Durability and sustainability of infrastructure — a state-of-the-art report[1]

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Abstract: This paper discusses the basic concepts involved in infrastructure, durability, and sustainability. At present, infrastructure facilities are designed and constructed on the basis of direct costs only, without explicit consideration of maintenance and depreciation over its service life as in other industries. Proper design, operation, and management of infrastructure must deal with every facet of its service life, ranging from conception, feasibility studies, design, construction, operation, maintenance, repair and rehabilitation, and finally decommissioning and disposal of the system after it has outlived its useful life. Every step of these considerations must be guided by overall socioeconomic and environmental concerns; in summary, they must be guided by the principles of sustainable development, which embrace the issue of embodied energy in the materials, construction, and both initial and recurring maintenance. The degradation of the performance of Canada's infrastructure over the past few decades is reviewed, along with the consequences of proper or deferred maintenance and their impact on Canada's infrastructure deficit. The roles of the civil engineering profession, including education and training, and those of the public and private sectors are discussed briefly.

Key words: depreciation, design, deterioration assessment, durability, durability audits, infrastructure surveys, maintenance, life-cycle performance and costs, repair and rehabilitation, sustainability.

Résumé : Cet article aborde les concepts de base des infrastructures, de la durabilité et de la viabilité. De nos jours, les infrastructures sont conçues et bâties uniquement en se basant sur les coûts directs, sans tenir compte explicitement de leur maintenance et de leur dépréciation au cours de leur cycle de vie utile, comme c'est le cas dans d'autres industries. La conception, l'opération et la gestion appropriées des infrastructures doivent tenir compte de chaque aspect de leur vie utile, allant de la conception, des études de faisabilité, des calculs, de la construction, de l'opération, de la maintenance, des réparations et de la restauration et, finalement, de la fermeture et de l'élimination du système une fois qu'elles ont atteint la fin de leur vie utile. Chaque étape de ces considérations doit être guidée par les questions socioéconomiques et environnementales générales; en bref, ces activités doivent être guidées par les principes de développement durable, qui aborde la question de l'énergie intrinsèque des matériaux ainsi que les activités de construction et de maintenance, initiales et récurrentes. La dégradation du rendement des infrastructures canadiennes au cours des quelques dernières décennies est examinée, de même que les conséquences d'une bonne maintenance ou d'une maintenance reportée, ainsi que leur impact sur le déficit en infrastructure au Canada. Les rôles de l'ingénieur civil, incluant l'éducation et la formation, et ceux des secteurs publics et privés sont abordés brièvement.

Mots clés : dépréciation, calcul, conception, évaluation de la détérioration, durabilité, audits sur la durabilité, examen des infrastructures, maintenance, performance et coût des cycles de vie, réparation et restauration, viabilité.

[Traduit par la Rédaction]

Introduction

Despite the early activity in the area of durability of concrete in the early 1950s, durability and infrastructure became buzzwords only in the early 1980s, when the extensive deterioration of the American infrastructure attracted media interest. Although the practice of sustainable development has been known to humankind for a very long time, the concept was popularized by the World Commission on Environment and Development in its publication *Our Common Future* (WCED 1987), which defined sustainable development as "a process of change in which the exploitation of resources, the direction of investments, the orientation of technical development, and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations".

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Sustainability and infrastructure

The design, construction, maintenance, and rehabilitation of infrastructure involve the use of products processed from raw materials extracted from the Earth. The present day construction process can be represented linearly (Fig. 1), with considerable expenditure of energy and generation of waste in each phase. At the end of the facility's service life, it is

