the United States will miss the opportunity to harvest full benefit from its vast investments in renewal and new infrastructure. A number of barriers – tradition, power relationships, personal perquisites, diversity and number of needed disciplines – militate against the task of designing and promoting suitable methodology being undertaken, or, if undertaken, having the desired outcome. The sole solution is a concentrated Federal commitment.

ASME-ITI has taken the initial step of organizing a panel of experts to define the needed methodology and the R&D to develop it. However, if this project is to be successful, it cannot be “owned” by any single organization. It will require a broad coalition of organizations and groups working together unselfishly to develop and implement this rational investment strategy.

The needed methodology must apply to all infrastructure investment proposals – at least those involving taxpayers’ or ratepayers’ funds – using consistent definitions, processes, criteria and metrics to yield results that are directly comparable before the fact and sufficiently operational to serve as performance evaluation criteria after the fact. Tailored versions are likely to be needed to deal with the diverse technologies, cultures and traditions of individual sectors.

The methodology should focus squarely the consequences of inaction versus those of investing in alternative solutions (the difference between them being the benefits of the investment). It should first and foremost estimate the value of the project – the probability-weighted multi-attribute objective of the investment, e.g., the expanded economic well-being of the to the asset’s owner, the local or metropolitan community, state, multi-state region, and the nation as a whole, the number of jobs created in the construction phase and supported in the operational phase, enhancements to environmental quality, quality of life. It should also estimate the level of risk (probability-weighted undesirable consequences)

and resilience (probability-weighted time to recover functionality after disruption) relative to a number of untoward hazards and the value of reducing risk and enhancing resilience. It should assess each investment opportunity in the systems context, including how it interacts with other facilities with which it is interdependent, and should consider non-structural and technological alternatives to the structural solution.

2.8 A Precedent of Note

While the prospects for institutional changes implied by a centralized process are daunting, the prospects are markedly less so for defining and developing a uniform investment-evaluation methodology, perhaps contained in a voluntary consensus standard. Even if there is little consolidation of decision-making, the application of a uniform methodological standard would advance comparability and rational selection. Transparency and consistency would encourage cross-sectoral comparisons. Decision-makers in both public and private sectors, at all levels, could at a minimum, ask the probing questions and demand cogent, transparent answers if such a standard method were widely adopted, especially if conformance assurance processes accompany the standards. Further, if progress is made in consolidating the selection process, such a methodology would be still more urgently required.

JUST A FEW YEARS AGO, A SIMILAR SITUATION EXISTED WITH INFRASTRUCTURE INVESTMENTS TO ENHANCE SECURITY AND RESILIENCE RELATIVE TO THE RISKS OF TERRORISM AND NATURAL HAZARDS.

Just a few years ago, a similar situation existed with infrastructure investments to enhance security and resilience relative to the risks of *terrorism and natural hazards*. The stakes were high, solutions costly and resources limited, requiring decision-support tools to facilitate rational resource allocation decisions within and across sectors of the economy. Myriad assessment tools were available, generally several in each sector, but there was little consistency or comparability among the tools *within* most sectors and none at all across sectors. Competing uses of security resources could not be compared so choices could not be optimized.

ASME-ITI developed a general *Framework for a Risk Assessment and Management for Critical Asset Protection (RAMCAP®)*, now evolved into RAMCAP Plus®, which has been published by ASME Press and used as the basis for an ASME voluntary consensus standard. The Framework has been complemented by a series of sector-specific versions that are consistent across sectors in terms of approach, definitions, transparency, methods and metrics, producing directly comparable estimates of risk, resilience, benefits (to the owner and to the metropolitan area) and costs of options for reducing risk and enhancing resilience.²² This has enabled direct comparison of competing alternatives in allocating resources for more secure and resilient infrastructures.

ASME is currently developing an all-sector voluntary consensus standard based on the RAMCAP Plus® process to assist in rapid and consistent application. The standard will be supported by one or more standing ASME committees of volunteer experts to keep the standard effective and up to date, including evaluating how well the process is meeting its stated purposes and any difficulties in application or new methods that could improve its performance. The standard will be updated and republished

²²The sectors and sub-sectors for which RAMCAP® sector-specific guidance have been completed are nuclear power plants, nuclear spent fuel transportation and storage, chemical manufacturing plants, petroleum refineries, liquefied natural gas off-loading terminals, dams and levees, and water and wastewater. Hazards due to supply chain disruption have recently been added to terrorism and natural hazards as a step toward assessing risks and resilience attributable to dependencies.

periodically and will be supported by training, certification and compliance assurance programs. In addition, ASME-ITI and the American Water Works Association are jointly developing a RAMCAP Plus® standard for the water and wastewater utilities, which will be consistent with all subsequent sector-specific processes and with a generic, “all-sector” RAMCAP Plus® standard, also in development. The water sector standard will also be supported by standing expert committees, training, certification and conformance assurance. These supporting activities are performed by volunteers, are self-liquidating, and have no cost to taxpayers.

This analysis of the challenges suggests a variety of desirable design features for any new investment evaluation methodology. Based on our experience with terrorism and natural hazards risk methodologies, no existing method will meet the implied criteria. These are the key questions that must be answered:

- What are the essential design requirements for an acceptable methodology for rational assessment and selection among alternative investments in infrastructure replacement, rehabilitation or renewal?
- How can such a methodology be disseminated and applied in the context of advancing technologies and emerging institutional arrangements?



3 | THE APPROACH

3.1 Commissioning the Project

The ASME Strategic Priority Grant Fund awarded a seed-money grant of \$255,000 to ASME-ITI to conduct an initial project to define the requirements and approach to developing a robust, rational methodology for evaluating the value of investing in renewal and new infrastructure. Other funding sources are expected to contribute to supporting the effort in the future if progress is being made.

ASME-ITI convened a Working Group on Infrastructure Investment made up of distinguished engineers, economists, risk analysts and infrastructure experts to define the problem and an approach to dealing with it. Issues of advanced technology (e.g., a self-healing power grid, stress and fatigue sensors, new materials) and societal policy (e.g., community and environmental benefits) will necessarily be addressed in the context of assuring the viability and effectiveness of the methodology.

3.2 Project Goal

The initial meeting of the Working Group was intended to concentrate on aging infrastructure, but the consensus of the assembled experts was that such a focus risked developing a process for repairing and rebuilding the infrastructure required for the last century, not the infrastructure needed for the present and future. Accordingly, the project goal and scope were extended to include all infrastructure investments – renewal and rehabilitation of aging infrastructure, construction of new infrastructure and full consideration of alternative technologies and alternative means of providing the essential lifeline services.

Across this expanded scope, the objective of the project is to *prepare design specifications and define an approach for a methodology to optimize a portfolio of infrastructure investments* that is:

THE OBJECTIVE OF THE PROJECT
IS TO PREPARE DESIGN
SPECIFICATIONS AND DEFINE AN
APPROACH FOR A METHODOLOGY
TO OPTIMIZE A PORTFOLIO OF
INFRASTRUCTURE INVESTMENTS.

- *Transparent in methods, data, assumptions and values;*
- *Capable of providing directly comparable estimates of value of investments in all of the five lifeline infrastructures – with expectations of being extended to most, if not all, of the 18 identified by DHS; and*
- *Effective in evaluating renewal of existing infrastructure, construction of new infrastructure and alternative means of providing infrastructure services.*

3.3 “Clients” of the Methodology

Having clarified the objective, initial clarification of the “client” for the methodology would provide a necessary perspective. With an initial focus on the five “lifeline” infrastructures identified in the BICE report – water and wastewater, transportation, power and telecommunications – one of the central

constraints on optimal investment in infrastructure is the “stovepipe” nature of the U.S. system for allocating infrastructure investment: from Congressional committees through to the spade point,

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INVEST IN INFRASTRUCTURE.

infrastructures are never examined as a holistic, interdependent whole. Trade-offs across stovepipes can only be made by the “general executives” – CEOs in industry, governors and mayors, and, of course, the President. The “infrastructure bank” and Federal capital budget proposals being considered by Congress could potentially add another cross-cutting infrastructure investment perspective.

The clients for the methodology are thus the general executives responsible for the lifeline infrastructures.

These individuals, as the final decision-makers, are supported by those who conduct the necessary analyses, e.g. the capital budgeting staff. Without adoption by the general executives and their capital budgeting staffs, stovepiped line agencies will find little or no incentive to change their methods or to adopt an approach that is more directly comparable with that of other agencies. But adoption of the new methodology will force all proposers of investment projects to use the new methods in justifying their project proposals.

Electric power and telecommunications in the U.S. are largely provided by private corporations, largely operating under charters as public utilities, while water/wastewater services are 90% provided by public agencies, and transportation is a mix of public and private organizations. This means that the needed investment evaluation methodology must be robust enough to fit not only diverse sectors, but diverse legal and incentive structures. The methodology will, therefore, need to include a generic, “all-sector” framework complemented by sector-specific versions appropriate to the respective sectors and subsectors. Any such approach should recognize that infrastructure investment decisions will increasingly be made within processes that include both public and private organizations and multiple levels of government. Indeed, if the needed finance is to be available, greater reliance on private investment and public-private partnerships is essential. If these lifeline infrastructures adopt a uniform methodology, the others will follow suit to the extent they must compete with the lifelines for capital and to the extent that institutional reform is successful.

The primary point of leverage to assure implementation is the capital budgeting staffs at each level of government and their equivalent in the private utilities and others who might invest in infrastructure. They set the ground rules that all proposers must follow and support project/portfolio selection by executive and legislative decision-makers. The White House Office of Management and Budget (OMB) and perhaps the larger states with reputations for being well-managed are the top priority target clients for the methodology. OMB sets not only the rules by which Federal agencies must prepare proposals, but also specifies the rules that must be passed down to states and localities for evaluating and selecting their grant-funded investments. If a National Infrastructure Bank is established, it will play a similar role. The Congressional Budget Office supports Congressional reviews in a similar way.

Through the years, OMB and its predecessors have been instrumental in establishing and enforcing a variety of holistic management process improvements, from Planning/Programming/Budgeting systems

of the late 1960s through a number of reforms by several administrations. Acceptance by OMB is the clear linchpin to implementation of the infrastructure investment methodology.

3.4 Design Specifications

The Working Group brainstormed about the characteristics that the desired methodology should exhibit. These ideas formed the basis for defining ten design specifications:

1. *Comparisons*: Must guide allocation of investments across all classes of infrastructure, independent and interdependent, within and across regions and possibly other classes of investment;
2. *Multi-criteria*: Valuation must accommodate a series of desired objectives for infrastructure, including efficiency and equity, sustainability, quality of life, jobs created in construction and in use, etc.;
3. *All outcomes*: Both potential upside gains and downside losses should be included in the valuation – cannot be exclusively risk-driven;
4. *Innovations*: Must permit investments in new infrastructure and new technology in the same paradigm as renewal/replacement of old infrastructures;
5. *Uncertainties*: Must capture uncertainties in the estimates;
6. *Dependencies*: Must recognize and capture dependencies and interdependencies;
7. *Comprehensiveness*: Must support both private and public decision-making – especially identifying and valuing “public goods”;
8. *Portfolio*: Must consider full portfolios of investments, in full context;
9. *Defensible*: Must be objective, transparent, consistent with accepted norms, produce directly comparable estimates of value, cost, risk, resilience, benefits, etc., for all investment options; and
10. *Simplicity and Credibility*: Must be capable of being applied by engineering, analytic and planning staffs and especially decision-makers – whether private sector or state and local governments infrastructure owners – with a minimum of outside expertise or training, using data that are readily available.

3.5 Scope of the Methodology

The methodology to be developed will provide decision-makers with the ability to review and select a portfolio of investment options within a functional regional context. It would display estimates of a multi-criterion objective function and investment and operating costs under three conditions: (1) assuming no new investments; (2) with each investment option individually; and (3) with a selected set (portfolio) of new options added to existing infrastructure. The decision tool would ultimately support an infrastructure portfolio of existing, renewed and new assets that optimize the economic, environmen-

tal and societal function of the given area (metropolitan, state, regional or national) relative to whatever budgetary and other constraints apply.

The foundation of the methodology will be an assessment of present and future infrastructure requirements of the region and individual infrastructure assets (existing or new) based on their current performance, safety and interdependencies. Investments would be justified based on improved performance for any or all of the elements in the objective function, e.g., reduced congestion or enhanced resilience. The approach would apply to all new and renewal infrastructure investment proposals – at least those involving taxpayers’ or ratepayers’ funds – using consistent definitions, processes, criteria and metrics. The results obtained would be directly comparable before the decision to invest in a given infrastructure and sufficiently operational to serve as performance evaluation criteria after the fact. Tailored versions are likely to be needed to account for the diverse technologies, cultures and traditions of individual sectors, but they must all result in directly comparable estimates of the ultimate value of a given outlay.

THE FOUNDATION OF THE METHODOLOGY
WILL BE AN ASSESSMENT OF PRESENT AND
FUTURE INFRASTRUCTURE REQUIREMENTS OF
THE REGION AND INDIVIDUAL INFRASTRUCTURE
ASSETS (EXISTING OR NEW) BASED ON THEIR
CURRENT PERFORMANCE, SAFETY AND
INTERDEPENDENCIES.

The methodology would focus squarely on the consequences of inaction versus those of investing in alternative solutions (the difference between them being the benefits of the investment). It would base the level of performance on each element of the multi-criterion objective function. It would place special emphasis on regional economic impacts, employment, sustainability, operational risk (lives, injuries, economic and financial losses) and resilience (ability to withstand or rapidly recover functionality after disruption), as well as the benefits of reduced risks, enhanced resilience and expanded economic well-being to the asset’s owner and the particular area being served, whether city, state, region, multi-state region, or nation. The methodology would assess each investment opportunity in a systems context, including how each asset interacts with others with which it is interdependent, and would consider alternatives to traditional structural solutions (e.g. wider roads) such as non-structural options (e.g., congestion pricing of highway access) or technological candidates (e.g., “smart cars” spaced safely closer by electronic means).

The approach would integrate analysis of infrastructures at four levels:

- Individual assets and facilities that are critical themselves or key elements of critical infrastructures;
- Systems of facilities and other assets that make up individual infrastructures, especially those that provide distributed services, e.g., power, water;
- Cross-system regional system-of-systems to capture dependencies and interdependencies and potential cascading failures; and
- Regional economic analysis to capture all direct and indirect impacts on regional output, income and employment, with extensions to larger systems, e.g., states, multi-state regions and the nation.

The larger regional system analysis would be needed for some decisions. For example, telecommunications, the power grid and long-haul transportation could require consideration of larger regions than merely metropolitan. The methodology must be complex enough to capture the important dimensions with acceptable accuracy, but its application in data collection, asset modeling, systems modeling, and economic analysis would need to be as transparent as possible, available for “what-if” analyses. A crucial design requirement is simplicity: the method should be able to be carried out by local personnel, perhaps with some training, rather than by experts alone. This feature will be useful to building and maintaining credibility in the face of counter-intuitive results that are bound to arise when interdependencies are analyzed on a regional scale.



4.1 Parallels and Differences between Infrastructure Real Assets and Financial Assets

All investment processes share certain necessary features. All seek to maximize value under constraints of available resources and other conditions – an optimization. Some are simple “go/no-go” decisions, but more frequently, the needed methodology is to select a collection, a portfolio, of investments. Financial portfolio optimization has been used for centuries in one form or another, but vastly refined in the last sixty years.

Financial assets (stocks, bonds, annuities, futures, options) differ from “real” assets such as infrastructure facilities in that they can generally be bought, sold or “swapped” on established, orderly markets at some price set by market forces. All such transactions can be evaluated in the common metric of money, especially as modified to incorporate time value, uncertainty and risk, meaning that they are “fungible” or readily converted from one form of wealth to another by buying and selling in markets. Real assets can sometimes be similarly fungible in that they can be sold for cash and new ones (or other investments) bought.

CONVENTIONAL FINANCIAL PORTFOLIO METHODS OR EVEN MOST “REAL ASSET” PORTFOLIO METHODS CANNOT BE USED DIRECTLY FOR THE PRESENT PROBLEM BECAUSE MOST PORTFOLIO MODELS ASSUME THE FUNGIBLE NATURE OF MONEY.

Conventional financial portfolio methods or even most “real asset” portfolio methods cannot be used directly for the present problem because most portfolio models assume the fungible nature of money. Dollar losses on one project in a portfolio can be offset by dollar gains on another; but power losses cannot be offset by water gains, just as one region’s water surplus cannot readily be “swapped” for another region’s drought. Moreover, lifeline infrastructure portfolios often cannot be valued satisfactorily in monetary terms alone (as

referenced in the design specifications). And, equitable distribution of infrastructure services matters, although equity has a very different meaning in a financial portfolio. This suggests that financial portfolio optimization can shed light on real asset portfolio optimization, but the differences between financial and real assets must be kept in mind. One of the most important of these is the necessity of valuing infrastructure investments from the dual perspectives of the owner and the public.

4.2 The Need for Dual Economics Analysis

One of the primary differences between financial portfolio analysis and infrastructure portfolio analysis is the requirement that the latter examine the proposed investments from the perspective of both the owner, where there is one, and of the public. The financial analysis represents the analysis from the perspective of the owner or investor in the infrastructure facility built or renovated with the investment funds, whether the owner is a private or public entity. (Most publicly owned utilities conduct their analyses in approximately the same way as if they were privately owned.) Because critical, especially lifeline, infrastructures provide life-sustaining services to the public, the public has a valid right to understand its interests. Usually a government agency, often the proposing agency or the general government

(mayor, governor, President) conducts an analysis from the public’s perspective. Figure 4 illustrates why this is needed.

The results of the analysis may be positive, negative, or in between (indifference) for either the owner or the public. Where the owner’s results are positive – when the business case is made – it is reasonable to expect that the owner will make the investment. If this happens, the public interest is served by the marketplace. Where these investments are made without resort to the public sector capital budget to be allocated, they should be included in the regional systems analysis but excluded from the portfolio optimization because they do not deplete the budget available for public investment.

Figure 4. Dual Economic Analyses

		The Public's Perspective		
		Public Negative	Public Indifferent	Public Positive
The PUBLIC Infra-structure OWNER	Owner Negative	No investment		Gov't pays or partners with Owner to share cost
	Owner Indifferent			Gov't provides inducement; Owner invests
	Owner Positive	Owner invests voluntarily – the business case is made – Gov't only needs to monitor		

If the owner’s assessment is negative and the public’s assessment is clearly positive, the government will need to make the investment alone or partner with the owner to share the costs. When the owner’s results are indifferent and the public’s are positive, the government may induce the owner to make the investment by providing any of a number of incentives, ranging from partial reimbursement, eligibility or preference for certain business, tax breaks of various types, etc. It may also be possible to develop coalitions of customers who would be impacted by service interruptions to compensate the owner to carry out investments that would otherwise be unattractive to the owner. An example would be if large commercial facilities that depend on sprinkler systems for fire suppression might collectively invest in water storage to maintain pressure in their systems when the public water system incurs a service interruption.

