Evolution of Infrastructure-Based Systems

But it came to me then, I am sure, for the first time how promiscuous, how higgledy-piggeldy was the whole of that jumble of mines and homes, collieries and pot-bands, railway yards, canals, schools, forges and blast furnaces, churches, chapels, allotment hovels, a vast irregular agglomeration of ugly smoking accidents in which men lived as happy as frogs in a dustbin. Each thing jostled and damaged the other things about it; each ignored the other things about it, the smoke of the furnace defiled the pot-bank clay, the clatter of the railway deafened the in church, the public house thrust corruption at the school doors, the dismal homes squeezed miserably amidst worshippers the monstrosities of industrialism, with an effect of groping imbecility. Humanity choked amidst its products, and all its energy went in increasing its disorder, like a blind stricken thing that struggles and sinks in a morass.

H.G. Wells, **In the Days of the Comet**, 1906

Introduction

More than a hundred years ago, H.G. Wells, following in the tradition of Dickens, Jules Verne and other great 19th century novelists, railed against the pollution, the ugliness, the immorality, and the disorder of city life in the industrial society. In one scathing paragraph he raises vivid images of many of the disorders that have plagued cities for thousands of years and that persist to this day: pollution, noise, corruption, thoughtless development, and horrid environments for children. Today, other ills and other fears could be added to the list: climate change, over-use of fossil fuels, looming crises with respect to water supply, fears of lethal flu pandemics, terrorism, and even collapse of civilized life in more than one country. What is to be done?

What is to be done is what has always been done: recognize the problems, understand the causes of the problems, and try to do something to deal with the problems. The worst excesses of the Industrial Revolution that were so well depicted by Dickens have been eradicated by regulation of industry, better energy technology, and provision of social services to the poor. The "dismal homes squeezed miserably amidst the monstrosities of industrialization" have, at least in the developed countries, been succeeded by urban regions that have evolved into places more suitable for people. Humanity struggled mightily during the 20th century with its World Wars, political upheavals, and innumerable lesser wars and disasters, but for the most part, we have not yet sunk into the morass, and we seek to improve the world for our children and grandchildren.

Over the past two hundred years, investments in infrastructure have made astounding differences in the quality of life for most people in most areas of the world. First railways, then automobiles, buses, and airplanes brought mobility to unprecedented levels. With cheap transportation and warehousing, it is possible to ensure that food and other supplies are available throughout the world; droughts and natural disasters still cause hardship, but relief efforts can at least limit the amount of on-going loss of life and despair that once followed such calamities. Construction of reservoirs, aqueducts, and water treatment facilities eliminated the ravages of cholera and other diseases and allowed cities to grow without destroying the health of their citizens. The telegraph, then the telephone, and now the internet have made instantaneous communications a reality and a global perspective a necessity. Innovations in design and materials have reduced the costs of construction, allowed construction of skyscrapers, and made it possible to create great cities. Better regulations have helped to reduce air quality and water quality, and public and private initiatives have created hundreds of parks and ecological reserves.

We have made a great deal of progress. But much more remains to be done. People need to continue working to create a more sustainable world, and much of this effort must be allocated toward creating more sustainable infrastructure-based systems. This will be a slow process, because infrastructure systems last for decades and cannot be changed overnight. This will be an evolutionary process that incorporates and responds to new technologies, new management techniques, and major changes in society's perception of infrastructure needs and performance. This will be an important process, because we will all benefits as we move toward systems that can be more easily maintained, that are better suited toward society's needs, and that are less intrusive upon the environment.

Infrastructure evolves through a series of incremental steps, including specific projects and programs, incorporation of new technologies, development of better management strategies, use of new types of materials and energy sources, and new regulations concerning the use and design of infrastructure. It is important to take a long-term perspective in thinking about moving toward more sustainable infrastructure. While progress may be slow, progress is certainly possible. Understanding how infrastructure systems evolve can be helpful in looking at any proposed project. The historical context will always be important, and knowing about the different stages in infrastructure evolution can be helpful in determining whether a particular proposal is meaningful step in the right direction or merely an ill-fated attempt to keep an obsolete system functioning for a few more years.

Very few infrastructure projects are either completely new or completely independent. Most projects will be implemented using proven technologies and construction methods, and the completed project will fit into an existing network or an existing pattern of similar facilities serving much the same purpose. Project evaluation may often boil down to rather simple ideas: rents are high so this is a good time to build office buildings; roads are congested so let's build more roads; demand for electricity is growing so let's build more power plants; demand for water is growing, so let's build more reservoirs; the number of children is increasing so let's build more schools. In all of these cases, the needs are clear; the costs of building some more capacity are well-understood; and it is easy to figure out whether the investment is justified given the potential revenue from rents, tolls, or fees or the willingness of the public to pay taxes for schools and infrastructure. There may be long periods of time when society continues along a well-defined path, expanding infrastructure as needed to handle growth in population and rising demand for services.

However, these periods of stability will eventually be disrupted by fundamental changes in technology, institutions, political power, economic conditions, or societal norms. Technological innovation, which will continually be offering opportunities to improve the functioning of an existing system, will from time to time make it possible to introduce much better systems. In the early part of the 19th century, canals took freight from toll roads; a few decades later, railroads began to take freight from the canals; a hundred years later trucks operating over paved roads began to take freight from the railroads. And throughout this period, technological improvements for roads, canals, railroads, vehicles, and communications helped to reduce the costs of all kinds of freight transportation.