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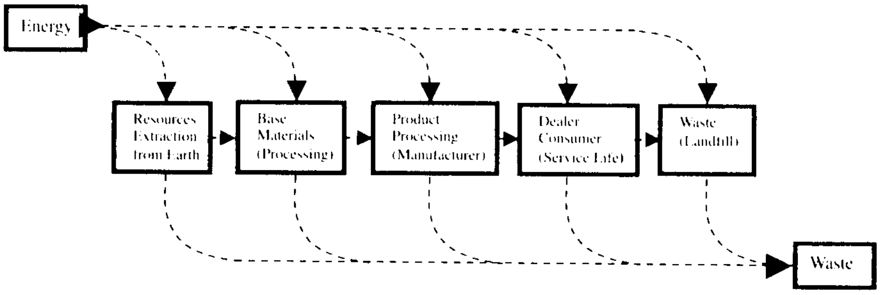
Fig. 1. Linear approach in current infrastructure activities (adapted from Roberts 1994).



normally decommissioned, and the debris is transported to a landfill. The waste generated by the construction industry constitutes about 50% of the total waste in landfills. Because of the tremendous improvements in transportation systems over the past 200 years, from canals to railroads, highways, shipping and port facilities, and airplanes and airports, the volume of goods transported in international trade has increased by a factor of more than 10. The construction industry acts as though the resources from the Earth are inexhaustible, the ability to process and supply construction products is considered to be unlimited, and the Earth's capacity for accepting construction waste is deemed to be endless. Before the Industrial Revolution, consumption of energy and generation of waste produced only minor pollution and slow global changes. With the sixfold increase in world population, however, energy consumption, pollution of land, water, and air, and landfills have become such a serious problem that the "traditional" linear approach needs to be modified significantly.

By contrast, most natural ecosystems function as closed loops that change quite slowly. For example, the hydrologic cycle involves continuous evaporation of water from the oceans, lakes, and other sources into the atmosphere. This vapour moves over the land and causes precipitation as rain and snow, which in turn returns to the ocean through surface flow (streams and rivers) or groundwater. The process is repeated over and over without cessation. Similarly, the food cycle, involving plants and animals, is another closed loop that is repeated continuously in nature. It should be noted that changes occur in nature over centuries or millennia, such as gradual climate change, evolution of plants and animals, and in some cases their complete disappearance or extinction. These very slow changes in natural ecosystems permit adaptation of the natural environment over time.

Sustainability has also been popularly restated as satisfying "the needs of the present without compromising the ability of the future generations to meet their own needs" (WCED 1987). A definition from the 1996 Civil Engineering and Research Foundation Symposium (CERF 1996) states that sustainable development seeks to meet "growing human needs for natural resources, industrial products, energy, food, transportation, shelter and effective waste management while conserving and protecting environmental quality and the natural resource base essential for future generations". In summary, sustainable development is a process of harmoniously exploiting resources, directing investment, and accomplishing institutional change to enhance both current and future potential to meet present and future human needs.

In light of past human practices, the definitions of durability and sustainable development imply a focus on human interests and needs around the world, despite the differences in values and cultural perspectives that characterize the present human condition. Current engineering knowledge is unable to provide guidance on designing, building, and managing infrastructure and the environment. Engineers need a lot of work to fully comprehend "sustainability" and "sustainable development" and to develop new technologies, along with changes in basic values and political thinking, to incorporate these concepts in the design process. The resulting objectives and criteria would influence life-cycle costs of facilities, the waste and pollution generated by the construction process, and the impact of the facility on the productivity of the accommodated activity.

This paper presents a state-of-the-art report on infrastructure durability and sustainability concerns. It deals with environmental planning, historical development, and surveys of Canadian and American infrastructure; issues of deferred maintenance; qualitative performance, life-cycle costing, and durability audits of infrastructure; education; and a national infrastructure policy.

On the basis of an analysis of the situation, Roberts (1994) proposed four fundamental principles of sustainability, termed the Natural Step:

Resources should not be extracted from the Earth at a rate faster than they can be redeposited, reabsorbed, or recreated (e.g., sustainable forest industry).

The use of resources extracted from the Earth should be reduced to the extent that it leaves no ecological footprint.