This is not always the case. The owner’s analysis may indicate a negative or indifferent result. If the analysis from the public’s perspective is also negative or indifferent, the investment simply is not made and all is well. If, however, the analysis from the public’s perspective is positive and the owner’s is indifferent or negative (the right-most column), it may indicate the existence of externalities – costs or benefits that occur, but do not enter the owner’s decision-making (e.g., industrial effluents that impose costs on near-by facilities and residences) – or the provision of “public goods” – goods or services the use of which cannot be restricted, so benefit all (e.g., national defense, many highways). These are “market failures” that can justify action by the public.

IF THE OWNER’S ASSESSMENT IS
NEGATIVE AND THE PUBLIC’S
ASSESSMENT IS CLEARLY POSITIVE,
THE GOVERNMENT WILL NEED TO
MAKE THE INVESTMENT ALONE OR
PARTNER WITH THE OWNER TO
SHARE THE COSTS.

4.3 The Process

Table 3 shows a typical financial portfolio optimization process as the series of six steps in the left-hand column, while the right-hand column lists the corresponding process for an infrastructure portfolio. The next few sections describe the portfolio analysis needed for infrastructure investments, in the order presented in this table.

Table 3. Financial Portfolio Process Adapted for “Real” (Non-Financial) Infrastructure Assets

Process for Financial Assets	Process for Infrastructure Assets
1. Develop strategic goals and plan. Define: <ol style="list-style-type: none"> a. Strategic and operational objectives and their relative weights; b. Constraints, e.g., budget total, geographic “balance,” lines of business, etc.; c. Valuation metrics to measure objectives and constraints. 	1. <i>Same.</i>
2. Value <i>existing</i> portfolio relative to strategic and operational objectives – value, risk: existing dependencies; gap analysis – from owner’s perspective	2. <i>Same</i> , except from <i>both</i> owner’s and public’s perspectives, “dual perspective,” below.
3. Assess new financial investment opportunities individually – full value, risk, performance relative to objectives	3. <i>Same</i> , but dual perspective with full multi-attribute value, risk, resilience, etc. – public <i>and</i> owner.
4. Estimate correlations among existing and new assets or with market as whole (covariance or “beta”)	4. <i>Same</i> , but estimate physical interdependencies among existing & new assets – unintended consequences, cascades & systemic failures
5. Optimize investment portfolio – efficient frontier; <i>maximize</i> value at acceptable risk level, within budget and other private constraints (performance, “balance,” etc.)	5. <i>Same</i> , but set aside investments private investors will make; then maximize multi-attribute value at acceptable risk level, within budget and other constraints (distributional balance, equity, etc.)
6. Examine constrained, optimal portfolios – owner’s perspective only – Select portfolio, invest, manage and evaluate performance for next iteration.	6. <i>Same</i> , but examine constrained optimal portfolios – <i>public’s</i> perspective only – Select portfolio, invest, manage and evaluate performance for next iteration.

4.3.1 Develop strategic plan. An overall assessment initiates the process for both financial and infrastructure portfolios. Existing strategic plans, of course, can also serve as the starting point. The organization's, jurisdiction's or region's strategy defines the goals and objectives to be pursued, the constraints to be observed on budget availability, lines of business to be provided, minimum acceptable levels of performance, and the metrics to be used to value investments and measure progress. For each objective and constraint, one or more specific metrics are defined to gauge the extent each proposed project contributes to each objective. In a financial portfolio, many of the needed metrics have been in use for so long that they are taken for granted, e.g., return on investment, financial risk, cash flows during key periods, reasonable distribution across lines of business and geographic regions. Other objectives and their metrics may be less conventional but no less valid, e.g., diversification of suppliers, equitable treatment of women and minorities, physical risk and resilience, environmental protection.

In infrastructure portfolios, the strategic plan is often occasioned by concerns about the level or safety of the infrastructure services provided, e.g., aging dams or bridges, traffic congestion, power black-outs. The temptation to deal with these issues as a series of stand-alone problems to be solved must be resisted because to do so runs two significant risks. The first is to ignore the complex, often counter-intuitive effects of interdependencies. Solving the congestion problem, for example, may encourage new suburban land development that strains the water and power infrastructures. Second, addressing each service inadequacy by "fixing" the existing infrastructure tends to replicate the infrastructure needed in the past rather than to design the infrastructure that will be needed in the future. For instance, widening a highway to reduce rush-hour congestion may ignore the option of expanding light rail to serve the same commuters and may also result in a parking crisis in the city center.

IN INFRASTRUCTURE PORTFOLIOS,
THE STRATEGIC PLAN IS OFTEN
OCCASIONED BY CONCERNS ABOUT
THE LEVEL OR SAFETY OF THE
INFRASTRUCTURE SERVICES PROVIDED.

Typically, infrastructures serve many purposes, so the strategic plan for infrastructures will often exhibit a diverse set of objectives. Appendix A contains an example of a set of possible objectives that might be considered. Of course, the seventy or so are more than are likely to influence actual decisions, so the list must be "pruned." Analytic Hierarchy Process, a decision-support technique, can be used to facilitate this pruning by a systematic process of paired comparisons to assign consistent weightings to the respective objectives. When an objective is seen to exert less than one per cent (the cut-off is set by the decision-makers) effect on the decisions to be made, that objective can be deleted from the analysis. This saves time and cost in the analysis and avoids allowing issues that cannot sway the selection decisions absorb staff or decision-makers' time. The example list was reduced to fifteen grouped into four broader groups, with the influence on project selection ranging from 1.5 % to 18.9%. This particular example resulted in the National Research Council report cited earlier.

4.3.2 Value the existing portfolio. The second step is to value the performance of the existing portfolio (before any additional investments or divestments) relative to the strategy's goals and constraints (using the metrics defined above) to see where investing in new assets and/or sales of existing ones would contribute value. In both financial and infrastructure portfolios, this serves two purposes. First, it determines whether new investment or disinvestment is needed and, if it is, the specific types of investments that should be considered, often called a gap analysis. Second, the valuation provides the necessary baseline for comparisons of the existing portfolio's value with the new portfolio's value that comes from

adding the new investments. This permits incremental analysis of the portfolio as a whole, with and without the investment. The value and risk of an individual investment option is the increments or decrements in the value and risk of the portfolio, not simply the value and risk as assessed on a stand-alone basis. This is necessary because of the interactions with other investments may synergistically add additional value or may detract from the asset's apparent value in the full system context. In a financial portfolio, risk is managed by investing in assets whose behavior is negatively correlated (i.e., when one loses value, the other gains, so the loss is minimized), so the relationships among the assets are largely statistical.

In infrastructure portfolios, the relationships among the infrastructure assets is one of physical and operational dependencies and interdependencies that can be mutually supportive or can lead to cascading failures and unintended consequences. Moreover, while the financial infrastructure portfolio is evaluated from only the owner's perspective, the infrastructure portfolio must be examined from both the owner's and the public's perspective, for reasons discussed later. A systems-engineering model is needed to simulate the interactions of the infrastructure systems to gauge the performance of the regional "portfolio" of existing infrastructure assets relative to the metrics derived from the objectives and constraints. This model does not exist at present but will be specified as an area for future work toward the end of this report.

IN INFRASTRUCTURE PORTFOLIOS, THE RELATIONSHIPS AMONG THE INFRASTRUCTURE ASSETS IS ONE OF PHYSICAL AND OPERATIONAL DEPENDENCIES AND INTERDEPENDENCIES THAT CAN BE MUTUALLY SUPPORTIVE OR CAN LEAD TO CASCADING FAILURES AND UNINTENDED CONSEQUENCES.

4.3.3 Assess new and renewal investment opportunities. In the third step, individual investment opportunities are analyzed and evaluated on a stand-alone basis with respect to the goals, objectives and constraints identified in the first step. In financial analysis, the underlying company is analyzed from its annual and quarterly reports, outside analysts' reports, and, if the investment is large enough to justify it, inspection visits at the headquarters and operating units of the company. The core discipline is to estimate the present value of future cash flows, the uncertainties involved, risks and other strategic aspects of the investment.

Infrastructure opportunities are assessed in the same general manor, estimating the present value of future flows of benefits, costs and all attributes for which metrics were derived from the goals, objectives and constraints. They are evaluated from both public and private perspectives to identify the situation when the valuation to the owner would not support investing in improvements that hold substantial value to the public in terms of vital lifeline services. This is the case of "public goods" – assets that have public benefits that cannot be captured by the owner in the marketplace, and where a widely recognized market failure justifies government action. In such instances, the public must either induce the owner to make the investment or make its own, a public investment in the asset.

In infrastructure investment analysis, a pre-screening stage preceding the detailed engineering/economics assessment is prudent. Architecture/engineering design can cost a significant fraction of the total investment and is time-consuming, so the pre-screening is conducted to gauge whether the investment

has sufficient value based on readily available information to justify the expense and time for the more in-depth analysis. No major engineering is required for the pre-screening, but qualified experts are called upon to advance reasonable estimates of the same or a subset of the criteria that will be used in the full evaluation. At this stage, many apparently attractive investment opportunities are recognized as infeasible and are eliminated from further consideration work. Those that pass the pre-screening are subjected to the full architect/engineering/economics evaluation, the results of which are passed to the fourth step.

4.3.4 Estimate the relationships among the investment options and the existing portfolio. In the fourth step, the relationships of the proposed investment, the existing portfolio and the other new investments are analyzed. In the financial portfolio, this is usually done by estimating the covariance among the assets or the correlation of the performance of the new asset with the performance of the rest of the portfolio (or, assuming wide diversification, with an overall, reference market, usually referred to as the asset's "beta," the amount of change in the asset's value per unit of value change in the market indicator.") The theory, tools and practice for assessing the financial relationships are well established and widely used. This is not yet the case with infrastructure assets or portfolios.

For infrastructure portfolios, the relationships are less statistical and more operational, accounting for the dependencies and interdependencies that can contribute to cascading failures, enhanced resilience or unintended consequences. These interactions are central to the challenge of infrastructure analysis. Several excellent models of individual infrastructure systems have been developed, e.g. for, regional traffic flows and, power grid performance, have been developed, but modeling of interdependencies among such systems is less well developed. The same systems engineering model used in the second step would be used to simulate the performance of the new asset in the context of the existing infrastructure system and estimate the changes in the metrics derived from the objectives and constraints.

FOR INFRASTRUCTURE PORTFOLIOS, THE RELATIONSHIPS ARE LESS STATISTICAL AND MORE OPERATIONAL, ACCOUNTING FOR THE DEPENDENCIES AND INTERDEPENDENCIES THAT CAN CONTRIBUTE TO CASCADING FAILURES, ENHANCED RESILIENCE OR UNINTENDED CONSEQUENCES.

As the analysis of new individual infrastructure investments options shows them to be promising in the third step, they are further analyzed in the context of the existing portfolio of infrastructures. This is done by placing them individually into the regional systems model to see their impact on the region. The true value of the asset is how it changes the value of the portfolio, not its stand-alone value only. The increment in regional well-being is the measure of the investment's value to the region. These are the values passed to the portfolio optimizer. Those investments that appear promising in this context are tried in a manageable number of combinations to see whether they have positive or negative synergies. Where new options reveal major synergies with one another, they are combined into a single proposed project and passed to the optimizer.

4.3.5 Optimize the portfolio. At a minimum, the portfolio optimizing model must be capable of maximizing the total benefit index subject to budget constraints. The usual algorithm is to maximize the investments with the highest benefit per budget dollar. Somewhat better is an optimizer that can deal with realistic constraints, including the ability to:

- Recognize fixed minimum investments that are required to be part of any solution;
- Recognize certain minimum investments that must be satisfied if the option is selected;
- Accept strategic constraints, such as a minimum geographic or product/service line distributions;
- Fund projects partially in one year and complete the funding in later periods (these are capital projects that often take more than one year to complete);
- Draw from multiple budget pools respecting each pool's purposes and constraints; and
- Manage logical combinations of projects such as mutual dependency (if one is selected then so must another with which it is associated, e.g., widening the bridge and widening the road to it).

Still more sophisticated portfolio optimizers, used when uncertainty and risk have been systematically captured, select projects that are negatively correlated with one another, so that “natural hedging” is achieved: when one investment is performing poorly, others will be performing well, offsetting any losses on the first with gains on the second.

Optimizing a financial portfolio means the maximization of value at acceptable levels of risk, within other constraints. Risk is represented variously as the estimated covariance of the investment's performance or a probability distribution of the investment's results estimated by Monte Carlo analysis, permitting the optimizer to use the full range of potential outcomes.

Financial portfolio optimization is made manageable by the fungibility of money – losses can be directly made up in gains. But, as noted earlier, *this fungibility is not present with lifeline infrastructure investments*. The point of lifeline infrastructures is the provision of services that cannot be directly exchanged for one another. Surplus drinking water does not compensate for a power outage. The portfolio optimization of infrastructure investments is correspondingly much more complex, compounded by the interdependencies among the infrastructures. The analysis using the systems model in the previous step is a compromise to deal with the absence of a portfolio optimizer that can account for interdependencies directly in the optimization process. Future infrastructure portfolio optimizers will address this shortcoming.

THE POINT OF LIFELINE
INFRASTRUCTURES IS THE PROVISION
OF SERVICES THAT CANNOT BE
DIRECTLY EXCHANGED FOR ONE
ANOTHER.

In selecting infrastructure investments from the public sector perspective, the analyst can examine the results of possible private sector investments and determine the ones for which the business case can be made for private investment. After assuring that private investors have come to the same conclusions and are planning to invest, the public sector analyst can add these investments to the systems model, but can delete them from the optimization of public funds. If private investors cannot be located to make these investments, the public sector can investigate ways to provide incentives or include these investments among those to be optimized from the public perspective.

THE RESULTS OF THE OPTIMIZATION ARE IMPORTANT AND USEFUL GUIDES TO THE FINAL DECISION, BUT ARE NOT SUBSTITUTES FOR THE FINAL JUDGMENT.

the final decision, but are not substitutes for the final judgment. On seeing the optimized results, many decision-makers recognize constraints and objectives that were not included in the analysis and may request additional evaluation or may simply override the optimization. The value of the optimization is to expose more subtle choices than can be made by simple “rank-and-cut” processes and can keep track of large numbers of investment opportunities systematically. It is the decision-maker’s final selection – grounded in judgment, informed by analysis – that is funded, implemented and managed. Evaluation of the performance of the selected projects and the changing infrastructure situation lead to a repeat of the process, updating the strategic plan and performing new analyses of new options in a cycle of continuous improvement.

In this step, a number of sensitivity and “what-if” analyses are conducted on the portfolio model to examine the effects of the uncertainties and alternative assumptions. This process should increase the decision-maker’s comfort with the results of the analysis and introduce any factors that are important but may have been left out of the analysis to this point. It is important that the decision-maker not feel that his/her discretion has been usurped by the analysis. Decision-support tools do just that – support the decision-maker, not displace him/her.

4.4 Infrastructure Investment Work Flow

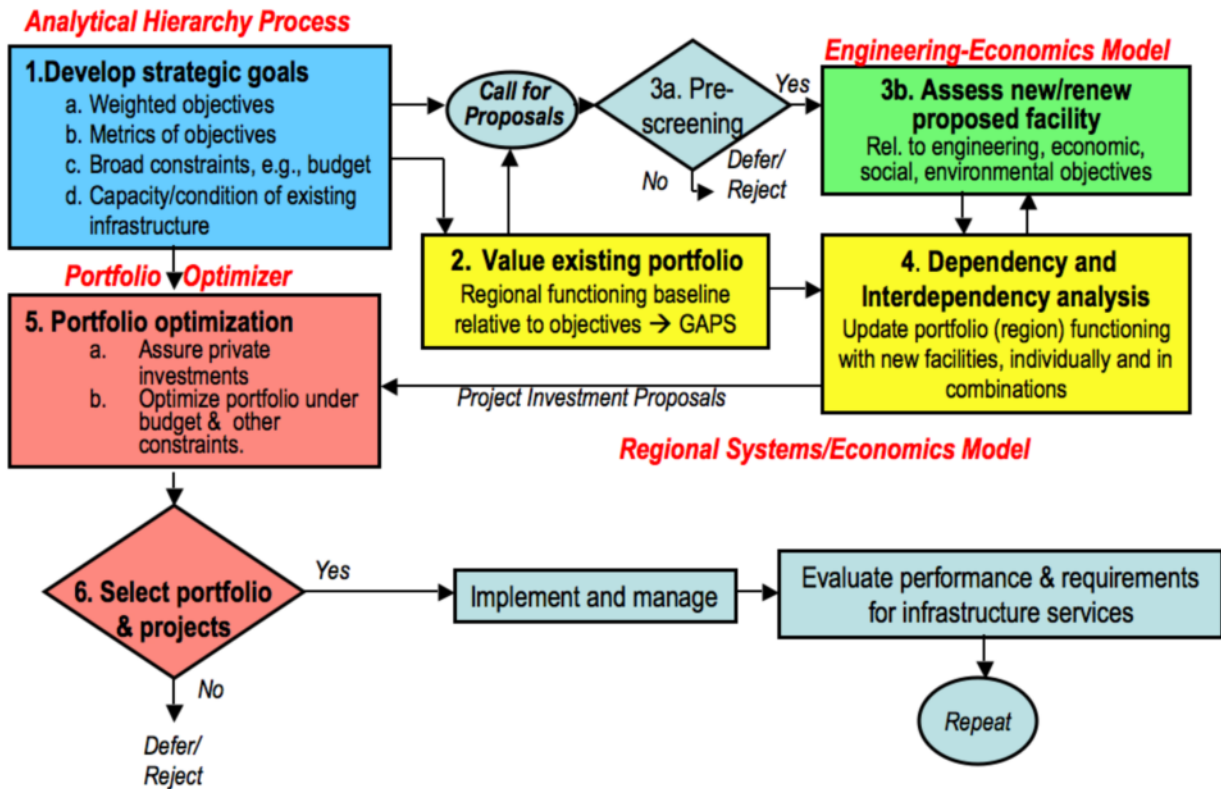
Figure 5 illustrates the infrastructure investment process described above as a work flow. The six steps actually require five analytic processes:

- The Analytic Hierarchy Process to support planning by weighing the objectives and criteria in a consistent, transparent manner (step 1);
- Pre-screening of investment alternatives (step 3a);
- An engineering-economics model to evaluate each investment option on a stand-alone basis and estimate many of the required metrics (step 3b);
- A regional systems/economics model to model the baseline regional functioning without new infrastructure investments (step 2) and to estimate the metrics that depend on assessment in the context of the region’s interdependencies (step 4); and
- A portfolio optimizer to select the mix of investments that maximizes value under the decision-maker’s constraints (steps 5 and 6).

Each of these processes is discussed below, supplemented by additional detail in the appendices.

4.3.6 Select and fund the chosen portfolio.

The optimized portfolio requires the application of the decision-maker’s judgment before the final investment decisions are made in both financial and infrastructure portfolios. It is never sufficient to rely on the optimizer’s results without close review. The results of the optimization are important and useful guides to



ANALYTIC HIERARCHY PROCESS BEGINS WITH THE DECOMPOSITION OF THE OVERALL GOAL OR PURPOSE OF THE DECISION INTO ITS COMPONENT OBJECTIVES AND EACH OF THESE INTO ITS COMPONENT CRITERIA.