Table 1 indicates different stages that may be encountered in the evolution of transportation or other infrastructure-based systems. As with freight transportation, the evolution may be something that proceeds over hundreds of years, with different infrastructure systems emerging to support new technologies. Reaching a new equilibrium may take decades, and if technological innovation continues, an equilibrium may never be reached. Instead, the new systems will be growing side-by-side with the older systems that are in decline.

Table 1 Stages in the Evolution of Infrastructure-Based Systems

I	Technological Experimentation and Demonstration
II	Wide-Spread, Uncoordinated Implementation
III	Development of Systems
IV	Consolidation and Rationalization
V	Technological and Institutional Advancement
VI	Responding to Competition
VII	Mitigating Social and Environmental Impacts
VIII	Retrenching and Obsolescence

We will address each of these stages, keeping in mind that there is no pre-determined sequence or timetable for passing from one stage to another. The basic methods and concepts of project evaluation can be useful in any of these stages of development:

- Identifying needs and objectives and generating alternatives for meeting those needs.
- Specifying criteria for evaluating alternatives and conducting financial, economic, environmental and social analysis.

- Assessing the differences among alternatives using weighting schemes and an appropriate political process involving major stakeholders.
- Selecting the best strategy and refining it to increase efficiency and effectiveness and to mitigate negative environmental and social impacts.

Understanding the themes and issues that are likely to be encountered in each stage of development may be helpful in focusing the evaluation on the most relevant concerns and avoiding some of the most costly mistakes in evaluation. It is useful to understand how infrastructure-based systems have evolved over a period of decades in order to gain some insight in the evolutionary process. For example, several technological developments of the late 19th century made it feasible to build much taller buildings, which meant the economics of urban real estate were markedly and forever changed. The ability to make more intensive use of land led to dramatic increases in urban development, with a perhaps inevitable cycle of boom and bust. Railroads have been evolving for nearly 200 years, providing an even longer perspective on the evolution of an infrastructure-based system. Large portions of the rail system have already reached the final stages of obsolescence, and the railroads have already retrenched; operating over smaller networks using better technology, they are now serve fewer customers whose traffic is best suited to the low-cost service that railroads can provide.

Engineers, planners, politicians, corporations, and the public will faced major challenges in the 21st century in order to move toward more sustainable infrastructure. Many kinds of projects will be needed to meet these challenges, including rehabilitation of existing infrastructure in order to extend its useful life, replacement of certain elements of existing infrastructure in order to enhance performance, and construction of new infrastructure that embodies more sustainable technologies and designs.

Stage I Technological Experimentation and Demonstration

From time to time, someone comes up with a new technology that seems to offer a better means of satisfying some basic need of society. The first task is to figure out how to make the technology work, which may take years of experimentation and tinkering. Eventually there will be a demonstration that the new technology works, and there will be a few entrepreneurs or government agencies who back some initial implementations to determine whether or not the technology is financially feasible. Two hundred years ago, inventors figured out how to use a steam engine to pull a few cars along a railroad track at 10-20mph, which was a great improvement over a horse & wagon or a canal boat; in the 21st century, there are a few demonstrations of how to use magnetic levitation for a train to reach speeds close to that of airplanes. The railroad proved to be an extremely successful technology, and hundreds of thousands of miles of rail lines were constructed throughout the world within a hundred years of its introduction. It remains to be seen whether magnetic levitation proves to be a wide-spread alternative to air travel or remains an odd-ball tourist attraction for getting to and from the airport in Shanghai and perhaps a few other locations.

Relevant methodologies:

- Measuring System Performance: what kinds of performance improvements are most critical? What technologies are likely to provide such improvements in performance? How will any proposed technology affect cost, capacity, service quality, safety and other aspects of system performance?
- Probabilistic risk assessment: what are the risks associated with the new technology? How can those risks be minimized? Will the new technology be perceived as safe by potential users, abutters, and the general public?
- Performance-based technology assessment: will the anticipated improvement in performance be enough to attract users or supporters who will be willing and able to pay for the new system?

Potential pitfalls:

- Excessive investments in technologies that, even if successful, are very unlikely to attract much of a market.

- Introduction of a technology without adequate safeguards, leading to highly publicized failures that cause governments or the public to reject the technology.
- Introduction of a technology without adequate consideration of externalities, leading to government or public perceptions that the technology should be rejected because of its impacts on abutters, communities, or the environment.
- Failure to consider the potential impact of new technologies, thereby delaying the introduction – and deferring potentially large benefits – of new technologies.
- Government regulations that reject or hinder new technologies that would have broad benefits to society, but that are opposed by special interests.

Stage II Widespread, Uncoordinated Implementation

Once the technical and financial feasibility have been demonstrated, there will likely be a great many uncoordinated, fiercely competitive attempts to build up the infrastructure and related systems for the new technology. Once the automobile was shown to be feasible, dozens of manufacturers emerged, producing a great variety of styles and experimenting with steam and electrical systems for propulsion as well as with the internal combustion engine. The early automobiles had to use the existing roads, which were little better in 1900 than they had been in 1800 (and not as good as the roads that the Romans had built nearly 2000 years earlier).

<u>Relevant methodologies:</u>

- Financial Analysis: how will introduction of the new technologies be financed?
- Brainstorming, sensitivity analysis, and scenarios: what are the options for deployment? What are the factors that are most likely to affect success or failure?