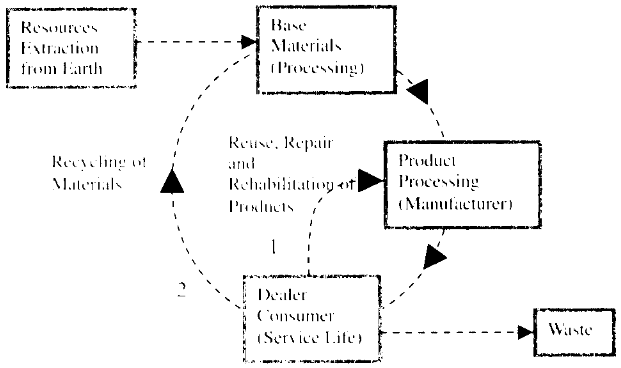
Resource-depleting activities should be balanced with restorative work so as to leave no negative impact.

Past environmental damage should be remedied to leave a net positive impact on the Earth.

The ideal would be to derive all raw materials from existing products so there would be no need for new resources from the Earth. This could be achieved by transforming the current linear systems (Fig. 1) to closed-loop systems, where the use, processing, transportation, and consumption of resources flow continuously as a closed loop and not as a once-through system (Fig. 2).

The outer loop involves recycling of intercepted waste materials before they are dispatched to the landfills. This recycling reduces the demand for new materials, but the consumption of energy is still high. The inner loop involves reuse of goods and products, with some repair and reconditioning. This cradle-to-cradle philosophy requires considerably lower expenditure of energy, and in the ideal situation, with nothing going to waste, it results in a considerable re-

Fig. 2. A proposed closed-loop system for infrastructure activities (adapted from Roberts 1994).



duction in energy consumption in remanufacturing activities. The probability of attaining this ideal is low; however, the approach can be more effective in a multiple-enterprise consortium, where the waste from one enterprise becomes the raw material for another, thereby reducing the need for virgin material extraction and considerable remanufacturing.

Environmental planning

Most North American environmental impact analyses (EIAs) are based on those developed in the 1960s; recently, their validity has been questioned. Present practice is shown in Fig. 3. Once a project is proposed for a specific site, the environmental evaluation may be delayed until after the evaluation of the project and before the initiation of the feasibility studies or their completion. At this stage, the environmentalists and government officials frequently get involved in disputes, each with independent environmental studies and extensive data that may have little influence on the design outcome. These environmental confrontations usually result in wasteful studies, significant legal costs, and lengthy delays. As the project gets approved, there is frequently inadequate monitoring of the environmental consequences of construction or of the completed project. Therefore, the impact of the project may be considerably different from that depicted in the original studies.

The above shortcomings have led some engineers and planners to use an improved approach for conducting environmental impact studies on infrastructure projects (Fig. 3). The environmental assessment starts earlier and continues throughout the project and in some cases after the project has been completed. Long-term strategic economic development plans must strike a balance between the development needs of a growing population and the need for environmental protection. Appropriate expert systems can be used to predict environmental impacts, albeit approximately, as part of long-range development studies. After project planning is initiated, the scope of the environmental studies should be gradually increased as the project alternatives are defined and considered. The various long-term economic costs of the project and social and cultural issues must be considered, along with the indirect costs resulting from offsite environmental pollution. Environmental monitoring should be undertaken during and after construction and throughout the service life of the facility until its decommissioning. If the anticipated environmental impacts differ from the predictions, the design should be appropriately modified.

Infrastructure history

Sound, well-functioning infrastructure in a country is essential for its sustained economic growth, international competitiveness, public health, and overall quality of life. These characteristics are closely linked to the adequacy of the transportation infrastructure, water quality, and waste disposal. The need for new infrastructure and the renewal of deteriorated infrastructure first became evident immediately after the Industrial Revolution (end of the 19th century); the infrastructure in urban centres was in deplorable condition. However, there was no systematic method for repair or replacement.

A broader awareness of the current infrastructure crisis emerged during the mid-1970s and the early 1980s, when serious problems were noted in the municipal infrastructure systems. The problems were due to budgetary constraints during the recessions, some post-World War II infrastructure approaching the end of its service life, the rapid inflation of the 1970s, a competing demand for municipal services, deferred maintenance as a result of reduced funding from all levels of government, and -increased public involvement in decision-making.