4.4.1 Analytic Hierarchy Process. The Analytic Hierarchy Process (AHP) is a method for dealing systematically with multi-criterion decisions or multi-attribute evaluation in a systematic, consistent manner. First developed in the 1970s by Thomas Saaty,²³ AHP “provides a structured framework for setting priorities on each level of the hierarchy using pair-wise comparisons, a process of evaluating each pair of decision factors at a given level on the model for their relative importance with respect to their parent.”²⁴ It allows decision-makers to prioritize

their strategic objectives, evaluation criteria and alternative choices to achieve an overall goal.

AHP begins with the decomposition of the overall goal or purpose of the decision into its component objectives and each of these into its component criteria, and so forth to whatever additional levels are needed. The example in this report used three levels, but the process could be continued to several more levels to capture the desired level of detail. After the hierarchical structure is built, each element is rated against each of the others at the same level through “pair-wise comparisons” of the relative impact on their

²³Thomas Saaty and Luis Vargas, *The Logic of Priorities: Applications in Business, Energy, Health and Transportation*, Kluwer-Nijhoff Publishing, Boston, 1982; Thomas Saaty and Joyce Alexander, *Conflict Resolution: The Analytic Hierarchy Approach*, Praeger, New York, 1989.

²⁴Decision Lens, “Analytic Hierarchy Process,” http://www.decisionlens.com/products/meth_hierarchy.htm, (accessed July 2009).

common “parent,” e.g., the criteria to their respective objectives, the objectives to the overall goal. The lowest level of the hierarchy defines the data or judgments that are used to characterize the decision options to be considered. These are combined into “weights” that sum to 1.0. The weights are used to describe the value or priority of the option relative to its contribution through the hierarchy to the overall goal. A consistency index identifies instances of circular logic for correction, so the goals, objectives, etc., exhibit a high level of internal consistency even though they may cover highly diverse dimensions.

The pair-wise comparisons use a nine-point scale, from one, indicating that the two items being considered are equal with respect to their mutual “parent” in the hierarchy, to nine, indicating that one is very highly preferred to the other or exhibits an extremely larger quantity of some attribute than the other. Where “hard” numerical data are available, the actual values are arrayed directly on a scale of zero to one.

Each option, in the present case the candidate projects vying for inclusion in the portfolio, are evaluated using whatever tools or elicitation methods are appropriate to the criteria, some from the other models, others by direct judgment. The values on the respective criteria are then weighted by the weights developed in the hierarchy for an overall relative value indicator, which ranges from zero to 1.0.

There are numerous advantages with AHP. It accounts for both quantitative and qualitative (but still scalar) considerations from various stakeholders when determining priorities. It is flexible enough to consider concrete numerical data, subjective judgments or countless “what-if” scenarios. AHP can also capture the risks, costs, benefits and opportunities so resources can be allocated in an optimal manner.²⁵ In the present project, AHP was used to reduce the seventy-plus ideas for criteria (Appendix A) into four major objectives defined by 20 constituent criteria (Figure 6). Each criterion was then “operationalized” into a specific metric that could be estimated using one or both of the other two models in the process. A mix of “hard” quantitative values is mixed readily with “soft” qualitative judgments to build up an aggregate benefit score between zero and unity. Because of the way the underlying mathematics work, these scores are a meaningful ordinal scale of values, allowing valid ratios of benefits to costs. Additional information on AHP along with an example use of AHP in infrastructure portfolios can be found in Appendix F.

4.4.2 Pre-Screening Investment Opportunities. As previously noted, it is generally useful to pre-screen investment ideas before committing resources to support detailed architectural/engineering studies. A prototype screening tool was developed for the example problem that uses essentially the same decision criteria as those used for the final portfolio analysis, but is somewhat simplified by reducing the level of detail necessary to obtain the input data. The criteria are loosely based on the recommendations contained in the National Research Council (NRC),²⁶ report plus additional criteria that the committee recommended, as weighted using the AHP model (Figure 6, previous page).

The screening approach must be sufficiently transparent, objective and comparable to permit cross-sector and multi-level assessment and disposition. At the screening stage, consistency and clarity of criteria definitions are essential to this transparency and objectivity.

²⁵John Kendrick and Dan Saaty, *Use Analytic Hierarchy Process for Project Selection*, Decision Lens Inc., 2007.

²⁶BICE/NRC, *op. cit.*

Figure 6. Illustrative AHP Weighted Criteria for Example Problem
(Courtesy of Decision Lens, Inc.)

Decision Goal: To prioritize infrastructure investments		
0.101	Global Economic Competitiveness	
0.049	Technology Exportability	
0.021	Global Impact	
0.032	Foreign Oil Dependency	
0.207	Social Equity	
0.121	Geographic Scale of Impact	
0.038	Economic Sector Affected	
0.048	Constituents Most Benefited	
0.478	Infrastructure Project Economics	
0.014	Replaces Existing Infrastructure	
0.08	Jobs Timeline	
0.046	Funding Source	
0.189	Net Benefit	
0.12	Benefit/Cost	
0.03	Breakeven Date	
0.213	Sustainability	
0.015	Terrorism Risk Reduction	
0.114	Environmentally Sustainable	
0.084	Disaster Resilience	

The screening tool is easy to use and the data necessary to populate the spreadsheet can be developed with a reasonable amount of effort using approximate methods. The projects that pass the screen and are further analyzed will confirm through detailed analysis the values that were only approximated in the screening process. This will provide incentives to avoid exaggerated claims in the screening phase. The output from the screening tool is a ranked set of proposals. The higher ranked proposals will be selected for further analysis. Appendix C discusses the screening tool more completely.

For each project that passes the preliminary screening, the investment proposal is developed further by estimating or confirming the estimates made in the screening step. This results in estimates for all the metrics derived directly from the objectives and constraints defined in the first step, so it captures the value of the investment in all relevant dimensions. Some of the metrics are quantitative, such as net benefits, or qualitative, such as impact on quality of life. The values for the metrics are estimated in two distinct parts of the analysis, the engineering-economics model and the regional systems/economics model.

4.4.3 The Engineering-Economic Model.

The metrics that relate to *inherent*, “stand-alone” attributes of the investment project are developed in the engineering-economics model. These include such things as the net present value of the capital and life-cycle costs and direct cash inflows of the project, its capacity to produce infrastructure services, useful life expectancy, its direct employment (to design, construct and operate), sources of finance, risk and facility-resilience levels, etc.

THE METRICS THAT RELATE TO INHERENT, “STAND-ALONE” ATTRIBUTES OF THE INVESTMENT PROJECT ARE DEVELOPED IN THE ENGINEERING-ECONOMICS MODEL.

The experience in developing RAMCAP Plus[®] informs the specifications of the engineering-economics model, especially in regards to establishing and maintaining direct comparability in estimates across diverse facilities within a sector and across sectors. A necessary element of design of this model is to establish a standard set of definitions of key terms, standard processes for making the needed estimates and combining them into the required metrics, and shared understanding of the meaning of the respective metrics.

The engineering-economics model works integrally with the design of the facility/system being proposed. Sometimes, a formal engineering model is constructed and linked to the economics model; other times, the economics model is a simple stand-alone spreadsheet that references a series of engineering documents. The key engineering elements include capacity to provide infrastructure services, the facility/system design in enough detail to estimate valid costs for construction and operations, and the source of all necessary inputs, e.g., raw materials, utilities, labor, etc.

Just as any feasibility or investment valuation approach, the core technique for the engineering-economics model is the present value of all relevant cash flows. The standard spreadsheet model captures all direct expenditures and revenues at the time they are incurred. The present value of all the costs is the “life-cycle cost” or total costs used in benefit-cost analysis, whereas investment costs are the amount of the capital budget that will be used to make the investment, used in optimizing the portfolio of infrastructures.

As the scenario-based cash flow analyses are completed, the economic metrics from the owner/operator’s perspective can be directly calculated. The net present value of the investment is the financial *value* of the investment to the investor; the return on investment indicates the *efficiency* of the investment in generating benefits per unit cost; *risk* is the expected value of the losses due to the untoward events in the scenarios; and *resilience* is the expected value of service denial, the product of the severity (in units of service) and duration (in days), normalized by pre-shortage price, in short, lost revenue. Finally, there are some metrics that require direct expert judgment to estimate. These include some quality-of-life and some environmental metrics, iconic value of certain landmarks, etc.

These metrics characterize the business case from the owner’s or investor’s perspective, but not the value to the public, and does so as a stand-alone investment, independent of the facility/system’s interaction with other systems. Most infrastructure investments of interest, especially in the lifeline infrastructures, are valued because of their contributions to the well-being of the affected public and can only truly be valued in the context of the other infrastructures with which they are interdependent in the metropolitan

area (and larger) they serve. Even the project’s vulnerability to risks and resilience arising from interdependencies can only be examined on a regional systems basis. Some of the indicators estimated by the engineering-economics model will, in fact, be amended based on the results of analyses using the regional systems/economics model, e.g., the resilience the facility rests, at least in part, on the resilience of the systems that support it, as described in the next model.

Table 4. Example Reference Events for Scenario Analysis

		<i>Event Type</i>	<i>Event Description</i>			
Systemic Value	Risk	Regional Economy	Declines	Level	Moderate Growth	Major Growth
		Population	Declines	Level	Moderate Growth	Major Growth
	Natural Hazards	Hurricanes	Earthquakes	Tornadoes	Floods	
	Dependency & Proximity	Loss of utilities	Loss of suppliers	Loss of employees	Loss of customers	
		Loss of transportation				
Crime/Accident	Wear & Aging	<i>Under Development</i>				
	Product Contamination	Chemical	Radionuclide	Biotxin	Pathogen	
		Weaponization of waste disposal system				
	Sabotage	Physical-insider	Physical-outsider	Cyber-insider	Cyber-outsider	
	Theft or Diversion	Physical-insider	Physical-outsider	Cyber-insider	Cyber-outsider	
Terrorism	Attack: Marine	Small boat	Fast boat	Barge	Ocean ship	
	Attack: Aircraft	Helicopter	Small plane	Regional jet	Long-flight jet	
	Attack: Automotive	Car	Van	Mid-size truck	18-wheeler	
	Attack: Assault Team	1 assailant	2-4 assailants	5-8 assailants	9-16 assailants	

4.4.4 Regional Systems/Economics Model. Metrics that relate to the project’s performance in the context of the rest of the infrastructure systems as they interact in a specific region are estimated in what we have called the regional systems/economics or “systems of systems” model. These include the value of the investment to the public in the region served and at larger aggregations, dependencies and interdependencies, the system-resilience, etc. In estimating the regional baseline and impacts of investments on the public, there are at least two useful approaches, input-output modeling and systems simulation modeling, each discussed below. Additional details may be found in Appendices D and E.

Input-output Modeling. The simpler, but less accurate, of the two is to use a regional input-output (I-O) model, adapted to adjust for the inherent resilience. An input-output model uses a matrix representing a region's (or nation's) economy to predict the effect of changes in one industry, e.g., an infrastructure) on others and on consumers, government, and those outside the region. Input-output depicts inter-industry relations of an economy. Usually, this economic activity is characterized as the gross and net output of the region and employment. Net output (gross output corrected for intermediate transactions, which would cause "double-counting") is comparable to Gross National Product, so is often called Gross Regional Product.

Dependencies and interdependencies of infrastructures lead to both direct and indirect – "ripple" – effects. In considering the public perspective, the primary concern is the impacts of inadequate or interrupted service as economic consequences to the utility's direct suppliers and customers. In addition to these "direct" effects, the community incurs "indirect" consequences through reduced economic activity in general.²⁷ The economic consequences "ripple" through the regional economy, with the total impacts being some multiple of the direct impacts, hence the term "multiplier effect."

Input-output modeling has the virtue of being a well-established, highly empirical, generally accepted approach for cost-effective gross estimation. It has several shortcomings that may compromise its application to the immediate problem. One is that I-O models are based on historical data, so changes in the historical relationships among industries due to, for example, changes in technologies, efficiency improvements, disruptions due to natural disasters, etc., must be reflected by interventions in the models for which there is little empirical basis. A second limitation is that the relationships are all necessarily linear, so non-linear dependencies cannot be captured. A third is that, even though the I-O model is disaggregated by industrial sector, it has no specific reference to geospatial reality, so it cannot reflect the location of a capacity bind or how specific investments in a networked infrastructure will affect the overall capacity. And, finally, I-O models are relatively poor at capturing the actions of certain infrastructures for which product pricing poorly reflects cost or value, e.g., highways and drinking water.

INPUT-OUTPUT MODELING HAS THE VIRTUE OF BEING A WELL-ESTABLISHED, HIGHLY EMPIRICAL, GENERALLY ACCEPTED APPROACH FOR COST-EFFECTIVE GROSS ESTIMATION.

GREATER PRECISION AND A MUCH MORE INSIGHTFUL TREATMENT OF DEPENDENCIES, INTERDEPENDENCIES AND THE EFFECTS OF INVESTMENTS IN SPECIFIC FACILITIES CAN BE HAD USING SYSTEMS SIMULATION MODELS.

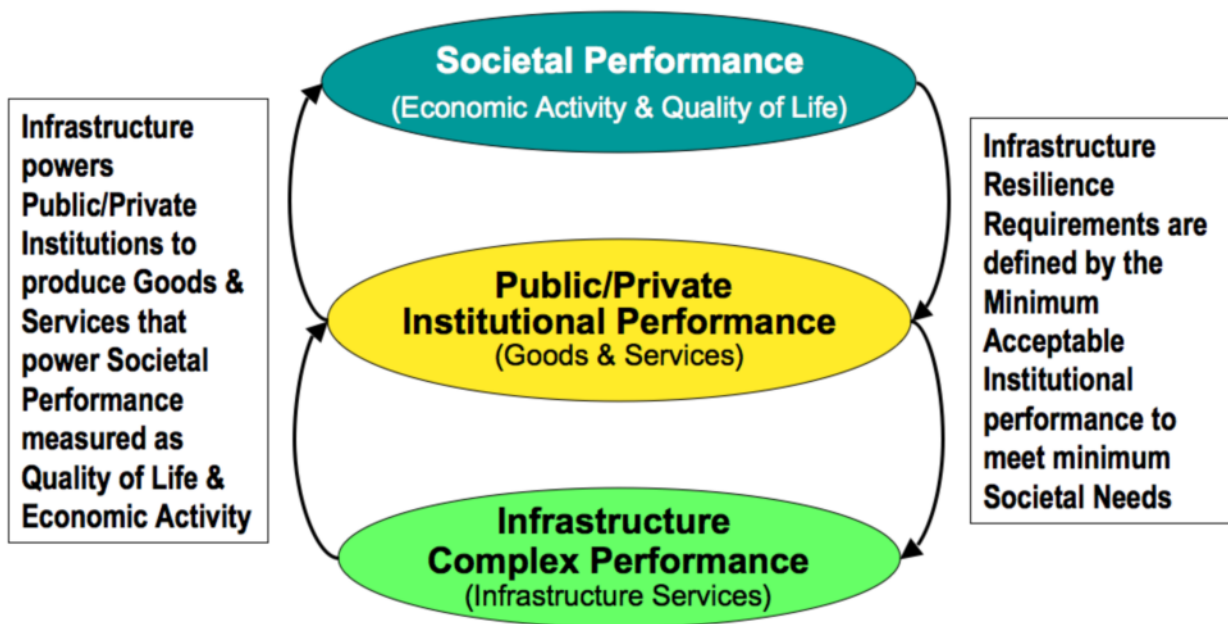
Systems Simulation. Greater precision and a much more insightful treatment of dependencies, interdependencies and the effects of investments in specific facilities can be had using systems simulation models. They expressly model infrastructure systems as nodes representing specific facilities and links by which the services provided by the facilities reach their intermediate and end users. Because they capture the interactions among infrastructures and their major customers, these are also called "systems-of-systems" models.

²⁷Adam Rose, "Economic Resilience to Disasters: Toward a Consistent and Comprehensive Formulation," in D. Paton and D. Johnston (eds.), *Disaster Resilience: An Integrated Approach*, (Springfield: Charles C. Thomas, 2006), 226-48.

A systems model is a scalable set of nested models that relate the impact of a wide range of natural or man-made events, including investments in new or up-dated infrastructures as well as hazards to existing infrastructures, on one or more metropolitan infrastructure components to key measures of metropolitan viability. Such models can be directly linked to geographic information systems maps as both sources of input data and geospatial displays of output.

The basis for the approach is a framework for assessment of critical infrastructure protection and foundational infrastructure development illustrated in Figure 7. The framework captures the relationships between infrastructures, public and private institutions, and society. The basic premise that defines the framework is that infrastructure drives public and private institutions to produce goods and services. These goods and services then drive societal performance that is measured as quality of life and economic activity. Therefore, infrastructure capacity and resilience requirements are ultimately defined by minimum acceptable institutional performance to meet minimum societal needs. An expanded discussion of systems simulation for infrastructure analysis is provided in Appendix E.

Figure 7. Schematic View of an Infrastructure Systems Model
(Courtesy of Alion Science and Technology²⁸)



4.4.5 Optimization Approach. At least two commercially available AHP software tools have a simple portfolio optimizer integrated directly into the general process flow. The tool selected for the example in this report²⁹ is one of those. After the specific values for each of the metrics is supplied by the other models and the judgments of the analysts and decision-makers for each investment option, the tool supports optimization of the portfolio of the investments. It does this by maximizing the aggregate multi-attribute value metric, given the constraints of multi-year budgets, prior obligations, logical linkages among projects, geographic or business line distributions, minimum meaningful partial allocations, etc. The resulting portfolio can then be examined through sensitivity and “what-if” analyses to increase the decision-makers’ comfort level in coming to a final decision.

²⁸Alion Science and Technology, <http://www.alionscience.com/> (Accessed June 2009)

²⁹Decision Lens, <http://www.decisionlens.com/> (Accessed June 2009)

In an alternative, more sophisticated approach, a core “genetic” algorithm generates a set of virtually all relevant combinations of investments through structured variation in the funding distribution among the candidate funding lines. The routine provides a range of solutions bounded on top by the lowest-cost solution that fully meets all criteria and on the bottom by the first candidate solution that fails to minimally meet any criterion. This is a more sophisticated solution than the optimization integrated with AHP tools that would be especially valuable if the methodology ultimately embraces full treatment of uncertainties in costs, performance, risks and resilience, especially if it can carry the interdependencies analysis into the optimization. It is an alternative worth exploring as the overall methodology is developed.

MAXIMIZING THE AGGREGATE MULTI-ATTRIBUTE VALUE METRIC, GIVEN THE CONSTRAINTS OF MULTI-YEAR BUDGETS, PRIOR OBLIGATIONS, LOGICAL LINKAGES AMONG PROJECTS, GEOGRAPHIC OR BUSINESS LINE DISTRIBUTIONS, MINIMUM MEANINGFUL PARTIAL ALLOCATIONS.

A worked example of the AHP tool being applied to infrastructure portfolio optimization, from step 1 to step 6, is provided as Appendix F.