<u>Potential Pitfalls:</u>

- Starting up too small, with insufficient coverage to attract enough users to support the service.
- Starting up too big, resulting in too much debt and too little revenue.
- Starting without adequate financial reserves, leaving the project vulnerable to a strong response from competitors or a downturn in the economy.
- Waiting too long to get started, which means that competitors capture the market.

Stage III Development of Systems

The initial, uncoordinated efforts will provide a great deal of information and insight concerning what is needed for reasonably efficient implementation of the new technology. Companies involved in network-based systems (such as electricity transmission, irrigation, transportation and telecommunications) will realize that there are economies of scale and density; they will try to expand, via construction or mergers, to obtain these economies. Cities will realize that some systems, such as water delivery, need to be coordinated to avoid costly duplication of infrastructure and to allow cost-effective services to customers. Companies and public agencies will decide how best to structure their systems, whether or not to integrate operations and maintenance of the systems, and how best to coordinate their activities with related activities. During this stage of development, attention must be given to structuring and integrating infrastructure and operations so as to handle growth.

<u>Relevant Methodologies</u>**:**

- Determining the extent to which there are likely to be economies of scale, scope or density, i.e. understanding how costs and other aspects of performance vary with the structure of the system.
- Identifying and assessing strategic options for expansion.

Potential Pitfalls:

- Creation of unregulated monopolies that in fact achieve great reductions in average cost, but that are able to charge excessive prices for their services.
- Difficulties in consolidation caused by lack of interoperability, i.e. the failure of companies and agencies to develop compatible technologies that will facilitate coordination and cooperation.
- Competition that reduces prices to marginal costs that are below average costs, thereby limiting the ability to finance desirable increases in capacity or enhancements to facilities.

Stage IV Consolidation and Rationalization

It is frequently the case that the enthusiastic response to new technologies leads to overbuilding, the creation of infrastructure that has too little or too much capacity, and the inevitable problems in design and network structure that come from the initial uncoordinated investments. Even though the size and scope of the systems may be reasonable, there will be many opportunities for improving performance by consolidating portions of the system, by eliminating bottlenecks, and by abandoning pieces that are obsolete or underutilized.

Relevant Methodologies:

- Basic modeling of costs, service, competition and financial viability.
- Estimation of public benefits of consolidation and rationalization (in order to obtain public support and perhaps public funding for complex projects that will cause major disruptions during an extended period of construction).

Potential Pitfalls:

- Difficulties in abandoning underutilized portions of a network because of public pressures to maintain services viewed as necessary by customers and local governments.
- Difficulties in assembling tracts of land suitable for consolidated facilities.
- Difficulties in financing the investments in a competitive environment where prices are likely to fall quickly to new, lower marginal costs following completion of desirable projects.

Stage V Technological and Institutional Advancement

Managers, researchers, consultants, and regulatory agencies will continually be seeking new technologies, management strategies, and institutional arrangements that will improve the performance of the system. The goals during this stage are to reduce costs, enhance safety or improve service, taking advantage of better control technologies, better materials, or better management. During this stage, system improvements come from looking inward so as to find opportunities for doing the job better. Technological advances may result in the use of new procedures or greatly improve the performance of what were thought to be obsolete procedures.

Relevant Methodologies:

- Basic modeling of costs, service, competition and financial viability.
- Performance-based technology scanning.
- Project and program audits.

Potential Pitfalls**:**

- Failure to provide for adequate maintenance and rehabilitation of the system.
- Failure to anticipate changes in competition, technology, or society; an over-confident management that may suddenly find that the capacity, cost, condition, or service quality of its infrastructure are woefully out of step with what is needed.

Example: New Technology Can Revive Old Methods – Wastewater Treatment in San Diego, California[1]

Recent technological advances have resulted in a major shift in the preferred methods for wastewater treatment. Metal salts were widely used in England in the 19th century to increase the level of coagulation and flocculation in municipal wastewater treatments. While the technique was effective, it greatly increased the amount of sludge that had to be disposed, adding substantially to the overall costs of treatment. As a result, by the 1930s, the preferred method of wastewater treatment changed to unaided gravitational settling followed by a biological process. New techniques, known as chemically enhanced primary treatments (CEPT), have recently improved the performance of primary wastewater treatment plants without generating nearly as much sludge. Since more of the pollutants are removed by CEPT, the demand upon the biological treatments is reduced. Research efforts at the Point Loma wastewater treatment plant in San Diego, California demonstrated the effectiveness of CEPT. Spurred by the need to meet new regulations regarding effluent, the operators came up with a CEPT method that was more efficient, produced minimal amounts of additional sludge, and increased the capacity of the system.

> *"Ultimately the system was so successful that Congress waived the usual requirement for secondary treatment, saving the city an estimated two billion dollars and allowing the construction of a tertiary water reclamation facility that now reuses 15% of the total wastewater flow instead of discharging it into the ocean."*[2]

CEPT is now seen as an excellent, low-cost option for treating wastewater, especially in the developing world, since this method makes it possible to achieve better performance from existing, over-burdened facilities.