The results of various infrastructure surveys in Canada and the United States were presented by Siddiqui and Mirza (1996). A brief summary is included here for completeness.

A survey undertaken in 1995 by McGill University and the Federation of Canadian Municipalities (FCM) examined Canada's municipal infrastructure for the cities within the following four population groups:

Group	Population
1	<10 000
2	10 000 – 100 000
3	100 000 – 400 000
4	>400 000

Although some of the problems, such as the funding shortage, were common to all four population groups, there were some differences in the needs, problems, and deficiencies in the different infrastructure categories, as well as in the issues revolving around them. In general, transit, roads, and curbs were worsening in all municipalities. However, in group 1 municipalities, roads and hazardous-waste disposal were the prime concern, whereas in group 2 the sanitary and combined sewers were of most concern. The larger municipalities, in groups 3 and 4, faced the most significant worsening of transit facilities and roads. Thus, the population of a city has a direct impact on its infrastructure needs, problems, deficiencies, and related issues, and this needs to be considered in developing long-range plans for infrastructure renewal and new facilities (McGill FCM 1996).

The survey determined that Canada's municipal infrastructure deficit was CAN\$44 billion, and it was about CAN\$100 billion for all infrastructure under the various jurisdictions — federal, provincial, and others. At present, these infrastructure deficits are CAN\$60 billion and CAN\$125 billion, respectively. Detailed results of the survey

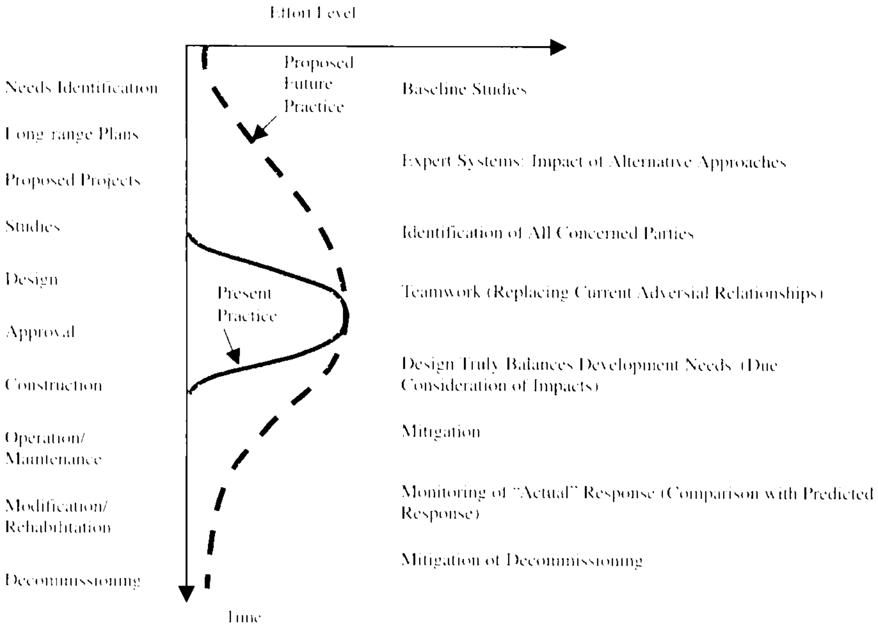


Fig. 3. Current and proposed future practices (adapted from Roberts 1994).

for each population group are presented elsewhere (McGill FCM 1996).