5.1 The Feasibility of the Overall Methodology

One of the basic objectives of the present project is to assess the feasibility of developing a comprehensive methodology that will permit more transparent, objective and rational decisions to invest in infrastructure. It must be concluded that the methodology is feasible and desirable. The approach sketched in Section 3, described in some detail in Section 4 and the appendices meets the full set of design specifications set for it and it requires no radically new technologies that must be invented. In fact, at least one existing tool (among several) was identified as apparently meeting the requirements of the approach and each analytic process.

IT MUST BE CONCLUDED
THAT THE METHODOLOGY IS
FEASIBLE AND DESIRABLE.

5.1.1 The Approach versus the Design Specifications. Ten design specifications were articulated by the Working Group, as defined in Section 3.4. These are reviewed below with comments as to how the approach meets them:

1. *Comparisons:* Must guide allocation of investments across all classes of infrastructure, independent and interdependent, within and across regions and possibly other classes of investment. The approach is fully general to all classes of infrastructures and many other classes of investment in “hard” assets. Its applicability may not generalize to “soft” investments such as education or equal opportunity programs. Moreover, the regional estimates of need and benefits can be compared across regions, provided that all regions used the same approach.
2. *Multi-criteria:* Valuation must accommodate a series of desired objectives for infrastructure, including efficiency and equity, sustainability, quality of life, jobs created in construction and in use, etc. The approach uses a multi-attribute objective function in which both quantitative and qualitative information are logically and consistently weighted and applied to all investments. In addition to the extent to which the demand for infrastructure services is satisfied effectively and efficiently, criteria relating to equity, sustainability, etc., are explicitly included and weighted among the selection criteria. Further, the constraints used in the optimization can include such considerations as geographic distribution, minimum investment in certain classes of alternatives, meeting of prior commitments, etc.
3. *All outcomes:* Both potential upside gains and downside losses should be included in the valuation. The approach explicitly includes uniform business-as-usual operations, growth, decline and failure scenarios for each investment alternative. The same engineering-economics and regional systems models and scenarios are used to value new investments and to estimate risks and resilience, with and without the investment. Benefits and costs to both the owner and the affected public are calculated for each relevant scenario.
4. *Innovations:* Must permit investments in new infrastructure and new technology in the same paradigm as renewal/replacement of old infrastructures. The approach accommodates investments

in technology and alternative infrastructure solutions insofar as they are reflected in enhanced performance, reduced risk and/or improved resilience, or other elements of the objective.

5. *Uncertainties*: Must capture uncertainties in the estimates. The approach reflects uncertainties in two ways: First, it includes a significant number of scenarios representing alternative possible futures, in both the baseline estimates and in the cases where the proposed investments are made. The investments are evaluated individually and in combinations to define their unique contributions to the alternative future scenarios. Second, the models used are all amenable to systematic sensitivity analysis at all levels, e.g., the weightings applied to the criteria in the AHP, the performance of investment alternatives in the engineering-economics models and the performance of whole infrastructure systems and interdependent regional systems/economics model. Future methodology advances may permit movement from scenario analysis to full probability distributions of performance and portfolio optimization that accounts for these and the relationships among the infrastructures.
6. *Dependencies*: Must recognize and capture dependencies and interdependencies. The approach explicitly captures the dependencies and interdependencies within infrastructure systems and across systems, especially at the metropolitan level, but extending also to multi-state regions and the nation. It also explicitly captures the logical linkages among the investments, e.g., the hydropower plant and the dam, the bridge and the road that crosses it and avoiding redundant selections, e.g., two alternatives to meet the same need.
7. *Comprehensiveness*: Must support both private and public decision-making – especially identifying and valuing “public goods.” The approach values infrastructure investments from the perspectives of both the owner of the facility and of the regional public, readily identifying public goods and externalities. The method permits examination of the business case for the investment from the owner’s perspective so the owner can be encouraged to make the investment when it is justified. It examines the value from the perspective of the public so that high-value investments can be made by the public, directly or through partnering with the owner or others.
8. *Portfolio*: Must consider full portfolios of investments, in full context. Projects are analyzed and selected in the full context of the regional portfolio of existing and new infrastructure. The major dependencies and interdependencies are fully modeled to incorporate these relationships in the regional models and the resulting synergies are included in the benefit estimation. The portfolio is capable of drawing from multiple budget pools, funding multi-year projects partially, and meeting a variety of constraints, e.g., budgets, project linkages, multi-year commitments, geographic distribution, etc.
9. *Defensible*: Must be objective, transparent, consistent with accepted norms, produce directly comparable estimates of value, cost, risk, resilience, benefits, etc., for all investment options. The proposed paradigm meets all standards of engineering and decision science and exhibits exceptional transparency, objectivity and consistency, permitting directly comparable estimates of all benefits and costs.

10. *Simplicity and Credibility*: Must be capable of being applied by engineering, analytic, budgeting and planning staffs and communicating directly with key decision-makers – whether private sector, federal funding agencies or state and local governments infrastructure owners – with a minimum of outside expertise or training, using data that are readily available. In application, the approach exhibits user-friendly interfaces and “common sense” explanations, with underlying sophistication of the methodology visible only when need be. The inherent transparency and common-sense logic permit analysts and decision-makers to develop credence in the results of the approach by conducting any number of “what-if” analyses and comparing the results with their own direct knowledge. At the same time, the models are in wide enough use that experts can be readily located to assist with any training or modeling modifications that might become necessary from time to time.

This brief review supports the statement that the suggested approach meets all the original design requirements.

5.1.2 The Needed Technologies Are Available. The approach does not require invention of new methodologies at any point. Not only are the methods available and well-established, but there are alternative analytic “packages” that support each method.

- A number of commercial-grade, automated versions of the *Analytic Hierarchy Process*, at least two with integrated portfolio optimizers, are available. The Decision Lens product used in the example is user-friendly and complete, with an established track record.
- The *engineering-economics* model is a straightforward spreadsheet application. Concepts drawn from methodological parallels to RAMCAP Plus[®] can be used to support consistency in application and comparability in results.
- *Input-output models* for regional application are readily available and can be acquired with the required data at very reasonable cost, directly from the Bureau of Economic
- Analysis of the U.S. Department of Commerce³⁰, which develops the data, or from IMPLAN³¹, who packages and markets federal data.
- Several *systems simulations* tools are available in the market. *SmartMoves* by Alion Science and Technology was chosen for the discussion in this report because it is user-friendly and capable of taking a variety of forms of data, ranging from geographic information system maps to opinions and approximations by local infrastructure experts.
- Numerous approaches to *portfolio optimization* are available and any would require some modification for the uses described here. The very simple optimizer built into Decision Lens AHP would suffice in the earliest applications of the method, but the greater sophistication of Alion’s *Pathways* or other advanced optimizer would permit explicit analysis of more combinations and might integrate with a scenario data base.

³⁰Bureau of Economic Analysis, U.S. Department of Commerce, *Regional Multipliers: A User Handbook for the Regional Input-Output Modeling System (RIMS II)*, Third Edition, March 1997, Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402.

³¹Minnesota IMPLAN Group, www.implan.com (accessed July 2009) available for U.S. Census Standard Metropolitan Areas. See also Minnesota IMPLAN Group (MIG). 2006. *Impact Analysis for Planning (IMPLAN) System*. Stillwater, MN.

Thus, all the necessary components of the suggested approach are available. Building the approach is a matter of selecting, integrating and testing existing methodologies and software for use in infrastructure investment portfolio optimization.

This report has shown that an infrastructure investment methodology can be developed that is capable of evaluating a multitude of diverse proposals, screening out the least promising and ranking the remaining projects according to multiple and varied criteria. The path to realization of this important goal is bifurcated: One branch is consensus building within organizations that can contribute to the process and, ultimately, convincing decision-makers of the need to use this approach. The other is continued development of the methodology. Both are necessary; when decision-makers gain an appreciation and acceptance of the need for this methodology, it will be available and mature enough to meet the stated objectives. The next section addresses building acceptance, while the section after that outlines the research and development that are needed.

5.2 Building Acceptance

There are 18 critical infrastructures as defined by the U.S. Department of Homeland Security (DHS) National Infrastructure Protection Plan (NIPP). Given the importance of these infrastructures across the economy, there is a vast potential market that would be interested in the approach sketched here in both the public and private sectors. In particular, asset owners in the private sector and decision-makers at all levels of government could derive benefit from a convincing methodology that addresses this pressing need.

Following the suggestion of the NAS/BICE, the initial focus will be on the “lifeline” infrastructures, water/wastewater, transportation, power and telecommunications, without which the other infrastructures and other assets cannot function.

THE INITIAL MARKET NICHE IS THE CHIEF EXECUTIVES WITH OVERSIGHT AND FUNDING RESPONSIBILITIES TOWARD THE COLLECTION OF LIFELINE INFRASTRUCTURES.

Because one of the central constraints on optimal investment in infrastructure is the “stove-piped” nature of the US system, infrastructures are never examined as a holistic, interdependent whole. Trade-offs across stovepipes can only be made by the “general managers” – CEOs in industry, governors and mayors, and, of course, the President. Thus the

“clients” are these chief executives. The National Infrastructure Bank and Federal capital budget proposals being considered by Congress could potentially add another cross-stove-pipe infrastructure investment perspective. The initial market niche is the chief executives with oversight and funding responsibilities toward the collection of lifeline infrastructures. More precisely, it is the capital budgeting staffs to these executives and those who propose specific investment opportunities. Without adoption by the chief executives and their capital budgeting staffs, stove-pipe line agencies and the related Congressional committees will find little or no incentive to change methods or to adopt a method that encourages more directly comparisons with other stove-pipes.

Electric power and telecommunications in the US are largely provided by private corporations, while water/wastewater services are 90% provided by public agencies, and transportation is a mix of public and private organizations. This means that the needed investment evaluation methodology must be robust enough to fit not only diverse sectors, but diverse legal and incentive structures. This is likely to necessitate a product line that includes both a generic, “all-sector” framework complemented by sector-specific versions appropriate to the respective sectors and subsectors, much like the RAMCAP Plus® approach of a general framework complemented by a series of sector-specific, tailored versions that maintain consistency and comparability. It is also likely that infrastructure investment decisions will increasingly be made in processes that include both public and private organizations and multiple levels of government.

If these lifeline infrastructures adopt a uniform methodology, the others are likely to follow suit to the extent they must compete with the lifelines for capital and to the extent of success in institutional reform.

IF THESE LIFELINE INFRASTRUCTURES ADOPT A UNIFORM METHODOLOGY, THE OTHERS ARE LIKELY TO FOLLOW SUIT.

A particularly useful process in gaining acceptance for increasing the amount of investment in infrastructure and enhancing the value of the projects selected has been initiated by the National Academies of Science Board on Infrastructure and the Constructed Environment

(BICE). Its Chair, retired Admiral Dave Nash, convened a working group to develop ideas on the future of American infrastructure. Their report³² called for a process to upgrade the infrastructure investment process broadly, beginning with the formation of a coalition of BICE, several professional societies and other groups whose purpose is to improve the level and quality of the infrastructure investments. At the time of this writing, this process is being organized.

ASME’s Industry Advisory Board, made up of senior executives from across American and global industry to advise ASME’s leadership and staff, has strongly recommended that ASME continue to support both the process begun by BICE and the continued development of the methodology described in this report. Pursuant to those recommendations, the Working Group will continue to participate in the BICE initiative while seeking resources to continue to advance the methodology.

5.3 The R&D Approach

The research program to develop the needed technology would consist of the following broad phases:

1. *Requirements definition:* Conduct in-depth interviews with the capital investment evaluation staffs of chief executives and decision-makers at the respective levels to define the processes now in use, their needs and constraints, and refine the design requirements that the approach must meet to be accepted and effectively applied. Obtain the commitment of a sample of decision-makers and key analytic/planning staff to participate in assessing and critiquing the technology as it is being developed.
2. *System design:* Refine the requirements into a detailed functional design that includes the needed processes and system components.

³²BICE/NAS, *op.cit.*

3. *Component acquisition:* Search for or adapt/develop components required by the system design. The ASME-ITI Working Group has identified at least two sources for each component defined to date that appear to be compatible, including:
 - Engineering-economics methods – Investment project characterization to define performance from the owner’s perspective and all of the dimensions of multi-criterion objective function that can be estimated on a stand-alone basis (i.e., not dependent on the systems model analysis);
 - Regional input-output economic models and data sources to assess regional impacts on regional output, income and employment;
 - Regional systems/economics models and geographic information systems data to describe distributed infrastructures and their interdependencies, as well as regional impacts; and
 - User-friendly graphic user interfaces to accept inputs, manage analytic cases, visualize results, “drill down” for details of specific infrastructures or systems, and display the results for use in decision-making.
4. *Component integration:* Place each component in the designed process, enable fast, accurate hand-offs between components, and test the integration as an analytic system.
5. *Test/refine/build/retest:* Conduct a “spiral development” process to test the integrated analytic process with actual field data on a small-scale set of diverse investment options in an *actual, specific region*, critique and refine the process and expand it for larger application, and test it on a larger number of diverse investments. Repeat the sequence until the system performs adequately at the scale desired and accounts for all major infrastructures. Note that this step could also be a test of methods to advance regional infrastructure resilience.
6. *Demonstration:* Conduct a demonstration project for decision-makers and their staffs who have not previously participated in the project using actual field data and critique its performance. Refine the technology to address the feedback.
7. *Training:* Develop and test user training packages for analysts and planners and create a summary orientation for decision-makers.
8. *Dissemination:* Evaluate alternative dissemination options, e.g., publications, templates or protocols, voluntary consensus standards, Federal and/or state requirements, and best practices. Because of the urgency of making improved infrastructure valuation technology widely available, the spiral development plan should aim to put simpler versions into use as soon as available, even as the more comprehensive processes are being refined and tested.

Successful execution of the research advocated here will require a metropolitan area site with local jurisdictions and infrastructures willing to serve as the object of the analysis, and to supply data on the infrastructures involved.

5.4 Concluding Comment

The availability of this decision-support methodology, especially if it took the form of an American National Standard supported by commercial-grade software, would permit forward-looking infrastructure owners and public policy officials to apply the method to their own decision-making. For wider use, Congressional, OMB and/or the pending National Infrastructure Bank could require a thorough analysis as a routine part of planning and applying for funding of infrastructure investments. This would be most easily done for competitive, selective grants, but could also be applied to formula grants as part of due diligence. OMB and its equivalents in States and localities could establish the analysis as the basis for consideration. Infrastructures owned, operated and maintained by the private sector would adopt the method as a way of negotiating rates and justifying new investments to state public utility commissions.

The Obama Administration is determined to make long-overdue investments in public works and new infrastructure. This is an expensive endeavor. Over the next decade, hundreds of billions of dollars will be allocated by all levels of government as well as by the private sector to prepare U.S. infrastructure to meet 21st century needs. This will take place in an environment of increasing scarcity of natural resources and taxpayer dollars, increasing competition for federal funds, generally tightening budgets, and perhaps attracting capital from new sources, such as private investors, public pension funds, and sovereign investment trusts. The usual processes for analyzing, prioritizing and selecting projects are widely viewed as inadequate and wasteful.

The ASME-ITI Infrastructure Investment Working Group is introducing a cogent concept for review and improvement. Its scientific underpinnings are not bound by partisan politics, vested interests, or lobbyists. It simply offers decision-makers of any political stripe at any level of government or industry a rational process to determine optimal return on investments. Ensuring every dollar is spent in the most advantageous manner will only contribute to the greater good and increase the quality of life for all Americans.

The advent of a methodology that supports rational infrastructure decision-making would bring discipline to the jumble of processes by which America now makes these vital investments. It would reject “bridges to nowhere” early in the process and treat “sunk costs” as gone (favoring repair over replacement) while introducing new technologies (materials, sensors, design concepts) in a context where their value is manifest. It would expose self-serving proposals and highlight those that are sound. It would enhance design of both new and renewal projects. It would elevate emerging values of safety, security, resilience, sustainability and social equity to their rightful position as decision criteria.

OUTCOMES COULD BE MEASURED BY
THE QUALITY AND RELIABILITY OF
INFRASTRUCTURE SERVICES PROVIDED,
THE SPREAD OF INFRASTRUCTURE
SERVICES TO A GROWING POPULATION,
REDUCTION IN THE NUMBER AND
DURATION OF SERVICE DENIALS.

In the near term, the quality and consistency of infrastructure investment proposals and plans would rise. The resulting infrastructure would clearly serve a full range of objectives – economic benefits and investment efficiency to the owner and to the community served, greater security, resilience, equity, sustainability, etc. The reality of interdependencies and the logic connecting the investment to the social benefits would be clearly addressed, options would be compared, and strategic portfolios would be defined on a regional and perhaps national scale.

Over the longer term, the outcomes could be measured by the quality and reliability of infrastructure services provided, the spread of infrastructure services to a growing population, reduction in the number and duration of service denials, and reduction of unit costs of the service as new, more efficient assets replace worn and obsolete ones. In line with the BICE recommendations, the infrastructure of the future should contribute to meeting the other great challenges facing the nation in the 21st century and particularly to economic growth.

The major outcome of use of this new approach would be a marked increase in the value of investment in new and renewal infrastructures. Regional economies would expand in sustainable, equitable ways; safety, security and resilience relative to man-made and natural events would be materially enhanced; cascading infrastructure failures would be less likely, less frequent and less widespread; and fewer “wrong” projects would find funding.

In brief, such an approach would bring “more bridge for the buck, more dam for the dollar, more levee for the levy.” It would delineate the difference between investing hundreds of billions of taxpayer dollars well and spending them poorly and bring about a significantly higher quality American infrastructure base than current processes can possibly consider. The results would vastly increase the efficiency and global competitiveness of American industry and contribute to the quality of life of all our citizens.

Time, however, is of the essence. Significant outlays are underway and will continue at an accelerated pace. The opportunity to capture the benefits of enhanced infrastructure investment could quickly pass, giving rise to wasted investments, unnecessary projects and unmet needs. The efficient and effective route to the infrastructure for the 21st century passes through the decision-support methodology described above. The R&D and outreach to assure its use must be accelerated.