Example: Replacing Old Infrastructure with More Effective Systems - Wastewater Treatment in Kaukauna, Wisconsin[3]

The Heart of the Valley Metropolitan Sewerage District of Kaukauna Wisconsin provides services to the city of Kaunauna and nearby towns. The district's original treatment plant was built in the 1930s, then converted into a regional treatment plant in the 1970s, and again upgraded and expanded in the 1990s. Two major factors made further enhancements necessary: population growth and stricter regulations regarding discharge. The district has a population of 42 thousand that was expected to grow to 68 thousand by 2029, which would cause peak demands to exceed the plant's capacity. Second, new state regulations required limiting ammonia nitrogen concentrations to 3.6 mg/L in summer and 10 mg/L in winter, while the existing facility discharged effluent with 20 mg/L. The crucial design problem was the lack of space, since the site had long since been hemmed in by a large mill on two sides and a canal and the Fox River on the other two sides. To handle the expected 100-year peak loads using conventional technology, it would be necessary to add substantial elements to the plant:

- Four primary clarifiers, each with a diameter of 115 feet and a capacity of 60 million gallons/day (mgd)
- Four final clarifiers, each with a diameter of 90 feet and a capacity of 25.4 mgd
- A nitrifying aeration basin area of an acre (200 ft by 200 feet)

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[1] Michael R. Bourke, Donald R.F. Harleman, Heidi Li, Susan E. Murcott, Gautam Narasimhan and Irene W. Yu, *Innovative Wastewater Treatment in the Developing World,* **Civil Engineering Practice**, Spring/Summer 2002, pp. 25-34

[2] Bourke et al., op. cit., p. 27

[3] Thomas E. Vik, Mark Surwillo, *Small Footprint, Big Promise*, **Civil Engineering**, February 2008, pp. 66-85.

Since the site was too small to accommodate these new facilities, it was impossible to consider using conventional technology at that site. The possibility of acquiring a new site was considered, but deemed to be too expensive. Instead, the District decided to use more efficient treatment processes, some of which had been used in Europe, but not in the U.S. To implement the new systems, the District was able to convert portions of the old facility to new uses, to replace some of the old plant with portions of the new system, and to convert some open space and a parking lot to other portions of the new system. The end result was a treatment plant that required a much smaller footprint, provided much higher capacity, and removed much more of the pollutants. Table 2 shows how the primary treatment technologies that were implemented as part of this project used a tenth of the space while removing more of three key pollutants: carbonaceous biochemical oxygen demand (CBOD), total suspended solids (TSS) and phosphorous.

Table 2 Comparison of Conventional Primary Treatment Technologies with Those Implemented in Kaunaua

	Area of Facilities	**Removal of CBOD**	**Removal of TSS**	**Removal of Phosphorous**
Conventional	40,000 sq. ft.	30%	50%	0%
Kaunaua	3,850 sq. ft.	50-60%	70-80%	75-85%

This example provides two major lessons. First, new technologies may make it possible to use existing sites far more effectively by reducing the footprint required for key facilities. Second, new technologies may be more effective, thereby resulting in a better level of service for the infrastructure.

Stage VI Responding to Competition

No system is immune to competition, and competitive threats are likely to increase as the system ages. Competition will reduce demand for a system, and over time competition could eliminate the need for a system. Several kinds of threats are possible:

- **Competition from similar systems**: competition is based upon the ability of the competitors to use similar technologies to provide services to customers.
- **Competition from systems based upon different technologies to provide the same service**: in this type of competition, the competitors use completely different technologies to serve the same types of needs.
- **Competition from systems based upon different technologies that eliminate the need for the service**: in this type of competition, some kind of technological innovation provides a new way of doing business that has the potential for reducing the demand for existing services.

<u>Relevant Methodologies</u>**:**

- Basic modeling of costs, service, competition and financial viability.
- Performance-Based Technology scanning.
- Brainstorming and scenarios.

<u>Potential Pitfalls</u>**:**

- Failure to consider how current conditions might change.
- Overconfidence based upon past glory or past profitability.
- Regulations relevant to old technologies that limit the introduction of new technologies that may require less frequent inspection, support higher loads, or allow different methods of operation

Examples: Competition Faced by the Airline Industry

Competition from Similar Systems: Low-Cost Airlines Competing with Legacy Airlines

During the late 20th century, new airlines decided to serve selected markets from smaller airports using low-cost crews and new, efficient planes. Some of these airlines, notably Southwest Airlines in the U.S. and Ryan Air in Europe, were extremely successful with this strategy and diverted substantial numbers of people from the older airlines. The success of these airlines helped provide an impetus to upgrade facilities and expand capacity at airports in many smaller cities. Airports in Manchester, New Hampshire and Providence, Rhode Island, which are about 50 miles from Logan Airport in Boston, began to compete with Logan for the same air travelers.

Competition from Systems Using Different Technologies to Provide the Same Service: High-Speed Rail Competing with Airlines

High-speed railroads can compete effectively with airlines for trips of 200 to 500 miles. Which mode captures the largest share of the market will depend in part upon technological capabilities and in part upon public policy toward investing in transportation. In many airports, a large percentage of travelers are taking these medium-distance trips, so diverting travelers to trains can reduce the need for investment in airport capacity.

Competition from Systems Using Technologies that Eliminate the Need for the service: Telecommunications Competing with Airline Travel

Video conferencing facilities, cheap telecommunications, and the internet allow virtual conferences that reduce the need for business travel; email allows the exchange of information without requiring the use of the post office; catalog or internet shopping allows people to purchase items without visiting stores. These changes reduce the demand for business travel, reduce the use of aircraft for mail, and increase the use of air freight to support delivery of all those items ordered on-line.