American infrastructure

In 1998, the American Society of Civil Engineers (ASCE) undertook a detailed survey of selected infrastructure categories in the United States and followed it with improved and more detailed surveys in 2001, 2003, and 2005. Each survey was directed by an advisory council, whose membership increased from 11 for the 2001 survey to 24 for the 2005 survey. The 1998 survey divided highways into two categories: roads and bridges. Rail, security, and energy were added as new categories in the 2005 survey. The surveys evaluated each designated category for all states and the country, and the results were tabulated in formal report cards, which were passed on to federal officials and made available to the media (ASCE 1998, 2001, 2003, 2005). The national results for each infrastructure category in the four report cards are summarized in Table 1. The results of a 1988 survey of about 10% of all USA infrastructure (eight categories) by the National Council on Public Works Improvement (appointed by the president of the United States) are also included in this table (NCPWI 1988). In general, the condition for a given infrastructure category either did not change significantly or deteriorated gradually from 1998 to 2005. The individual grades were based on examination of condition and capacity and of funding versus need, but they also summarized the opinions of 2000 engineers, solicited to determine what was happening in the field. The final grade for all USA infrastructure was derived by averaging the grades in all categories. The overall infrastructure grades ranged from C in 1998 to D in 2005, with projected 5-year needs increasing from US$1.0 trillion in 1988 to US$1.6 trillion in 2005. After having received a D+ in 2001, the USA infrastructure showed little or no improvement in the next two surveys, with some areas sliding toward failing grades.

In reviewing the 2003 ASCE report card, Infrastructure Canada (2003) noted that the main message was the need for new federal legislation and increased federal funding. The report also emphasized the creation of a long-term infrastructure agenda and increased federal funding for research on waste-to-energy programs. In 2002, the federal government of Canada committed itself to long-term measures to modernize Canada's infrastructure. Unfortunately, infrastructure surveys similar to those of the ASCE do not exist in Canada. *The Technology Road Map* (CSCE 2003) recommended the creation of an inventory of Canada's infrastructure, along with its existing state of health. Such an inventory would be essential for developing a strategic long-term policy, for decision-making, and for establishing priorities and future directions. The socioeconomic and environmental impacts of these new waste-to-energy programs also need to be considered, in consultation with the stakeholders. The current experience in the United States, Australia, Japan, and some other countries clearly demonstrates the need for proactive leadership from all levels of government in Canada, as well as from the professional societies and individual experts in the various sectors.

Qualitative performance of Canada's infrastructure

A significant proportion of civil and marine structures around the world has deteriorated considerably as a result of ageing, overuse, misuse, initial design inadequacies, poor-quality control in construction, lack of maintenance, or deferred maintenance. Here, maintenance is defined as a set of activities undertaken to keep infrastructure in a fully functioning or operating condition, or to return it to that condition, and to ensure long-lasting benefits for the users. A qualitative relationship between the deterioration of Canada's infrastructure and the level of maintenance (maintenance expenditures expressed as a percentage of the facility

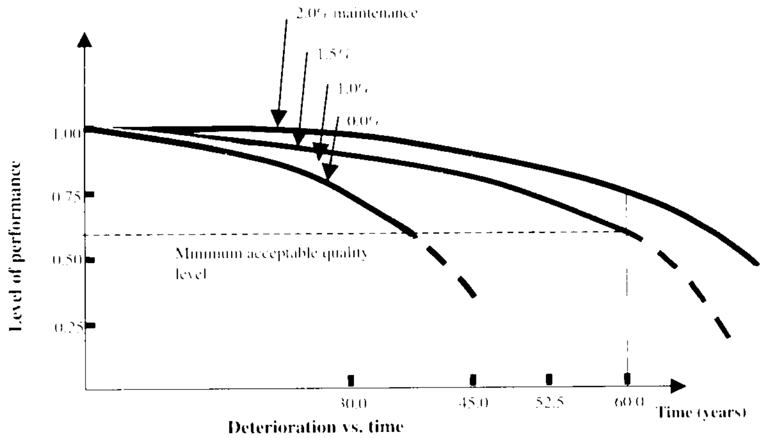
Table 1. Summary of USA infrastructure survey findings (1988, 1998, 2001, 2003, and 2005).