1. Group 1 – Provide adequate and efficient infrastructure services

- 1.1. Infrastructure services affected
 - 1.1.1. Direct focus (e.g., water/wastewater, power, mobility, and/or connectivity)
 - 1.1.2. Interdependent services
- 1.2. Infrastructure service performance impacts
 - 1.2.1. Current level of service performance (e.g., excellent, sufficient, inadequate, vulnerable to failure)
 - 1.2.2. Direct (e.g., maintained, improved, new) – health, safety well-being impacts
 - 1.2.3. Indirect (e.g., for interdependent services – maintained, improved, new) – health, safety, well-being impacts
- 1.3. The proposal develops a broad and compelling vision that will inspire individual and organizations to pull together. The focus of the vision is on a future of economic competitiveness, energy independence, environmental sustainability, national security, and quality of life.
- 1.4. The project will provide essential services with special emphasis on water/wastewater, power, mobility, and/or connectivity.
- 1.5. The proposal provides performance measures: quantified links among infrastructure investments; the availability/reliability of essential services; support for national imperatives (economics competitiveness, energy independence, environmental sustainability, national security, and quality of life.).
- 1.6. Pre-use employment – temporary jobs and subcontracts
- 1.7. Post-use continuous employment – salaries and taxes plus training
- 1.8. Cyclic Employment – salaries and taxes

2. Group 2 – Remain economically competitive with European Union, China, India, and other economics powers

- 2.1. Employment impact duration
 - 2.1.1. Short-term (design, fabrication, construction) – Salaries and taxes plus training
 - 2.1.2. Long term (e.g., production, services) – Salaries and taxes plus training
- 2.2. Employed personnel
 - 2.2.1. By trade, economic sector
 - 2.2.2. By income bracket
- 2.3. Employment character
 - 2.3.1. Skill level (e.g., unskilled, skilled, professional)
- 2.4. Economic impact
 - 2.4.1. Start time availability (e.g., immediate, 12-24 months, etc.)
- 2.5. Effective resource use
 - 2.5.1. Material availability (e.g., local vs. foreign supply, scarcity, re-use)
 - 2.5.2. Installed equipment (e.g., availability, expected life)
 - 2.5.3. Production/construction equipment (e.g., availability, re-purposing potential)
- 2.6. Global economic impacts
 - 2.6.1. Advancement of state-of-practice
 - 2.6.2. Advancement of state-of-knowledge (e.g., R&D-based)

- 2.6.3. Applicability to non-US infrastructure services
- 2.6.4. Opportunity for new international business/market formation
- 2.7. Timeline for affecting economy: shovel ready; short-term payoff within a year; midterm payoff – 2-3 years; long term payoff – >3 years
- 2.8. Global competitiveness: Makes USA more competitive in global market-creates intrinsic value in economy i.e., competitiveness or other advantages
- 2.9. Could result in exportable technology (estimated probability)
- 2.10. Growth potential – Financial/Jobs/Markets/Products/R&D/Reach

3. Group 3 – Reduce US dependence on imported oil

- 3.1. Effective resource use
 - 3.1.1. Energy impacts (e.g., alternative sources, local power)
- 3.2. Reduce dependence on foreign oil: No reduction; some reduction; significant reduction; eventual eliminated
- 3.3. Energy efficiency – Fuel/Air/Other Resources/Waste/Loss/Reliability

4. Group 4 – Protect the environment, reduce greenhouse gas emissions and conserve increasingly scarce natural resources, including potable water

- 4.1. Reduce greenhouse gas emissions linked to global climate change
- 4.2. Ecosystem services impact
 - 4.2.1. Regeneration of natural systems (e.g., wetlands for storm water runoff)
 - 4.2.2. Protection of critical natural resources (e.g., fresh water sources)
 - 4.2.3. Food security and independence (e.g., local, regional, national)
- 4.3. Effective resource use
 - 4.3.1. Water impacts (e.g., Local treatment, groundwater recharge)
- 4.4. Extent of impact on United States: Local; regional; national
- 4.5. Green Initiative: Reduce greenhouse gas emissions; adapts to changing climate; uses renewable resources
- 4.6. Land use – amount/type/multi-use/fully productive
- 4.7. Water use – quantity/recycle/release/lost/subsidies/clean
- 4.8. Energy use – provided/consumed/lost/cost/subsidies/reliable
- 4.9. Environmental impact – improvements/ damages/repairs/losses

5. Group 5 – Develop the capacity to withstand and recover quickly from natural and man-made disasters

- 5.1. Infrastructure services performance impacts
 - 5.1.1. Disaster survivability impacts (e.g., expected functionality during disaster)
 - 5.1.2. Disaster resiliency impacts (e.g., expected time to recover)
 - 5.1.3. Capacity to accommodate change over time (e.g., population density increase, sea level rise)
- 5.2. Ecosystem services impact
 - 5.2.1. Disaster survivability and resiliency impact (e.g., buffer zone for storm surge)
 - 5.2.2. Adaption to climate change impacts (e.g., drought, temperature increases)
- 5.3. Economic impact
 - 5.3.1. Expansion opportunities (e.g., new businesses vs. existing)

- 5.4. Reduces risk to terrorism, natural hazards: No reduction; some reduction; significant reduction; risk eliminated
- 5.5. The proposal demonstrates understanding of the interdependencies among critical infrastructure systems: it uses those interdependencies to enable the achievement of multiple objectives; it avoids narrowly focused solutions that may well have serious, unintended consequences due to interdependencies.
- 5.6. The proposal employs a collaborative, systems-based approach; it leverages available resources; it provides for cost-effective solutions; it works across institutional and jurisdictional boundaries.
- 5.7. Sustainability of business – financial/resources/hr/education/competition

6. Group 6 – Distribute infrastructure benefits equitably

- 6.1. Infrastructure service performance impact
 - 6.1.1. Quality of life impacts (e.g., recreation opportunities, stable community, economic opportunity, education opportunity)
- 6.2. Employed personnel
 - 6.2.1. By disadvantaged category (e.g., veterans, minority, women)
 - 6.2.2. By location (e.g., local, urban, etc.)
- 6.3. Employment character
 - 6.3.1. Up-skilling opportunities (e.g., durable skill training)
- 6.4. Economic impact
 - 6.4.1. Locale (e.g., town only, metro zone, region, etc)
 - 6.4.2. Economic sectors affected (e.g., Housing; industrial; automotive; transportation; power generation; power distribution)
- 6.5. Organization Involvement
 - 6.5.1. Public interest oversight (e.g., regulatory, advisory)
- 6.6. Global economic impacts
 - 6.6.1. International safety and health impacts
- 6.7. Constituent Income level most affected (objective: Create Jobs: Main St to Wall St): Blue collar; Minority (used by decision makers-not used for estimating numbers of jobs created); white collar; professional; executive/CEO; Wall Street bankers and investment houses
- 6.8. Economic Sector affected: Housing; industrial; automotive; transportation; power generation; power distribution; all; ETC. (add to list as necessary)
- 6.9. Public Funds Use – Education and training grants

7. Group 7 – Financial – Descriptors

- 7.1. Organization involvement
 - 7.1.1. Financing (e.g., Immediate, short-term, long-term)
 - 7.1.2. Revenue capture (e.g., fee for use, public allocation)
 - 7.1.3. Return on investment – by organization (e.g., R&D-based)
- 7.2. Funding source: Full funding by Feds in current fiscal year; Full funding by Feds over several years; partial funding – i.e., shared costs between applicant and Fed; Guarantees or loans only – municipal bonds, privatization of infrastructure, i.e. toll roads, bridges, etc.
- 7.3. Original Resources use – Purchase, consumption, disposal
- 7.4. Recycled resources use – Eco/enviro/transport/dispose

APPENDIX B. THE ANALYTIC HIERARCHY PROCESS IN INFRASTRUCTURE INVESTMENT



The Analytic Hierarchy Process (AHP) is a structured technique for dealing with complex and multiple-criterion decisions. It was developed by Thomas L Saaty in the 1970s based on mathematics and psychometrics and has been refined and reduced to software several times since.

Several firms supply computer software to assist in implementing the process. Based on ASME-ITI's limited investigation into AHP software, the candidate most suitable to the present requirements appears to be Decision Lens™, Inc., based in Arlington, VA. This company was founded by Thomas L. Saaty, the original developer of the AHP methodology. They market a commercial-grade software product that is user-friendly with high quality graphical output. Their private sector clients range from Johnson & Johnson to the National Football League, while its public sector clients range from the Joint Staff and the U.S. Navy, to USDA, the Department of Education, and every major intelligence agency, as well as several state-level agencies.³³

In the present application, the Decision Lens version of AHP is useful in two steps of the overall process: setting weights for the decision criteria and optimizing the portfolio of options.

In the first, AHP supports structuring the goal hierarchy and systematically and consistently weighting the major criteria and each of their respective components for use in scoring investment proposals. The goal was decomposed to four broad objectives, which were, in turn, decomposed into 20 specific criteria, approximately corresponding to the objectives sited in the infrastructure report by the National Research Council³⁴ and organizing the more than seventy criteria suggested by Working Group members (Appendix A).

The objectives were then compared in pairs relative to their contribution to the overall goal using a nine-point scale from 1, indicating “same level of contribution” to 9, indicating “extremely greater (or lesser) contribution to the goal. The criteria were then compared in pairs (using the same scale of comparison) relative to their contribution to their respective objectives. The AHP process, using mathematical and psychometric principles, converts these comparisons into the weightings displayed in Figure B-1. In this way, the broad goal is refined into a set of twenty specific, weighted criteria. This process directly captures the decision-makers' priorities and expresses them as a multi-attribute definition of value in the specific decision problem.

³³Decision Lens, <http://www.decisionlens.com/company/>, (accessed June 2009). Decision Lens, Inc., provided demonstration software and technical support for use in the present study. The project team is grateful for this assistance.

³⁴National Research Council, *op. cit.*

Decision Goal: To prioritize infrastructure investments		
0.101	Global Economic Competitiveness	
0.049	Technology Exportability	
0.021	Global Impact	
0.032	Foreign Oil Dependency	
0.207	Social Equity	
0.121	Geographic Scale of Impact	
0.038	Economic Sector Affected	
0.048	Constituents Most Benefited	
0.478	Infrastructure Project Economics	
0.014	Replaces Existing Infrastructure	
0.08	Jobs Timeline	
0.046	Funding Source	
0.189	Net Benefit	
0.12	Benefit/Cost	
0.03	Breakeven Date	
0.213	Sustainability	
0.015	Terrorism Risk Reduction	
0.114	Environmentally Sustainable	
0.084	Disaster Resilience	

Figure B-1. Illustrative AHP Weighted Criteria for Example Problem
(Courtesy of Decision Lens, Inc.)

The software also outputs a consistency score that allows decision-makers to recognize and correct instances of circular logic or errors in weightings or definitions of objectives or criteria. Further, systematic sensitivity analyses can be conducted easily at each step of the analysis and at the end.

Each criterion was then “operationalized” into a specific metric that could be directly assessed using the judgment of decision-makers and/or experts or estimated using either or both of the Engineering-Economics and Regional Systems/Economics models. Results from the two economics models can be used directly when scaled from maximum value to minimum value. This permits the criteria to be a mix of “hard” quantitative values and “soft” qualitative judgments to build up an aggregate value score between zero and unity. One important aspect of this method is that value is defined by multiple criteria in their natural measures.

AHP does not require conversion of all criteria of value into monetary terms, as some decision-support methods do. This assists decision-makers in understanding the trade-off that they are making and to

“drill down” into the value index to see the basis of any specific investment’s value definition. Because of the way the underlying mathematics work, these scores are a meaningful ordinal scale of value, allowing valid ratios of value (benefits) to investment.

This use of multi-attribute value criteria is similar in purpose to the “double-” and “triple-bottom-line” methods advocated in some management circles. These recognize the importance of values beyond simply economic performance and add them as additional decision criteria. This approach recognizes that multiple criteria should be considered, but allows them to be combined by weighting them against an overall value concept.

After the specific values for each of the metrics is supplied by the other two models and the judgments of the analysts and decision-makers for each investment option, the Decision Lens product supports optimization of the portfolio of the investments that maximizes the aggregate benefit given the constraints of multi-year budgets, prior obligations, linkages among projects, geographic or business line distributions, minimum meaningful partial allocations, etc. The resulting portfolio can then be examined through sensitivity and “what-if” analyses to increase the decision-makers’ comfort level in coming to a final decision. Appendix F shows a worked example of the AHP and portfolio optimization as applied to a simple hypothetical problem.



APPENDIX C. PRE-SCREENING INVESTMENT OPPORTUNITIES

As previously noted, it is generally useful to pre-screen investment ideas before committing resources to support detailed architectural/engineering studies. A prototype screening tool has been developed that uses essentially the same decision criteria that are used for the final portfolio analysis, but is somewhat simplified by reducing the level of detail necessary to obtain the input data. The criteria are loosely based on the recommendations contained in the National Research Council (NRC),³⁵ report plus additional criteria that the committee recommended, as weighted using the AHP model (Figure 6). These criteria can be applied to virtually all projects regardless of economic sector, type of project, or whether the project is being assessed at the national, state, regional or local level. This approach has been partially automated by programming the selection attributes in a spreadsheet that serves as the prototype.

The initial collection of investment ideas will be filled with widely disparate proposals emanating from a multitude of proposers. Funding could be sought for everything from repair and replacement of roads and bridges to long-term research projects that create few jobs and take years to produce benefits and which have large uncertainty but great potential. Some of the proposals will address short-term needs whereas others will be long lived: some will have immediate impact on creating jobs or stimulating the economy, while others' contributions will spread over a longer period.

The NRC criteria provide a vision for sorting out such investment proposals. The investment strategy outlined here is designed to implement the NRC's conceptual approach and provide a methodology for applying it to specific projects. Proposals for projects will be submitted at all levels for funding – local, state, regional, national. Many of these are subject to decisions at multiple levels, as when a city proposes to a state for a grant, or a state proposes to the federal government for a loan guarantee. The approach must be sufficiently transparent, objective and comparable to permit cross-sector and multi-level assessment and disposition. At the screening stage, consistency and clarity of criteria definitions are essential to this transparency and objectivity.

The initial screening tool is used to select candidates from all the proposed projects for further, much more detailed architectural, engineering and economic design and analysis. The screening tool is easy to use and the data necessary to populate the spreadsheet can be developed with a reasonable amount of effort using approximate methods. The projects that pass the screen and are further analyzed will confirm through detailed analysis the values that were only approximated in the screening process. This will provide incentives to avoid exaggerated claims in the screening phase.

This approach provides a mechanism for individuals at all levels of governance to have an impact on the projects selected for further evaluation. All inputs, both the values of the input criteria and the weighting factors should be made available for public scrutiny.

The output from the screening tool is a ranked set of proposals as indicated in Figure C-1. The higher ranked proposals will be selected for further analysis. For example, the benefit/cost ratio that was approximated in the screening tool would be recalculated based on a more detailed economic model or additional expert elicitation. The number and type of jobs created should be estimated more accurately and each of the decision criteria inputs should be thoroughly documented.

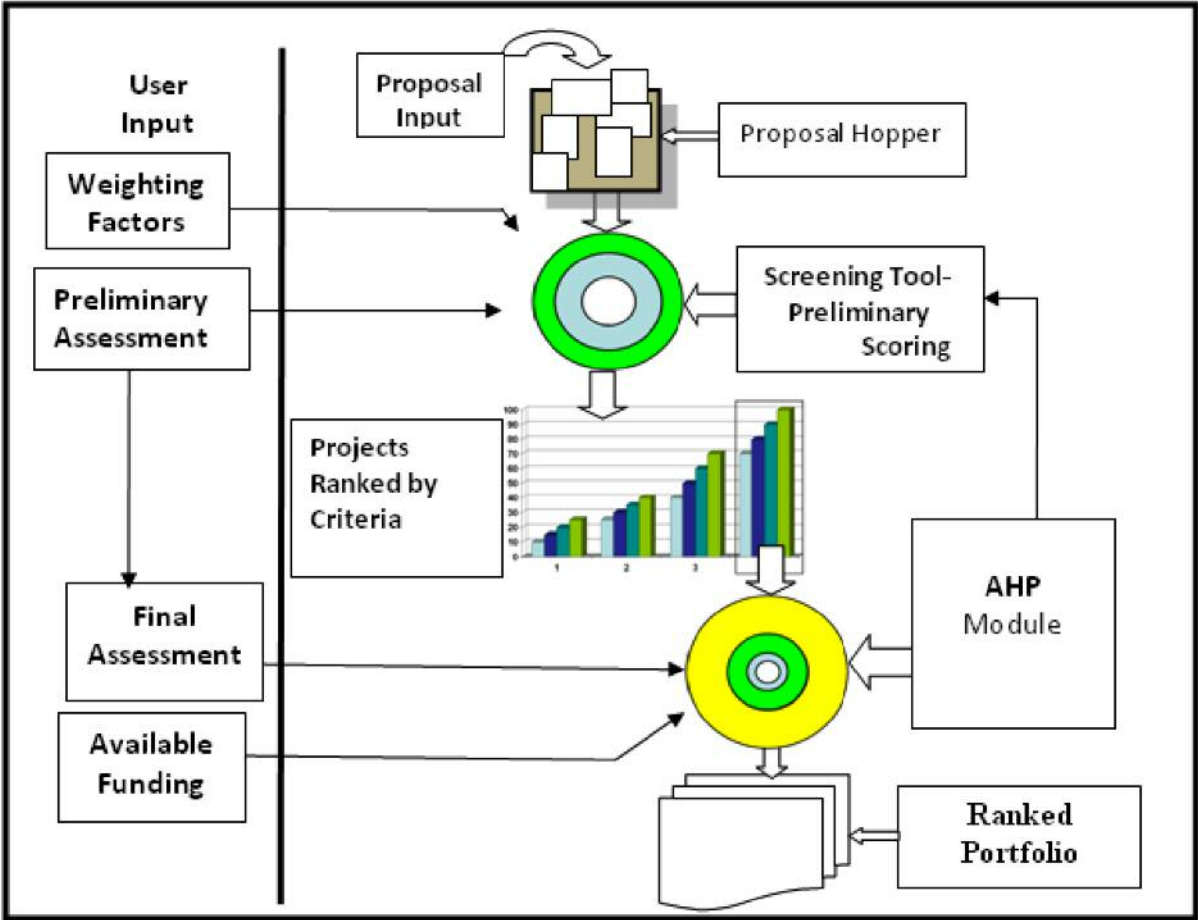


Figure C-1. Schematic of Infrastructure Investment Methodology



APPENDIX D. THE ENGINEERING-ECONOMICS MODEL

The experience in developing RAMCAP Plus[®] informs the specifications of the engineering-economics model, especially in regards to establishing and maintaining direct comparability in estimates across diverse facilities within a sector and across sectors. A necessary element of design of this model is to establish a standard set of definitions of key terms, standard processes for making the needed estimates and combining them into the required metrics, and shared understanding of the meaning of the respective metrics.

The engineering-economics model works integrally with the design of the facility/system being proposed. Sometimes, a formal engineering model is constructed and linked to the economics model; other times, the economics model is a simple stand-alone spreadsheet that references a series of engineering documents. The key engineering elements include capacity to provide infrastructure services, the facility/system design in enough detail to estimate valid costs for construction and operations, and the source of all necessary inputs, e.g., raw materials, utilities, labor, etc.

Just as any feasibility or investment valuation approach, the core technique for the engineering-economics model is the present value of all relevant cash flows. The standard spreadsheet model captures all direct expenditures and revenues at the time they are incurred. Positive cash flows are the revenues or other fees paid to the facility's owners by users of the services the facility provides. Negative cash flows or costs include both investment (capital outlays that are "booked" as assets and depreciated over time as they are "used up") and non-capital costs (costs of operations, maintenance and repairs, and final abandonment and environmental restoration, all of which are "expensed at the time incurred"). If the project is to be self-liquidating, under "project finance" arrangement, debt service (principal and interest) are included. In all other cases, the costs of financing are paid from general revenues of the entity owning the facility. The present value of all these costs is the "life-cycle cost" or total costs used in benefit-cost analysis, whereas investment costs are the amount of the capital budget that will be used to make the investment, used in optimizing the portfolio of infrastructures. When conducting a risk or resilience analysis, losses in revenues, costs of repair and restoration, and liabilities for fatalities or personal injuries are also negative cash flows.