Stage VII Mitigating Social and Environmental Impacts

Social and environment impacts are likely to become more important over the life of any infrastructure-based system for two primary reasons. When a system is first developed, the societal needs may be so clear that any obvious negative impacts of the new system are easily accommodated. However, society eventually demands that something be done about these problems. For example, the benefits of railroads and automobiles in enhancing mobility and opportunity far outweighed the fact that both modes were originally very noisy, dirty and risky.

After a system has been functioning, it may become apparent that its social or environmental impacts are unacceptable. As automobile accidents began to account for tens of thousands of fatalities annually, highway safety became a major issue in both vehicle design and highway design. When the public realized that drunk drivers caused a high proportion of the fatalities, they forced government agencies to impose stricter penalties and greater enforcement of laws intended to reduce driving while drunk.

Implementation of new technologies often creates problems that were not anticipated and that were only identified after many years or decades of experience. For example, automobile exhaust was not a major public concern until well after there were enough automobiles to cause a noticeable degradation in air quality. The initial concerns about automobile emissions were related to air pollution and its effects on visibility, deterioration of buildings, and above all human health. By 1970, it was clear that automobile exhaust contributed heavily to smog and that air pollution was a serious health problem. About that time, governments began to impose regulations on emissions and on fuel consumption, with the result that air quality improved despite increases in automobiles and trucks. The efforts to reduce emissions focused on pollutants, including carbon monoxide, hydrocarbons, and nitrogen oxides. In the United States, emission standards for new vehicles were first imposed in 1968 and strengthened with the passage of the Clean Air Act in 1970. Within twenty years, the average emissions of carbon monoxide and hydrocarbons from new cars were only 4% of what they had been in 1970, while emissions of nitrogen oxides were only a quarter of what they had been. These dramatic improvements were enabled by a new technology, the catalytic converter, which effectively prevented the release of most of these pollutants.

Although the air quality in major cities improved because of regulation of emissions, a new, more difficult problem emerged, namely the threat of global warming and climate change. As the 20th century came to an end, scientific evidence increasingly pointed to an accelerating world-wide rise in average temperatures and a link between global warming and the emission of greenhouse gases. These gases not only included carbon monoxide, hydrocarbons and nitrogen oxides, they also included carbon dioxide, which is much more difficult to control and which is not normally considered to be a pollutant. By the early 20th century, the threat of global warming was clearly linked to the increasing levels of carbon dioxide in the atmosphere. Today, there are serious efforts to reduce consumption of all fossil fuels, and, in particular, to develop alternative fuels for and to increase the fuel efficiency of automobiles and trucks. In the U.S., federal legislation required the use of ethanol as an additive to gasoline. Ethanol can be produced from corn, sugar cane or other biological sources, so the use of ethanol can reduce the use of fossil fuels. This legislation led to the construction of numerous facilities for producing ethanol along with substantial investment in rail lines that would serve the new ethanol plants. The requirement for using ethanol in gasoline created such an increase in the demand for corn that the price of corn for food increased around the world - another problem that society must deal with.

Other problems that will influence the evolution of infrastructure in the 21st century include:

- Awareness that activities in one area are threatening the environment in other areas.
- Concerns for energy cost may require new materials and new designs for buildings and transportation systems.
- Societal norms may change, making environmental quality and sustainability much more important factors in evaluation factors.
- Societies may decide to devote more resources toward protection from natural disasters such as earthquakes, tsunamis, and hurricanes.

The following examples illustrate some of the problems that have emerged and some of the steps that have been taken to deal with them.

<u>Activities in one area threaten the environment in other areas:</u> widespread use of irrigation and fertilizers were part of highly successful efforts to improve the yield of farms in the Midwestern U.S. Vast networks of irrigation canals and drainage systems were used to make it possible to farm areas that otherwise would have been too dry or too wet. Moreover, in order to maximize production, lands very close to waterways and wetlands were cultivated. As a result of these agricultural practices, excess fertilizers are washed into the rivers that feed into the Mississippi River and eventually flow into the Gulf of Mexico, with devastating consequences.

<u>Concerns for energy cost influence design of buildings</u>: as energy costs and public concerns with global warming rise, companies are beginning to be interested in reducing the energy required in large buildings. For example, the Pearl River Tower in Guangzhou, China was designed to be the most energy efficient of the world's tallest skyscrapers. Although the original goal of being energy neutral proved to be too expensive, the building is expected to consume less than half of the energy of a similar building that was built to a traditional design.[4]

An independent, third-party rating system has been developed that certifies sustainable building practices that is used by many companies interested in being leaders in sustainable construction (see text box). LEED certification is available for different kinds of construction, including office building, apartment buildings, schools and homes. A complex set of criteria has been established for each type of building, and points are awarded for such things as energy efficiency, water conservation, and landscaping. Detailed information is available from the website of the U.S. Green Building Council.

[4] Roger E. Frechette III and Russell Gilchrist, "Seeking Zero Energy", **Civil Engineering**, January 2009, pp. 38-48.

LEED Certification and the Design of "Green Buildings"

"The Leadership in Energy and Environmental Design (LEED) Green Building Rating System™ encourages and accelerates global adoption of sustainable green building and development practices through the creation and implementation of universally understood and accepted tools and performance criteria.

"LEED is a third-party certification program and the nationally accepted benchmark for the design, construction and operation of high performance green buildings. LEED gives building owners and operators the tools they need to have an immediate and measurable impact on their buildings' performance. LEED promotes a whole-building approach to sustainability by recognizing performance in five key areas of human and environmental health: sustainable site development, water savings, energy efficiency, materials selection and indoor environmental quality."