	1988	1998	2001	2003	2005
Infrastructure category evaluated					
Aviation	B–	C	D	→	D+
Bridges	C+	C–	C	→	C
Dams	—	D	D	→	D
Drinking water	B–	D	D	→	D–
Energy	—	—	—	—	D
Hazardous waste	D	D–	D+	→	D
Navigable waterways			D+	→	D–
Public parks and recreation	D				C–
Rail	—	—	—	—	C–
Roads	C+	D–	D+	→	D
Schools		F	D–	→	D
Security	—	—	—		I
Solid waste	C	C	C+	→	C+
Transit	C–	C	C	→	D+
Waste and Energy	—	—	D+	D	—
Wastewater	C	D+	D	→	D–
Water resources	B				
Infrastructure GPA	C	D	D+	D+	D
Total investment needs (CAN$ trillion)[a]	1.0	1.3	1.3	1.6	1.6

Note: Adapted from ASCE (1998, 2001, 2003, 2005). Grading criteria: A, exceptional (90%–100%); B, good (80%–89%); C, fair (70%–79%); D, poor (41%–69%); F, inadequate (<40%); →, condition remained unchanged; I, insufficient information. The 1988 data, for comparison, are from NCPWI (1988).

[a] Estimated 5 year needs.

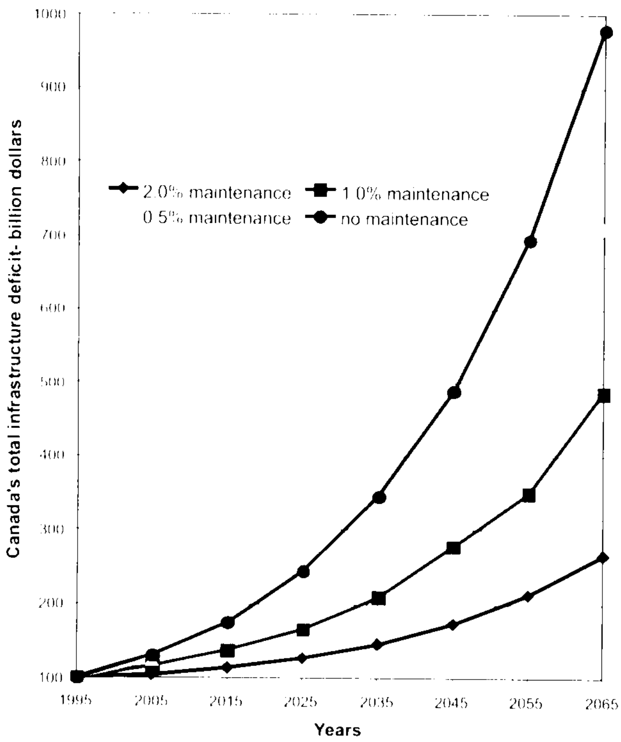
Fig. 4. Qualitative deterioration – time relationship for various levels of maintenance (Mirza 2004).



cost), repair, and rehabilitation over a period of 60 years is shown in Fig. 4, which is self-explanatory (Mirza 2004). The qualitative infrastructure performance is rated on a scale from 0 to 1, with 1 being perfect. It can be noted that with a higher level of maintenance (e.g., equivalent to 2% of the infrastructure construction costs), performance increases significantly, along with anticipated service life. It can be seen that if maintenance is completely neglected (0% maintenance), the deterioration level after about 45 years would be so high that the facility could not be rehabilitated and would have to be replaced. Depending on the type and condition of the facility, the annual maintenance costs normally incurred vary between 2% and 4%; however, maintenance expenditures in Canada have traditionally varied between 0% and 2%. The current financial constraints at the different levels of government suggest that these trends are likely to continue over at least the near future.

As well as developing the qualitative performance versus time curves described above, Mirza (2004) calculated Canada's infrastructure deficit versus time curves for four levels of maintenance: 0%, 1%, 1.5%, and 2%. The infrastructure deficit is the difference between the funds needed to upgrade Canada's infrastructure to an acceptable level and the funds available from all levels of government and other sources. As mentioned earlier, Canada's infrastructure deficit in 1995 was CAN$100 billion for facilities under all jurisdictions – municipal, provincial, and federal. At present, this deficit is about CAN$125 billion. If Canada's infrastructure is al-

Fig. 5. Variation of Canada's infrastructure deficit with time (Mirza 2004).



lowed to deteriorate, without any significant maintenance, the accumulated infrastructure deficit could easily grow to about CAN$1 trillion in 60 years (Fig. 5).