Only actual cash flows are counted; previously paid expenses are "sunk" and excluded. Also excluded are "non-cash" expenses such as depreciation, which is used only in estimating tax liabilities. For non-taxable entities, of course, no adjustments are needed for taxes. For taxable entities, however, adjustments must be made to "after-tax" cash flows. This is done by using the most rapid permissible "write-off" rate to shelter the maximum revenue from taxes, but the depreciation is not considered an outlay in cash flow analysis. If the taxable entity is large enough to use losses from the facility to shelter income from other operations, losses are treated as "negative taxes." Organizations that cannot plan to use this approach should treat losses as a "tax loss carry-forward" to shelter income from the present facility in future years.

Uncertainties in future cash flows are incorporated using a standard suite of scenarios and sensitivity analysis. Ultimately, estimates of the uncertainties directly as probability distributions and combining them through Monte Carlo simulation might prove valuable, but, this approach is seen as too demanding to include in the initial system. Such an approach would be very complex if it is to capture the

interdependencies among the infrastructures, although future work may show it to be tractable. A standard suite of scenarios, developed for the RAMCAP Plus[®] process, is provided as a starting point for defining a new suite for the standard engineering-economics modeling (Table D-1).

Because these scenarios were originally established to analyze risks and resilience to untoward events, this particular set is unduly negative in tone, but represents the types of possible future events that would be included in a more suitable suite. The effects of the regional economy and economic growth or decline was added to the RAMCAP Plus[®] set to enable an exploration of large-scale systemic changes that could materially affect the performance of the infrastructures that support the regional population. Other systemic events are natural hazards and simple wear and aging. The rest of the scenarios are “man-made” in the sense that one or more human agents commit a purposeful or accidental act that can potentially cause harm to the facility. These include human error, vandalism, crime and terrorism. The mode and scale of attacks vary to assess the levels of risk and resilience of the facility. For the scenarios to be used successfully to assess risk and resilience, standard definitions and processes for estimating consequences, vulnerability and event likelihood are necessary. The RAMCAP Plus[®] handbook³⁶ suggests standard approaches for these estimates.

Standardized assumptions will be needed for discount rates to be used in calculating the present value. Ordinarily, in a conventional feasibility study, the correct rate is the weighted average cost of capital for the proposing entity. This would lead to widely different valuations of the same project. To maintain comparability, a specific rate must be specified. The Office of Management and Budget (OMB) publishes the rate Federal agencies must use in their benefit-cost analyses. Recently, it has been set at 7%, which in real terms is comparable to the weighted average cost of capital for a number of large organizations, provided the analysis is conducted in “real” dollars (no allowance for inflation).

As the scenario-based cash flow analyses are completed, the economic metrics from the owner/operator’s perspective can be directly calculated. The net present value of the investment is the financial value of the investment to the investor; the return on investment indicates the efficiency of the investment as a use of cash; risk is the expected value of the losses due to the untoward events in the scenarios and resilience is the expected value of service denial, the product of the severity (in units of service) and duration (in days), normalized by pre-shortage price, in short, lost revenue.

³⁶ASME-ITI, *All-Hazards Risk and Resilience: Prioritizing Critical Infrastructure Using the RAMCAP Plus[®] Approach* (Washington, DC., ASME Press, 2009).

	<i>Event Type</i>	<i>Event Description</i>			
Systemic Value	Regional Economy	Delcines	Level	Moderate Growth	Major Growth
	Population	Delcines	Level	Moderate Growth	Major Growth
	Natural Hazards	Hurricanes	Earthquakes	Tornadoes	Floods
	Dependency & Proximity	Loss of utilities	Loss of suppliers	Loss of employees	Loss of customers
		Loss of transportation			
Risk	Wear & Aging	<i>Under Development</i>			
	Product Contamination	Chemical	Radionudide	Biotoxin	Pathogen
		Weaponization of waste disposal system			
	Sabotage	Physical-insider	Physical-outsider	Cyber-insider	Cyber-outsider
	Theft or Diversion	Physical-insider	Physical-outsider	Cyber-insider	Cyber-outsider
Crime/ Accident	Attack: Marine	Small boat	Fast boat	Barge	Ocean ship
	Attack: Aircraft	Helicopter	Samll plane	Regional jet	Long-flight jet
	Attack: Automotive	Car	Van	Mid-size truck	18-wheeler
	Attack: Assault Team	1 assailant	2-4 assailants	5-8 assailants	9-16 assailants
	Terrorism				

Table D-1. Example Reference Events for Scenario Analysis

Once the engineering and cash flow models are established, they can be used to generate many of the other direct metrics. Direct employment was implicitly estimated in the construction, subcontracting and operating costs, so can be made explicit directly from those estimates. The siting of the facility and the revenue projections provide a basis for characterizing the labor pool for construction and direct users of the infrastructure services to be provided, including demographics and income levels for assuring social equity. The processes to be used and the fuels and raw materials and the nature of the damages resulting from the risk scenarios permit characterization of any environmental consequences. As noted, the scenarios will provide information on the safety, security and resilience of the facility.

Finally, there are some metrics that require direct expert judgment to estimate. These include some quality-of-life and environmental metrics, iconic value of certain landmarks, etc.

These metrics characterize the business case from the owner's or investor's perspective, not the value to the public, and does so as a stand-alone investment. Most infrastructure investments of interest, especially in the lifeline infrastructures, are valued because of their contributions to the well-being of the

affected public and can only really be valued in the context of the other infrastructures with which it is interdependent in the metropolitan area they serve. Even the project's vulnerability to risks and resilience arising from interdependencies can only be examined on a regional systems basis. Some of the indicators estimated by the engineering-economics model will, in fact, be amended based on the results of analyses using the regional systems/economics model.



In estimating the regional baseline and impacts of investments on the public, there are at least two useful approaches, input-output modeling and systems simulation modeling, each discussed below.

E-1. Input-output Modeling. The simpler, but less accurate, of the two is to use a regional input-output (I-O) model, adapted to adjust for the inherent resilience. An input-output model uses a matrix representing a region's economy to predict the effect of changes in one industry on others and on consumers, government, and those outside the region. Input-output depicts inter-industry relations of an economy. It shows how the output of one industry is an input to each other industry and to households. A given input is typically enumerated in the column of an industry and its outputs are enumerated in its corresponding row. This format, therefore, shows how dependent each industry is on all others in the economy both as customer of their outputs and as supplier of their inputs. Each column of the input-output matrix reports the monetary value of an industry's inputs and each row represents the value of an industry's outputs.

Input-output models estimate the amount of output in all sectors results from a defined amount of input from all sectors of a region. It can be used to estimate the overall changes in economic activity that results from a change in the regional economy. Usually, this economic activity is characterized as the gross and net output of the region and employment. Net output (gross output corrected for intermediate transactions, which would cause "double-counting") is comparable to Gross National Product, so is often called Gross Regional Product.

The general public of the regional community is usually represented by public authorities at various levels of government and/or by public/private partnerships. The public's issues are generally concerned with capacity, reliability, quality and resilience – the adequacy, in quantity and quality, of the available level of service capacity, how often service is interrupted, how quickly service is restored after an interruption, so the community can resume normal functioning as well as how best they can cope with the lack of services during an interruption.³⁷

Dependencies and interdependencies of infrastructures lead to both direct and indirect – "ripple" – effects. In considering the public perspective, the primary concern is the impacts of inadequate or interrupted service as the economic consequences to the utility's direct suppliers and customers. In addition to these "direct" effects, the community incurs "indirect" consequences through reduced economic activity in general, i.e., to the suppliers' suppliers and customers' customers, and so on.³⁸ The economic consequences "ripple" through the regional economy, with the total impacts being some multiple of the direct impacts, hence the term "multiplier effect." Both direct and indirect business interruption impacts resulting from inadequate or damaged infrastructure can be calculated by a straightforward algorithm in the I-O model. Adam Rose developed a methodology originally to fill a gap in the computational ability of HAZUS, the Federal Emergency Management Agency's loss estimation software, and is thus sometimes

³⁷Adam Rose, "Economic Principles, Issues, and Research Priorities in Natural Hazard Loss Estimation," in Y. Okuyama and S. Chang (eds.) *Modeling the Spatial Economic Impacts of Natural Hazards*, (Heidelberg: Springer, 2004), 13-36 and Rose, A. and S. Liao, "Modeling Regional Economic Resilience to Disasters: A Computable General Equilibrium Analysis of Water Service Disruptions," *Journal of Regional Science*, (Vol. 45, No. 1, 2005), 75-112.

³⁸Adam Rose, "Economic Resilience to Disasters: Toward a Consistent and Comprehensive Formulation," in D. Paton and D. Johnston (eds.), *Disaster Resilience: An Integrated Approach*, (Springfield: Charles C. Thomas, 2006), 226-48.

³⁹Multihazard Mitigation Council (MMC), *Natural Hazard Mitigation Saves: Independent Study to Assess the Future Benefits of Hazard Mitigation Activities*, (Washington, DC: Study Documentation. Prepared for the Federal Emergency Management Agency of the U.S. Department of Homeland Security by the Applied Technology Council under contract to the Multihazard Mitigation Council of the National Institute of Building Sciences, 2007), Volume 2; and Rose, Oladosu, and Liao, "Business Interruption Impacts of a Terrorist Attack on the Water System of Los Angeles: Customer Resilience to a Total Blackout," in H. Richardson, P. Gordon, and J. Moore (eds.) *Economic Costs and Consequences of Terrorist Attacks*, (Cheltenham, UK, 2007), 291-316.

referred to as a “HAZUS patch.”³⁹ However, the algorithm can be applied to any estimate of utility service adequacy or disruption to compute both the losses of output to direct utility customers and the indirect (multiplier effect) losses throughout the economy of a given region.

A baseline is estimated by using a conventional I-O analysis (based on as IMPLAN data⁴⁰) with no disruptions, and with forecasts of regional growth. The output is the gross and net regional output and employment, reported in total and sector by sector. Where growth is constrained by the capacity of the region’s respective infrastructures, this is noted as an issue for the strategic plan, the initial step in the overall process. A set of systematic experiments is conducted as additional runs of the model to see the effects of investments that increase capacity and interruptions of infrastructure services based on risk and resilience analysis conducted in the engineering economics model.

Input-output modeling has the virtue of being a well-established, highly empirical, generally accepted approach for cost-effective gross estimation. It has several shortcomings that may compromise its application to the immediate problem. One is that I-O models are based on historical data, so changes in the historical relationships among industries due to, for example, changes in technologies, efficiency improvements, etc., must be reflected by interventions in the models for which there is little empirical basis. A second limitation is that the relationships are all necessarily linear, so non-linear dependencies cannot be captured. A third is that, even though the I-O model is disaggregated by industrial sector, it has no specific reference to geospatial reality, so it cannot reflect where a capacity bind occurs or how specific investments in a networked infrastructure will affect the overall capacity. And, finally, I-O models are relatively poor at capturing the actions of certain infrastructures for which product pricing poorly reflects cost or value. Some of these, such as most highways, do not charge an explicit fee for their services. For others, such as most potable water, charge fees that cover the operations, maintenance, debt service, etc., but not for the primary raw material, the water that enters the system. The price of water poorly reflects its value.

E-2. Systems Simulation. Greater precision and a much more insightful treatment of dependencies, interdependencies and the effects of investments in specific facilities can be had using systems simulation models. They expressly model infrastructure systems as nodes representing specific facilities and links by which the services provided by the facilities reach their intermediate and end users. They require more data and greater sophistication in the analytic staff who use them.

A systems model is a scalable set of nested models that relate the impact of a wide range of natural or man-made events, including investments in new or up-dated infrastructures as well as hazards to existing infrastructures, on one or more metropolitan infrastructure components to key measures of metropolitan viability. The basis for the approach is a framework for assessment of critical infrastructure protection and foundational infrastructure development illustrated in Figure E-1. The framework captures the relationships between infrastructures, public and private institutions, and society. The basic premise that defines the framework is that infrastructure drives public and private institutions to produce goods and services. These goods and services then drive societal performance that is measured as quality of life and economic activity. Therefore, infrastructure capacity and resilience requirements are ultimately defined by minimum acceptable institutional performance to meet minimum societal needs.

⁴⁰IMPLAN, *op. cit*

As an example, an event that reduces the electrical power production at an individual power plant on a metropolitan power grid is potentially related to the performance of all other key infrastructures. Given that there is an impact, the net effect on the infrastructure complex is determined and the impacts are mapped to the utilization patterns of the public/private institutions that generate the goods and services that are consumed by individuals and commercial entities to produce a regional quality of life and economic activity.

Measures of impacts at each level of interest in this example would include the reduction in electrical production capacity and in distribution patterns. In turn, the impact on household and commercial availability of electrical power is related to a reduction in the quality of life and economic activity. Impact on quality of life is measured in terms of reduced household incomes, reduced free time, and reduced mobility. Impact on economic activity is measured as a reduction in commercial activity in terms of industrial output, knowledge worker productivity, and Gross Regional Product.

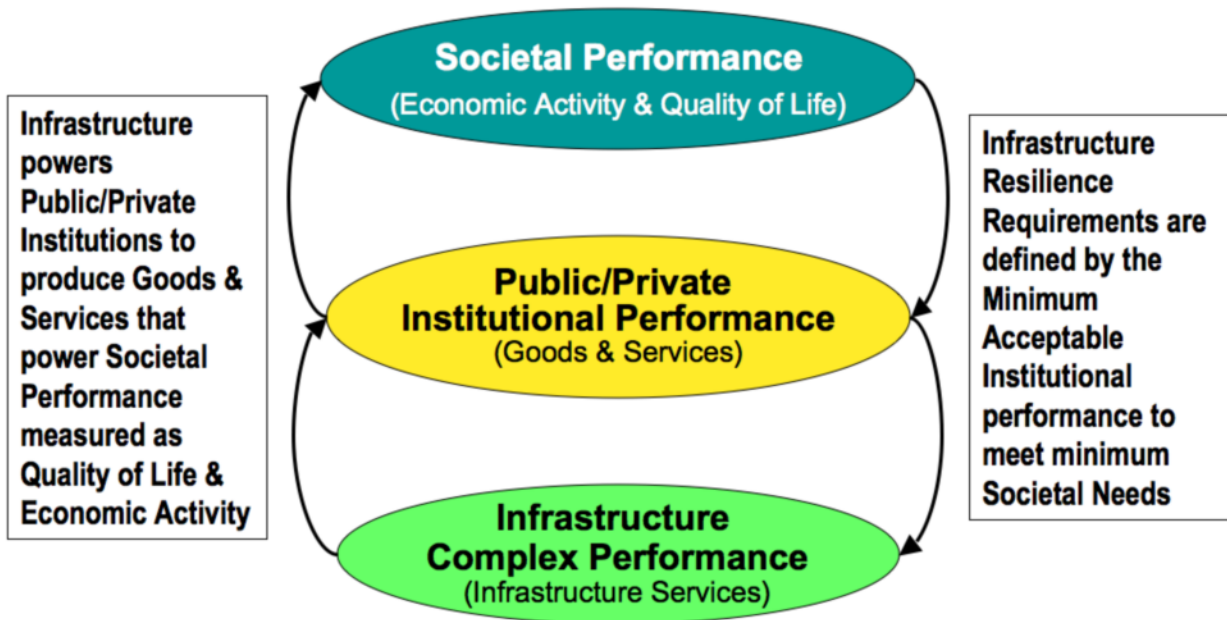


Figure E-1. Schematic View of an Infrastructure Systems Model
(Courtesy of Alion Science and Technology⁴¹)

Nested models follow the infrastructure-institution-societal-performance framework. Nested models represent a metropolitan region as an interactive, interdependent network formed by nodes and links. Nodes represent points of infrastructure production or points of infrastructure consumption. Visualization of a simple node and link mode are displayed in a geographical context, providing decision makers with the ability to observe critical nodes and links and their interactive, interdependent response to natural or man-made events that impact infrastructure performance or the delivery mechanisms. Interactivity with nested models at the node and link level allows decision makers to make adjustments to nodes and links representing investments of limited resources. Immediate feedback on the impact of the investments is provided supporting a business case analysis of individual or bundled resilience investments.

⁴¹Alion, *op. cit.*

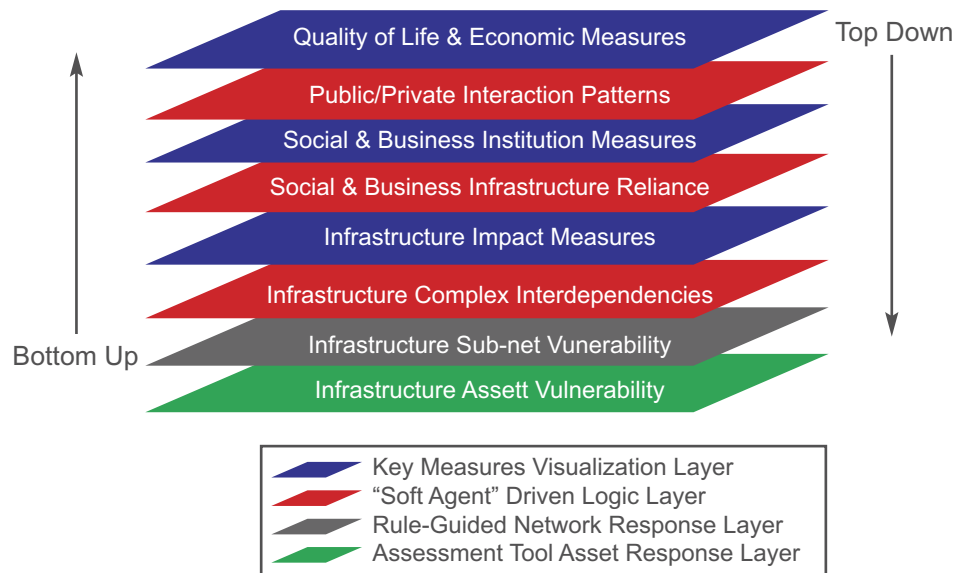
The approach is carried out by development of a three-tier modeling environment. An upper tier represents the performance of the metropolitan region addressing measures of impacts of quality of life, and economic activity. This layer is informed by the type of information that would be found in higher level regional reports such as those prepared by metropolitan and regional development commissions. An intermediate tier represents the nature of the relationships and interactions between public and private sectors that combine to deliver the goods and services that drives social and economic activity. This layer is informed by regional reports on social and business patterns and an understanding of the regionally specific interconnectivity between key public and commercial institutions and their dependence on infrastructure services ranging from electrical power and internet connectivity to basic transportation and drinking water. A lower tier represents the infrastructure layer. In this layer, the individual infrastructures are represented as sub-nets formed by all of the contributors within an infrastructure sector. Each of the contributors is represented as producers within the sub-nets.

The approach employs a simultaneous top-down and bottom-up model development effort (Figure E-2). The top-down model development component serves to generate the integrating layer relating the impact of natural or man-made events on individual or multiple infrastructure components to key measures of quality of life and to economic activity. The upper integrating layer generates the key metrics that indicate the vitality of a metropolitan region while accounting for the impacts on the major regional industrial sectors due to the impact on the underpinning infrastructure complex.