U.S. Green Building Council, www.USGBC.org

Reducing the risks of earthquakes: it is possible to build structures that are more likely to withstand earthquakes, and it is possible to design systems that are more likely to continue operations even if an earthquake destroys some of its components. New buildings and other structures in earthquake zones are today designed to withstand earthquakes. In many locations, structures are strengthened so that they will be more likely to withstand the lateral and vertical movements that could be causes by an earthquake. In Japan, for example, where earthquakes are a very common experience, JR East and other railroads retrofitted many of their bridges to reduce the risk that a high-speed train would derail or overturn in the event of an earthquake. In northern California, it was decided to retrofit the Claremont Tunnel, which was constructed in 1929 to transport water to Oakland and other cities. If a portion of this tunnel were destroyed, then a half million people would be without water. To avert such a disaster, the East Bay Municipal Utility District spent $66 million to construct a by-pass tunnel through the fault zone. The by-pass tunnel was designed to accommodate a lateral movement of up to 8.5 feet (2.6m).[5]

Societal norms change – the need for instant communication: Over time, as societies become more affluent, they tend to be less tolerant of risk, more interested in style and aesthetics, and more conscious of the factors that affect their personal well-being. As a result, systems that were acceptable when built may no longer be acceptable twenty or fifty years later.

Changes in societal expectations are perhaps most notable in the area of telecommunications. In ancient history, the Persians, Chinese, and Romans built highways that were intended in part for armies to move quickly throughout their empires. The same roads were also used to provide communications between the capital cities and the other cities and states that were part of the empire. In the mid-19th century, the telegraph allowed instantaneous communications – but at a cost that only governments and corporations could afford on a routine basis. The telephone provided direct communication for the masses, but the cost for long distance calls was so high as to make each such call a family event just 50 years ago. Cell phones freed users from their land lines, and allowed people to make calls from almost anywhere to almost anywhere. Today, e-mail, texting, the world-wide web, and twitter today allow people to be in almost continuous contact.

Societal norms change – airline terminals resemble shopping malls. Travelers are no longer willing to go to the airport, check-in, and sit patiently waiting to board their plane, and they can no longer show up just before flight time, because of the need to pass through security. Thus, it is no longer enough to provide a few seats near the departure gates. Moreover, it is clear that people are willing to spend quite a lot of money when they are forced to spend a half hour or more in a confined area. Airports today must have restaurants, shopping opportunities, first-class lounges, internet

[5] Sarah Holtz Wilson, David F. Tsztoo, Carl R. Handford, and Kenneth Rossi, "Safeguarding a Lifeline," **Civil Engineering**, May 2008, pp. 58-65

connections, and attractive design; these features not only improve the comfort and quality of the traveling experience, they provide income to help pay for the expansive and expensive terminals. For similar reasons, colleges today not only require adequate housing for students, they also must provide excellent sports facilities and dining options and wireless internet connections in every classroom and in every dormitory room. The quality of the living experience may be as important as the quality of the education for students deciding where to apply.

Example: Evolution of London and the Thames Embankment

The Victoria Embankment was constructed in the 1860s for multiple purposes, including creation of open space along the river. It also helped to channel the river and provided space for a new sewer system and an underground railway.[6] Upgrading infrastructure, coordinating major investments affecting different kinds of infrastructure, invigorating downtown areas, creating more walkways to encourage pedestrians, and highlighting a city's architecture are all part of what is needed to create more sustainable cities.

St. Paul's, a magnificent structure that was constructed following the Great London Fire of 1666, was barely visible from the tourist boats plying the Thames. In 2000, a new pedestrian bridge linked the historical center of the City with the rapidly re-developing South Side. Pedestrians walking across the river are now treated to an unhurried view of this architectural gem (Figure 1). The bridge also connects well designed walkways along the south side of the river with the 19th century linear park along the north side.

Figure 1 St. Paul's Cathedral and Millenium Bridge, London

[6] For the history of London's sewers and the construction of the embankment, see Stephen Halliday, **The Great Stink of London: Sir Joseph Bazalgette and the Cleansing of the Victorian Metropolis**, Sutton Publishing, Phoenix Mill, England, 1999.

Example: Building New, More Sustainable Infrastructure: One Bryant Park[7]

Bank of American, working with the Durst Organization, designed their 55-story headquarters so as to achieve the highest level of LEED certification, thereby demonstrating their commitment to sustainable development. In order to become one of the first skyscrapers to achieve platinum certification, the new Manhattan skyscraper had to incorporate sustainable features that distinguish it from conventional office towers:

- Energy requirements:
  - The building has a 4.6 MW natural gas-fired power plant; excess heat is used to heat hot water for heating the building in the winter and cooling it in the summer via an absorption chiller.
  - A thermal storage plant is located in the basement that produces ice at night, when energy demand is low and helps with air-conditioning during the day. This reduces the building's peak energy requirements, thereby lessening the demand for electricity from the most polluting and least efficient power plants serving the city (since these plants are only used during peak periods).