An investment on maintenance of at least 2% of the infrastructure construction costs would decrease the deterioration rate and future repair costs and enhance the life of the infrastructure, thereby delaying any costly replacement. This investment would result in significant economic growth, increased productivity, better international competitiveness, and improved quality of life for all Canadians. The renewal process would also lead to the development and transfer of innovative technologies and best practices (InfraGuide 2003). InfraGuide, Canada's national network of experts on sustainable municipal infrastructure, was founded by the FCM and the National Research Council of Canada (NRC), is funded by Infrastructure Canada, has been assisted by national and international organizations (see www.infraguide.ca/aboutus/), and has developed more than 50 best practices. Some engineers and practitioners claim that adopting the best practices for repairing and rehabilitating the deteriorated infrastructure and constructing new facilities could result in annual savings of between CAN$1 billion and CAN$2 billion. It should also be noted that 79% of Canada's infrastructure is already beyond its anticipated service life (CSCE 2003).

Failure to address these serious problems will result in an unsustainable infrastructure system, which in turn would seriously jeopardize Canada's international competitiveness and ability to capitalize on existing and future market opportunities. Also, it would leave a large infrastructure deficit as a legacy for future generations, which would initiate a serious financial crisis. It is not appropriate that the present generation should enjoy a high quality of life at the expense of future generations. The time to act is now, and the various levels of government must ensure that maintenance for any existing facility or new infrastructure projects is not deferred for any reason.

Life-cycle costing

The durability design requirements in the various national codes are basically empirical, derived from long-term experience with various types of structures in various aggressive environments. Such design requirements have not been developed in terms of performance criteria. For example, for concrete, they relate to water/cement ratio, minimum cement content, minimum concrete cover thickness, maximum crack width, and other variables. In addition, these code provisions have proved to be inadequate in some aggressive environments and too rigorous in other environments (Siemes 1996).

Increased durability should normally result in an increased initial cost but lower maintenance costs over the service life of the facility. Unfortunately, current design methods, which are basically for the construction stage only, cannot be used to determine the cost benefits that would be attained during the service life of the facility. Because of the empirical nature of code provisions, which are not always clearly understood by practising engineers, it is not possible to determine the service life in terms of the performance of the system. Also, no guidance is available to determine the maintenance requirements or the probability of failure. Thus, it is difficult to demonstrate the savings in future maintenance costs, which is a serious drawback for costing the life cycle of a facility. In summary, the current design practice inhibits any competition based on optimum durability considerations and life-cycle costing.

It is clear that any objective assessment of durability must be established on performance-based durability design. The behavior of the structure over its service life must be based on accurate, probabilistic time-dependent environmental and material models. Such design procedures must also be applicable for any preventive maintenance, rehabilitation, or retrofit of the structure. The performance of the structure over its service life requires consideration of life-cycle costs based on extension of the principles underlying the current limit-states design methods to ultimate and serviceability limit-states over its service life. In other words, efforts should be focused on developing a reliability-based code for the design of durable concrete, steel, or wood structures to ensure safety and serviceability over the entire service life.

Comparison with other industries

Industries such as offshore platform building and ship and car manufacturing devote more attention to inspection, maintenance, and regular replacement of components than does the construction industry, which needs to change its basic attitude. Instead of using continually updated standards and codes as for structural engineering, the ship or navigation industry uses classification societies with the close involvement of surveyors to check a design and oversee construction and workers. Manning (1992) noted that the nuclear industry has rigorous requirements for design, quality assurance, inspection, and maintenance, controlled by a strong regulatory agency. He stressed that service-life prediction is a sensitive issue, and very often the inspection requirements may compromise on durability. The various systems should be designed with a sound knowledge of the problems and an understanding of their causes, and the designer must strive to minimize the problems.