The bottom-up component starts with primary event impact assessment as each of the infrastructure sectors of interest is assessed to examine the effects of investments in new or renewed infrastructures and the vulnerability to specific natural or manmade events using the common engineering-economics model described above. Assessments of individual assets are conducted to generate a base layer relationship understanding of the value and resilience of the infrastructure sub-systems and the system as a whole.

The result of the engineering-economics assessment is the ability to translate the occurrence of an event scenario into an impact target list. The event impact target list is fed into the base model layer in a time series generating an infrastructure performance profile over the assessment time horizon. The output of the base model layer is a performance forecast for each infrastructure asset as it responds to the event target list.

Figure E-2. Top-Down/Bottom-Up Systems Model Development
(Courtesy of Alion Science and Technology)



The resulting nested model is reflected as a series of intermediate layers that alternate between aggregation layers and visualization layers. The aggregation layers employ logic that captures the interdependency, consumption, and interaction patterns that generate measures of how the metropolitan region performs at the infrastructure, institution, and societal levels. Key measures are displayed supporting decision makers seeking to determine mitigation and investment strategies.

Several systems models are commercially available. One that appears to meet the present requirements particularly well is *SmartMoves*[™] offered by Alion Science and Technology. *SmartMoves* is a network analysis tool that allows analysts to generate a representation of system behavior using nodal methods that employ “soft agents,” a model component that can employ a wide range of methods to affect the transfer function. The methods range from Bayesian methods associated with probability and certainty to “Fuzzy” inference systems that capture operational experience and empirical data while overcoming ambiguity or incompleteness in supporting data sets. “Soft agents” provide a means to emulate phenomena in a mathematical context serving as the response engine at each node within the system. The agents call upon a wide variety of stimulus-response functions that efficiently characterize the response to each of the incoming stimuli. Much of the input data can be obtained from existing geographic information systems maps and interviews with local experts in the respective infrastructures. Using existing and experiential information allows useful modeling even with partially incomplete data.

The *SmartMoves* system allows sensed or user specified values to stimulate the model. Impulse and time-dependent stimuli are accepted. Time series runs generate the impacts caused by the increase, cessation, reduction, or gradual decay of critical flows between infrastructure components that make up the system. Nodes representing key infrastructures are connected together in a network diagram in which flows of energy, material, funds, and information are depicted as connecting arrows representing dependencies. Interdependencies are modeled within the context of the unique metropolitan area or regional infrastructure complex. The network diagram allows a change at one node (representing a new investment or a disruption) to be pulsed through the system providing insight into the cascade pattern and the magnitude of impact at any particular node within the system. As the nodes within the system are affected, the performance of the infrastructure sectors within the system is affected. Measurements of changes in performance are linked to key socio-economic measures of interest providing insight into the negative impact of a failure or the positive impact of a new investment. The complex is represented in an intermediate layer that captures the interactions between infrastructures. Connections are established according to actual lines of geospatial connectivity. Primary and backup connections are included and protocols for switching between them are embedded in the “soft agents”. The inter-connections reveal the ripple effect and the cascading failures that may be associated with a change in performance of one or more key infrastructures at specific locations in the region.

SmartMoves allows empirical information to be used as the basis for predicting system behavior under a range of conditions. *SmartMoves* methodologies simplify the network modeling process allowing a ‘inference’ based solution to be used as a means of overcoming the impossibly complex mathematical calculations that would be required to resolve the dimensional incompatibility associated with a purely computational evaluation of the impact of a change in one of many inputs at one of many nodes in an output producing system. The method recognizes the different, non-linear relationships that link one function with another. Analysts make assessments and categorize a relationship by choosing from a library of basic functions. As data are acquired and analyzed, the typical functional shapes are modified

and calibrated to reflect the empirical information. As an example, a power plant that has a dependency on a municipal water system may realize a 50% reduction in power generation capability at a 25% reduction in cooling water availability.

APPENDIX F. EXAMPLE USE OF AHP IN AN INFRASTRUCTURE PORTFOLIO OPTIMIZATION

A small example problem was developed using the Decision Lens software. The criteria were the ones introduced in an earlier section. This section uses a series of screen shots to illustrate the logic of the solution through a simple step-by-step application of AHP and portfolio optimization.



Figure F-1. Define the Criteria of Merit

The first step is to define the infrastructures goals, objectives, and criteria. In this case, economic competitiveness, social equity, infrastructure project economics and sustainability are primary criteria with a number of sub-criteria (all are not shown). Structuring this hierarchy, the first step, was the result of considering a much longer list (Appendix A).

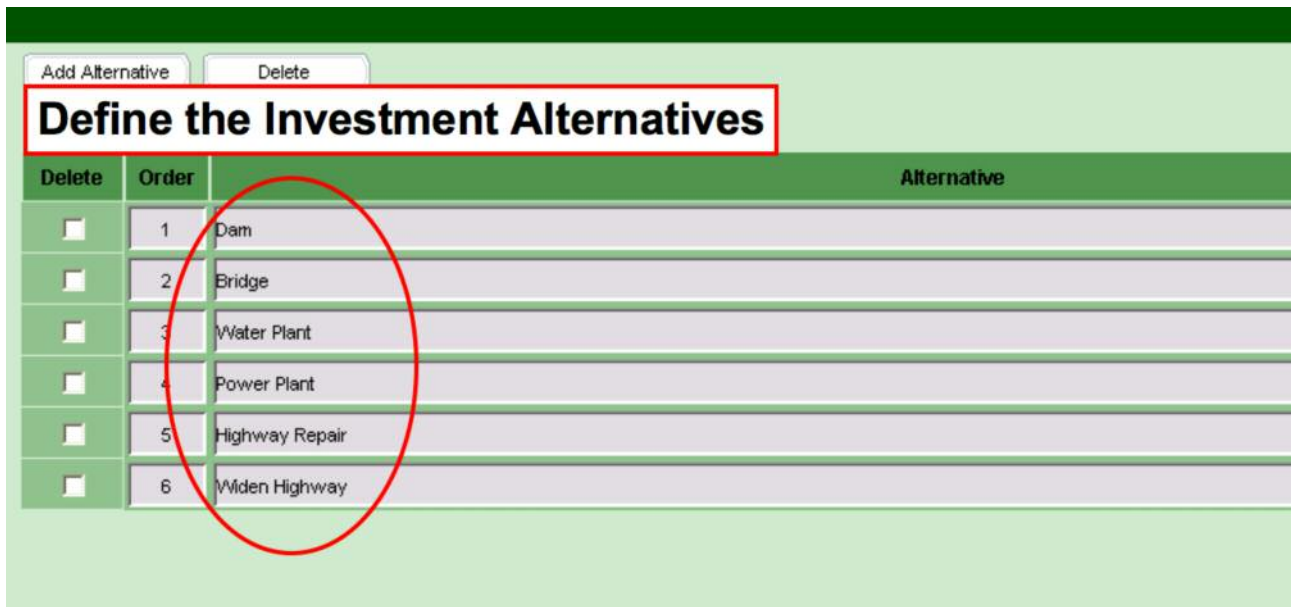


Figure F-2: Define Investment Alternatives

Once the criteria have been determined, investment alternatives are defined. In the example, only six have been included, but a virtually unlimited number could be added. Below, three decision-makers were to be included. A much larger number could have participated and their priority levels could be adjusted as necessary.

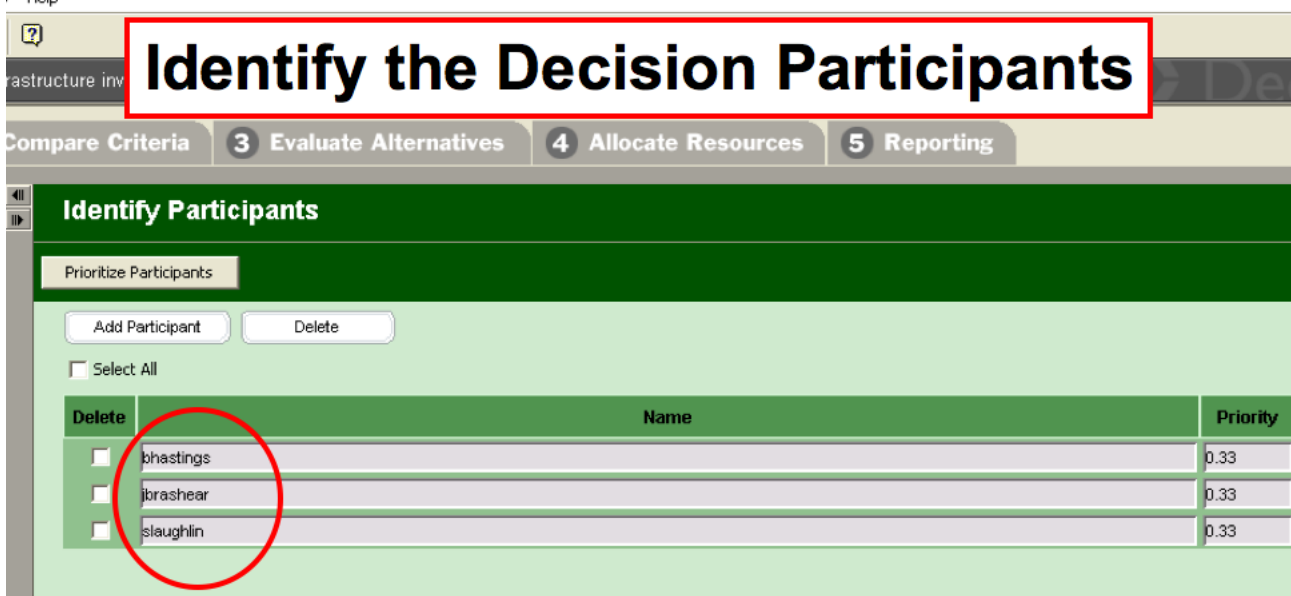


Figure F-3: Identify Decision Participants

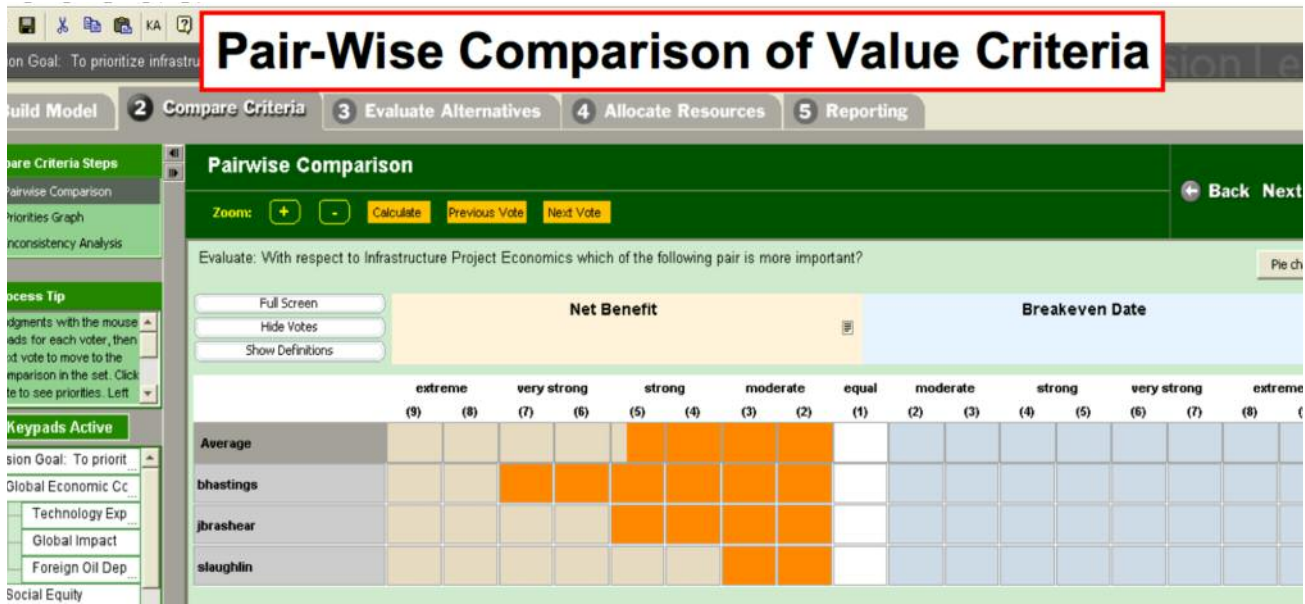


Figure F-4A. Pair-Wise Comparison

The participants then took up each possible pair of criteria and judged whether one or the other criterion is more important to the goal and, if so, by how much.

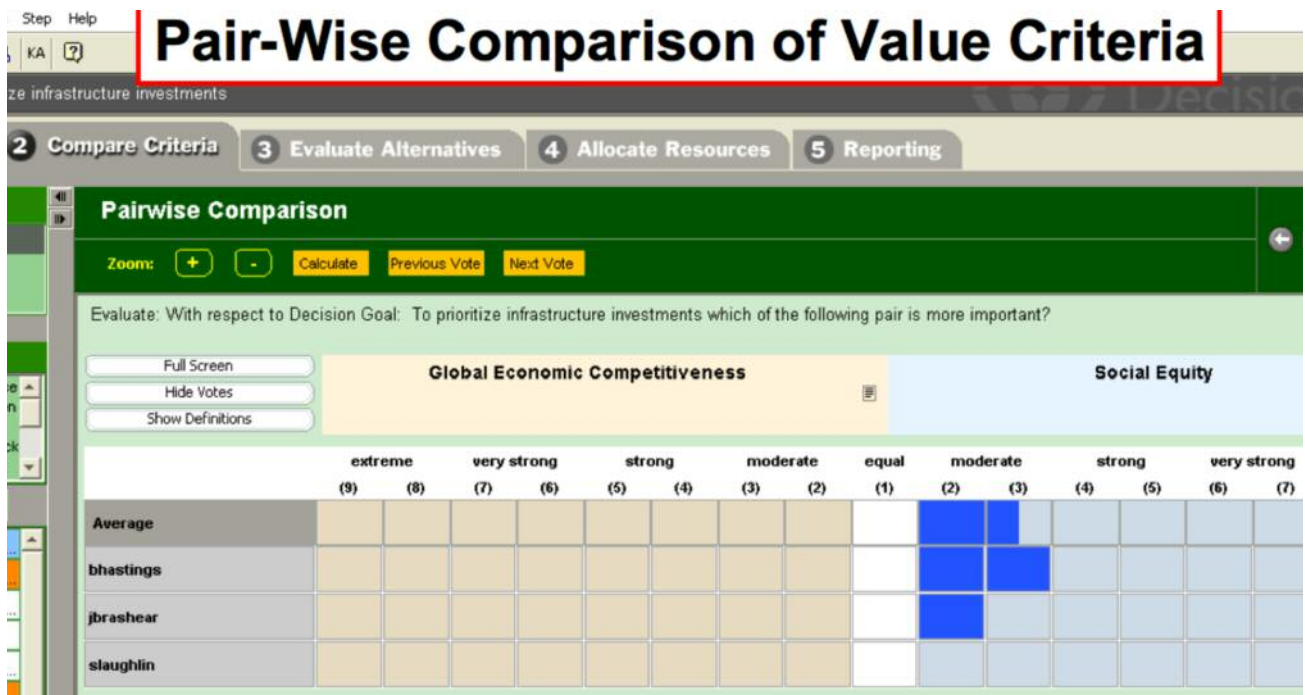


Figure F-4B. Pair-Wise Comparison

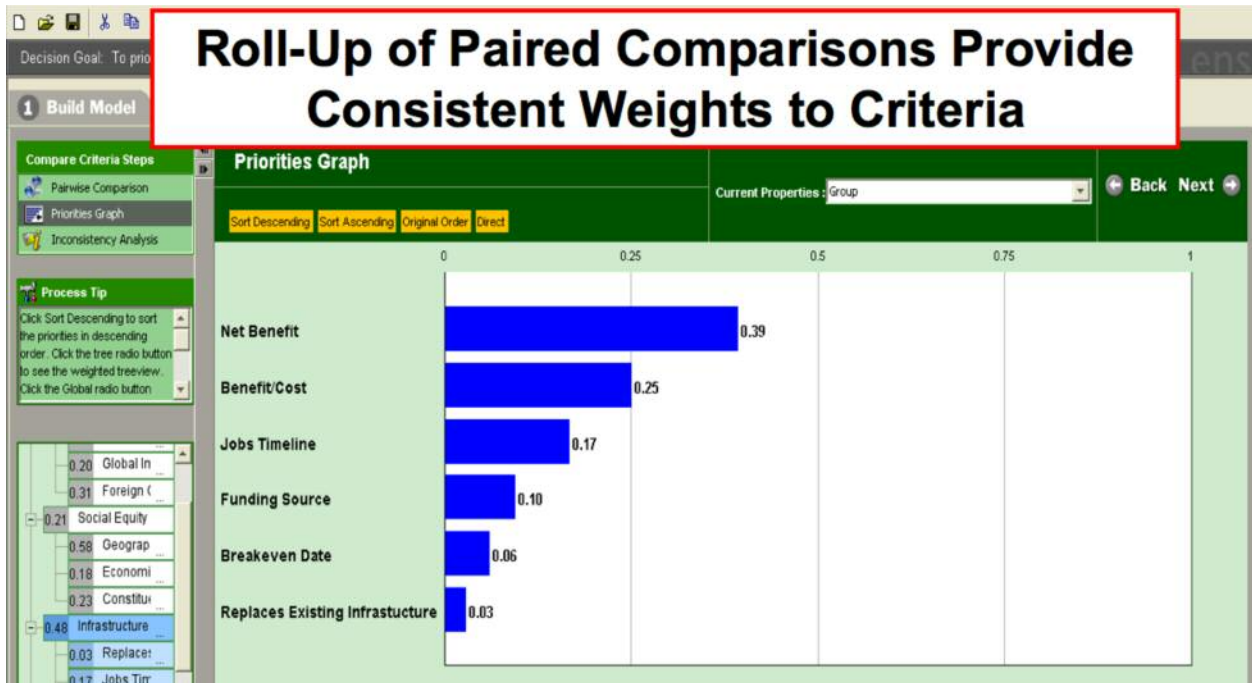


Figure F-5A. Weighted Criteria

These paired comparisons are rolled up to yield weights for each sub-criterion and criterion. The consistency index shows a very good consistency (significantly less than 0.1).