- Water requirements are half that of a conventional building:
  - Rail water is collected and used as grey water to flush toilets and supply the cooling system
  - Waterless urinals are used in all men's restrooms, saving three million gallons per year

- Interior design is healthier than a conventional building:
  - The interior incorporated many recycled materials and avoided materials with volatile organic compounds.
  - The heating and ventilation systems filter out 95% of the airborne particulates, compared to 35% for a conventional building; the air discharged from the building is cleaner than when it entered.
  - The glass-shrouded building lets in natural light

- Use of recycled materials in the structure
  - The 25,000 tons of structural steel had at least 75% recycled content.
  - 45% of the cement used in the building was granulated blast furnace slag (GBFS), a waste product of steel smelting that produces a stronger, denser, and more durable concrete. Use of GBFS was estimated to reduce material waste and new cement by 17,000 tons each, while also reducing the emission of carbon dioxide by nearly 16,000 tons.
  - The construction process resulted in less debris and less need for recycling.

- Integration within the city:
  - An underground pedestrian walkway will eventually connect subway stations on the north and south sides of the site and a mid-block subway entrance will eventually be added.
  - The tower's entrances are sited to enhance access to Bryant Park.
  - The project helped in the reconstruction of Henry Miller's Theatre, a playhouse located on a corner of the site.

The $1.3-billion building includes 2.2 million square feet of office space, most of which was initially occupied by Bank of America beginning in 2008. In addition to its sustainability, the iconic building is noted for its beauty, as it "features crisp folds that appear to be sculpted and precise vertical lines animated by the movement of the sun, the clouds, and the moon."

It is clear from this example that it is possible to build high-rise buildings that are much more sustainable in terms of their materials requirements, their energy and water needs, the quality of the indoor environment, and their integration

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[7] Andrew Mueller-Lust, *Crystal Clear*, **Civil Engineering**, December 2008, pp. 38-71. The tower is owned by One Bryant Park, LLP; it was developed by the Durst Organization; and Band of America is the largest tenant. The architect of record was Adamson Associates Consulting Engineers, P.C.

with the nearby urban environment. Whether the innovations used in One Bryant Park will be cost-effective in other applications is something that designers will have to determine for other locations and for other building projects.

Stage VIII Retrenching and Obsolescence

Competition and changes in societal needs will cause some systems to shrink and perhaps disappear. If well-managed, a system can decline slowly, over a matter of decades, by continually eliminating unnecessary or unprofitable components and cutting back to profitable core operations. If poorly managed, a system may simply hold on for too long, then suddenly collapse. Today, there is an on-going drama involving telecommunications. Are land-lines obsolete? Will everyone go wireless? Will people communicate only via the internet? What will happen to all of those telephone poles?

As with the previous stages, many of the standard methodologies of project evaluation will be useful in deciding whether or not a system or technology is obsolescing and, if so, figuring out how to age gracefully. Short-sighted management may fail to foresee problems until it is too late to do anything; bull-headed managers may decide to invest vast sums to rehabilitate a system that is actually no longer competitive. Some of the largest expenditures on rail passenger stations were made in the 1930s, just at the time when air travel and automobiles were about to put most rail passenger services out of business. It is far better to have a realistic outlook on competition than to blindly go ahead with major investments aimed at providing marginal improvements to a system that is more than marginally non-competitive.

21st Century Challenges: Sustainable Infrastructure

Technological changes can, over time, dramatically affect the way that infrastructure is designed, how it is used, and how it impacts society. For skyscrapers, railroads, and other types of infrastructure, technology has allowed great reductions in cost, but regulation has been required to curb private sector excesses related to pricing, aesthetics, over-building, or safety. Skyscrapers and railroads today are more energy efficient, more attuned to user needs, and more sustainable that they were 50 or 100 years ago. Presumably both types of infrastructure will continue to evolve in response to social, economic, financial, and environmental pressures.

Today, the need to consider sustainability is much more evident than it was in the 19th century at the height of the industrial revolution. The impetus to consider sustainability comes from various sources:

- Over-dependence upon fossil fuels.
- Global warming and related aspects of climate change: more severe weather patterns, rising sea-levels, threats to ecosystems.
- Societal concerns with equity and social justice: the vast difference in quality of life in different countries and the vast inequality in incomes among the richest and poorest within each country.
- Instability in many societies related to disintegrating economies, internal conflicts, and lack of opportunity.
- Congestion and pollution within the largest cities: are there limits to growth? What can be done to improve quality of life in mega-cities, especially in developing countries?
- Cracks in the automobile culture: recognition of the disproportionate amount of resources devoted to automobiles and highways, the enormous loss of life on highways, the dependence upon fossil fuels, the contribution to green-house gases, and the waste of time and resources caused by urban congestion.
- Environmental degradation, including an accelerated rate of extinction of species, loss of habitat, the long-term threat of toxic chemicals to the water supply, and erosion.

These factors will influence how infrastructure performance is measured, how goals are established, how problems are defined and how project and programs are evaluated in the 21st century. However, the same multi-objective framework for evaluating infrastructure projects will remain useful, even if the relative importance of cost, environmental quality, sustainability change dramatically. Financial analysis will remain important, because an essential aspect of sustainable infrastructure will always be the ability to raise the cash to pay for construction, maintenance, and operation, and the ability to raise cash ultimately will reflect what is going on in the financial markets. The ability to deal with uncertainty and risks, the ability of the public and private sectors to work together, and the ability to manage projects and program will all continue to be essential aspects of the development and evolution of infrastructure systems.

Enhancing the sustainability of infrastructure will be a continuing challenge for planners, engineers, and politicians in the 21st century. Urban problems related to pollution, congestion, disease, water supply, wastes, and natural disasters will grow, especially in mega-cities in developing countries, but also in all large or rapidly growing metropolitan areas. Battles over water supply will intensify, and the needs for waste water treatment will increase. Renewable energy sources will need to be developed to lessen dependence upon fossil fuels, and safer, more efficient, more secure systems will be needed for greatly expanding the role for nuclear energy. It will be necessary to transform transportation and land use patterns that were developed over decades when oil was cheap, highways were easy to build, and cities were forsaken. Massive efforts will be needed to create or protect the world's green infrastructure and to reverse some of mankind's worst encroachments on harbors, waterways, wetlands, and threatened ecosystems.

Responses to these challenges will include efforts in many different areas:

- Managing the demands on infrastructure.
- Maintaining and rehabilitating existing infrastructure.
- Managing infrastructure more effectively.
- Using infrastructure more effectively.
- Mitigating the negative social and environmental impacts of existing infrastructure.
- Building new, more sustainable infrastructure.
- Retiring old, unsustainable infrastructure.

In any of these areas, success will depend upon the same factors that have been emphasized throughout this collection of essays and case studies:

- Clear identification of the problems.
- Development of objectives and measurable criteria.
- Generating possible alternatives for dealing with the problems.
- Analyzing alternatives with respect to financial, economic, social an environmental impacts.
- Selecting and refining the most promising projects and programs.
- Implementing projects and programs efficiently and effectively.
- Monitoring performance and taken actions as necessary to achieve the objectives of the project.

The evolution of infrastructure depends to some extent on leadership, innovation, technologies, and regulation. Efforts to transform infrastructure do not happen overnight, and it may take time for society to recognize either the need for changes or the need to regulate development. Once the technology for high rise construction was available, real estate economics quickly drove buildings skyward in Chicago and New York; however, only after several decades of unfettered development, were city authorities able to institute zoning regulations to preserve light and air quality by requiring setbacks as the towers rose from street level. The rail industry struggled for nearly a century to transform itself from its role as the dominant transport mode of the late19th century to a well-managed niche player with potential for growth at the beginning of the 21st.

Summary

Most infrastructure projects are completed as an extension to, as an upgrade of, or as a competitor to an existing system. Infrastructure projects therefore are almost always conceived and evaluated in the context of existing systems. At times, perhaps for very long periods of time, there will be very clear projects that can and should be implemented with little or no controversy and with little or no need for extensive analysis. Projects that improve the performance of a successful system or projects that replicate systems in new locations may not require a great deal of specialized evaluation, because the costs and benefits associated with such projects are well understood. However, over time, changes in technology, institutions, political power, economic conditions or societal norms will lead to new ideas for projects, new estimates of the potential costs and benefits of projects, and new criteria for evaluating projects.

It is useful to consider the stages in the evolution of an infrastructure-based project, for the opportunities and problems are different in each stage. Table 3 lists some of the questions that are to be encountered in each of the seven stages of evolution that have been discussed in this essay. These stages are not necessarily sequential, and different parts of a large system may well be at different stages of development. For example, the infrastructure required to support cell phones and other wireless communications is still in the early stages of evolution, while the infrastructure used to support traditional land-line telephones is in the latter stages of evolution – even though the same companies may be involved in both types of communication.

Over time, society's needs and resources change, and as they change, the roles for and perceptions of infrastructure will also change. In the 19th and 20th centuries, new technologies and mammoth infrastructure projects enhanced mobility, helped make agriculture more productive, allowed more intensive urban development, provided heat and light, and shrank the world, together creating unprecedented prosperity and a global economy, While many of the consequences of these technologies and project have been highly beneficial, there have also been negative consequences, including pollution, over-dependence upon non-renewable energy sources, congestion, excessive use of water, inequalities in development, and degradation of the environment. In the 21st century, much of the interest in infrastructure will be aimed at resolving these problems and extending the benefits of modern technology to all regions of the world. Many projects and programs will need to be initiated in order to move the U.S. and the world toward more sustainable infrastructure.

Efforts to create more sustainable infrastructure will likewise takes decades of steady progress. While examples abound to illustrate how different systems are evolving, it is unclear which approaches will be most successful and which will ultimately be found to be too costly, too inefficient, or ineffective.

Table 3 Stages in the Evolution of Infrastructure-Based Systems

I	Technological Experimentation and Demonstration • Will the technology work? • Will investors support projects? • Will there be a market for the new technology? • Will public agencies approve the new technology?
II	Wide-Spread, Uncoordinated Implementation • What will be needed to implement the new technology? • Who can build the fastest? • Whose approach will be the best? • What is needed to obtain public approval for new or expanded systems?
III	Development of Systems • How can we achieve economies of scale and density? • What organizational structure is best? • How much coordination is required among government agencies and developers or private companies? • What is the best way to handle growth? • How can we avoid overbuilding?
IV	Consolidation and Rationalization • How can we rationalize the system so as to become more efficient and more effective in providing services? • What is the optimal structure of our system?
V	Technological and Institutional Advancement • What is the source of competition: similar systems, different technologies that provide the same service, or systems that eliminate the need for the existing service? • What is the role for new technology? • How can the system be managed and regulated more effectively?
VI	Responding to Competition • What is the best role for the system? • Can the system survive competition?
VII	Mitigating Social and Environmental Impacts • How can the system respond to changes in societal views of the role of the system and the nature of its impacts on society and the environment? • How can negative social and environmental externalities be mitigated?
VIII	Retrenching and Obsolescence • When is it necessary to downsize? • What is the best approach to downsizing? • How can the system be re-used, recycled, or dismantled?

Resource: Project Evaluation: Essays and Case Studies
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