Criteria Judgments Roll Up to Criteria Weights

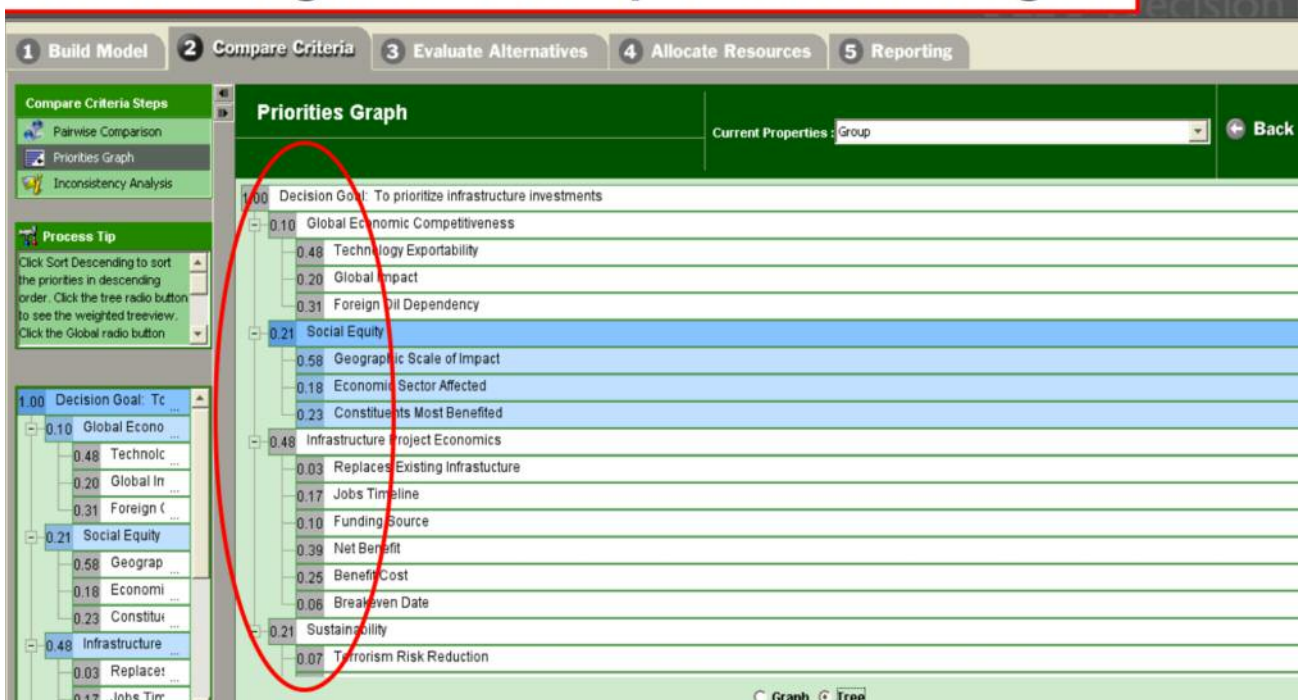


Figure F-5B. Weighted Criteria

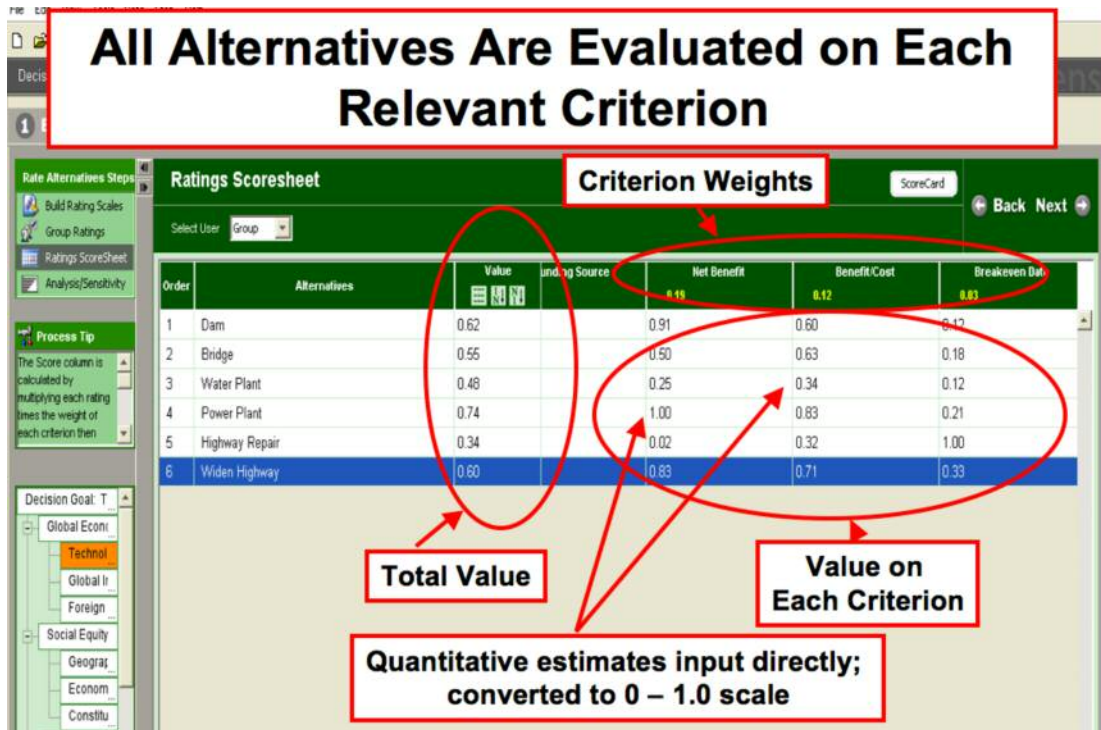


Figure F-6. Alternatives Evaluated

Each alternative investment is then valued overall and on each criterion. This value is the total multi-attribute benefit of each alternative investment. The alternatives are reviewed to assure correct scoring. The simple “dashboard” facilitates understanding of strengths and weaknesses.

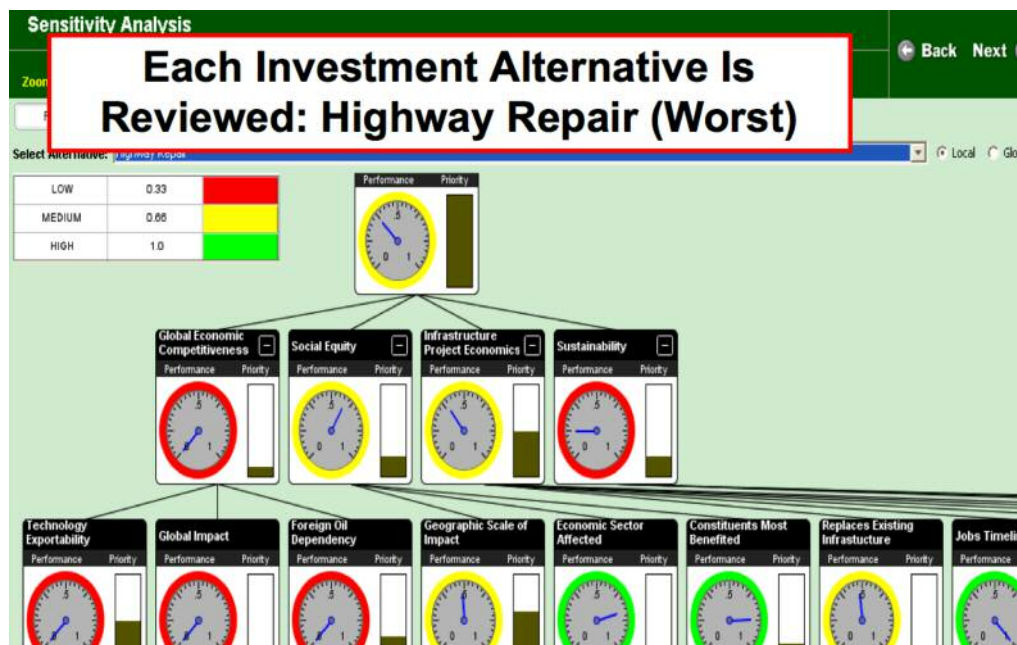


Figure F-7A. Alternatives Reviewed

Highway repair scored relatively poorly...

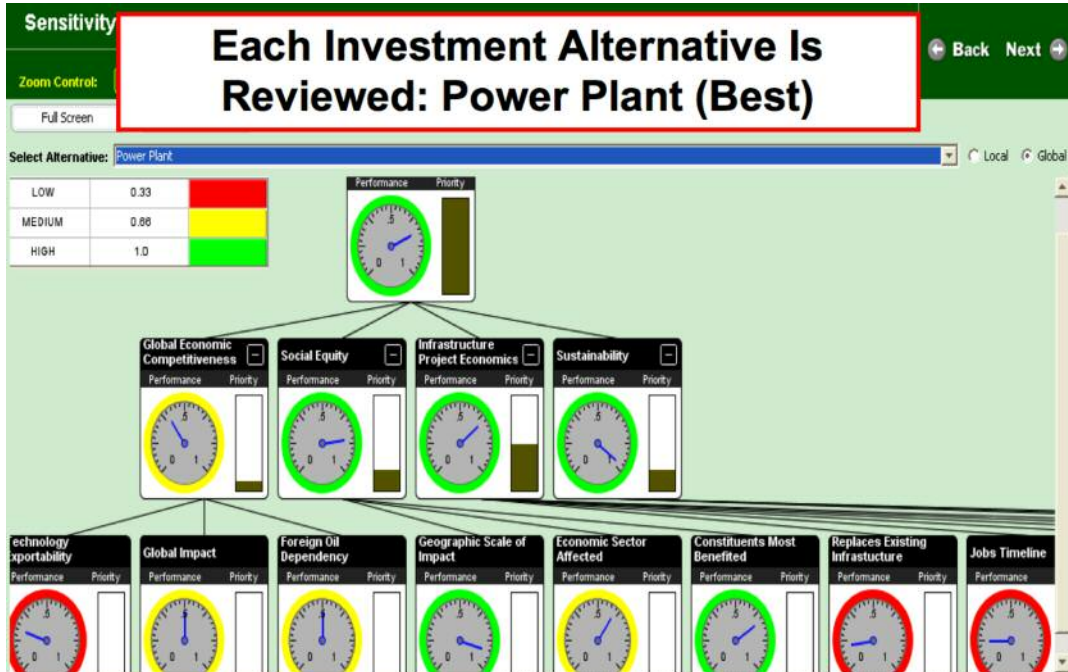


Figure F-7B. Alternatives Ranked

... while the power plant investment scores substantially higher.

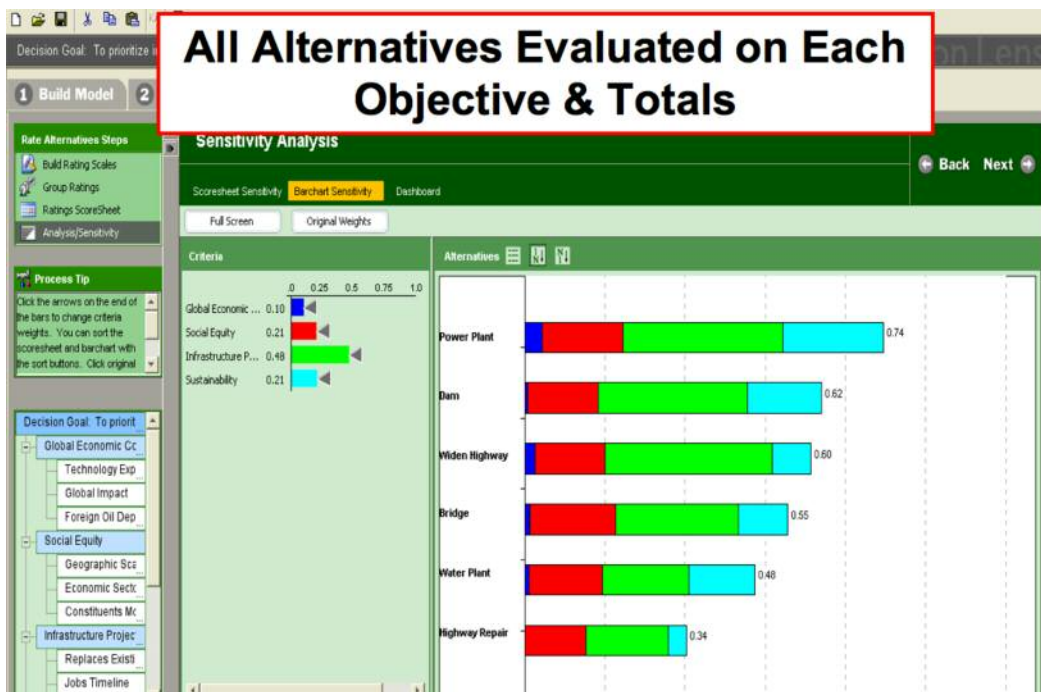


Figure F-8. Alternatives Evaluated on Objectives

This display shows which criteria contribute to the scores for each. The arrows in the upper left of the screen permit sensitivity analysis of alternatives to variations in the criteria weights.

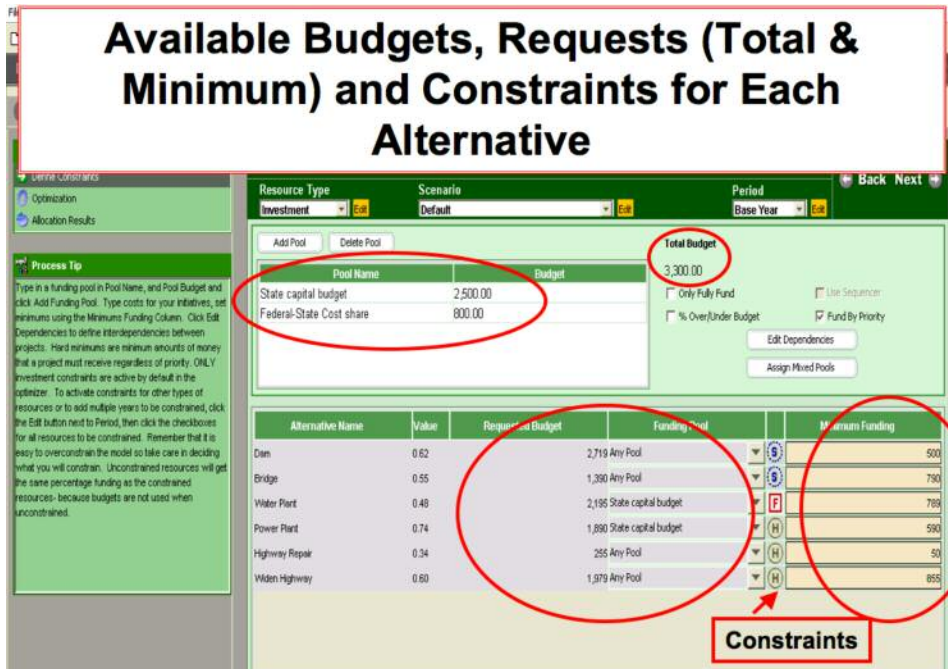


Figure F-9. Constraints on Alternatives

Each alternative is priced in the engineering economics model. Budgets from multiple pools are defined and constraints are set, mandating certain projects, eliminating incompatible combinations, setting required minima and multi-year funding.

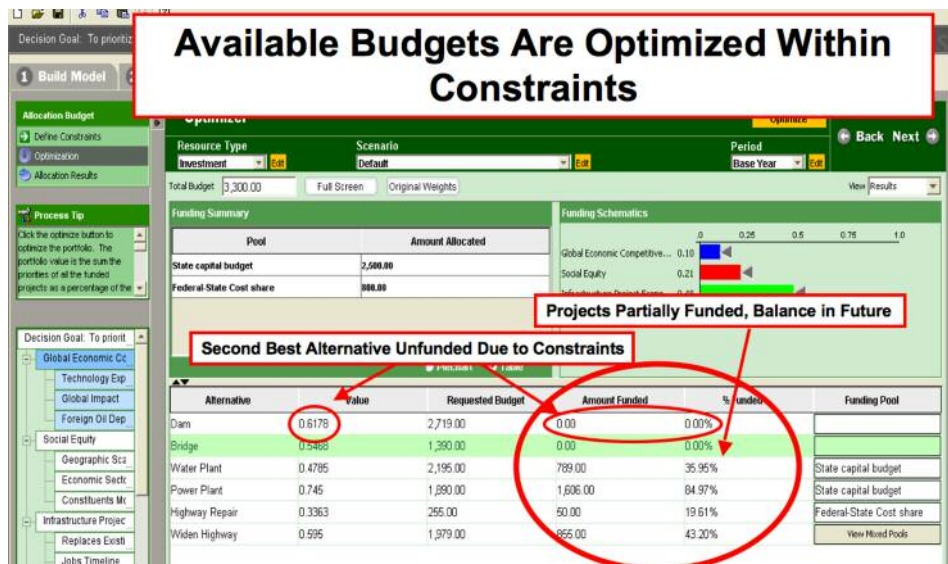


Figure F-10A. Budgets Optimized within Constraints

The software optimizes by benefits per dollar of investment (different from benefit per life cycle cost used as one of the criteria), within all the constraints. Some projects are partially funded to be completed in later years, typical of multi-year construction. The optimizer found a solution that best fit the constraints by not selecting the alternative with the second highest benefit score, but a lower benefit per investment dollar score.

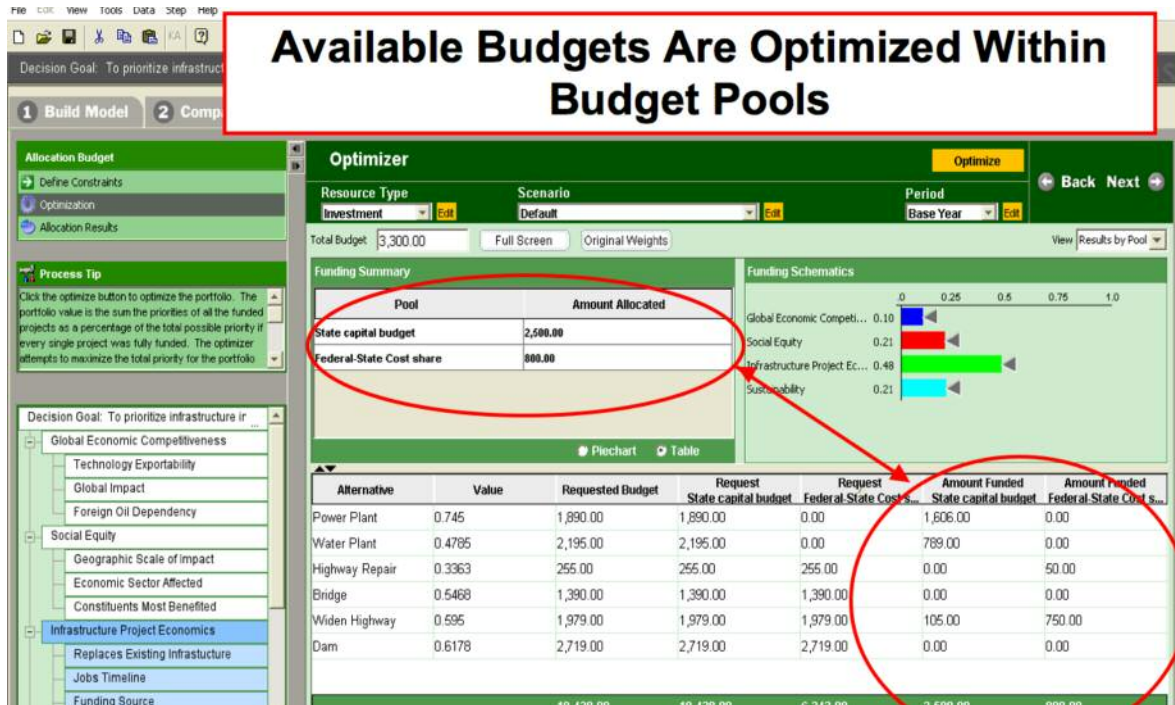


Figure F-10B. Budgets Optimized within Constraints

The AHP software is intuitive and can fully optimize investments and allocation of other resources for particular projects.



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