Building structures are generally difficult to inspect properly; however, there are similarities with the nuclear, aircraft, and automobile industries, all of which contain a skeleton of critical components and redundancies, or multiple load paths. Most of those industries have the following (Quinion 1992): (*a*) an explicit requirement for inspection and maintenance, (*b*) warranties, (*c*) strong regulatory agencies with jurisdiction for in-service performance, (*d*) scheduled replacement of parts, (*e*) occasional use of identical high-cost products, (*f*) economic incentives for product uniformity, (*g*) testing of components and finished products under abnormal loading conditions, (*h*) products with a finite service life, (*i*) manufacturer's vested interest, and (*j*) alteration during product use.

Durability achievement

All parties involved with the construction industry agree on the need for better quality control during all stages of planning, design, construction, operation, and maintenance of the system. In most cases, a small increase in the initial cost of the facility will pay dividends in terms of improved service life. The selection of the contractors must be based on proven good performance and maintenance of the high standards required for the type of construction involved; and it must be on evidence of the successful use of established quality management systems. This will ensure that the required quality and durability are achieved in a given project. Normally, durability problems are manifested during the first 10–15 years of the system's life, which are critical years in an aggressive environment. It has been observed that about 60% of these problems become apparent during the first 3 years (Quinion 1992). Despite limited success with different types of facilities, the engineer must focus on attempts to achieve improved service life, continually expanding accumulated knowledge through research and development, experience, and innovation. However, due consideration must be given to the impact of knowledge through research and development on practice and on the durability of the systems.

Industry difficulties

The solutions adopted to augment durability are the design and construction of robust structures and the improvement of joints and other features that have led to durability problems. The construction industry is having so many difficulties for a variety of reasons. For example, clients do not recognize durability problems and the long-range impact on service life, so they are unwilling to invest more money to increase durability. As well, the industry is fragmented, with a large number of owners and clients, designers, contractors, subcontractors, and suppliers with large and small businesses. Their mode of operation can be best described as "divide and compete", rather than "unite and improve" (Quinion 1992). Obviously, addressing these issues would be helpful.. In addition, there is a strong need for civil engineering graduates to study management and the design, preservation, and renovation of durable systems. The knowledge of the practising engineer can be similarly enhanced through specially designed continuing education programs.

Design and construction

The difficulties that hinder progress toward acceptance and adoption of performance-based design and construction fall basically into two categories: technical and nontechnical (Somerville 1992). The technical difficulties consist of uncertainty, variability, sensitivity, interaction, and a general lack of knowledge.

Somerville (1992) stated that the nontechnical difficulties can be more important than the technical ones and include the following:

(*a*) a general need for broad acceptance by all parties involved, especially the owners, who should be made aware of the benefits of using investment appraisal and value engineering to integrate financial, functional, and technical performance in terms of life-cycle costs.

(*b*) the owner's preferred breakdown of initial capital investment and subsequent maintenance costs.

(*c*) the legal liability of the designer for a given nominal life. Should the liability extend over a period of 5–10 years if a durability assessment is undertaken at the end of that period ?

(*d*) fulfilling the defined objectives and developing a consistent approach, when many parties are involved in financing, designing, constructing, operating, and maintaining any system.

Durability audits

Durability audit procedures are especially suited for the assessment of deteriorated infrastructure. Usually, some damage or deterioration occurs before the service life of the facility has expired. The engineer needs to have knowledge of the properties, geometry, and response of the existing facility and to be able to easily make observations and measurements. However, unlike when a new facility is being designed, the engineer has no freedom to adapt materials, components, and geometry at this stage. The construction and maintenance history of a facility and all the damage, deterioration, and other changes that have occurred make it a complex system. Further differences between an existing and a new facility are the increased cost for upgrading and improvement, the added difficulties of analysis, and the possibility of a reduction in the performance requirements or the intended service life.

Recent federal budgets

The 2005 federal budget proposed a new infrastructure program funded by a share of the federal gasoline tax; this would bring the number of current federal infrastructure programs to five. The Canada Infrastructure Works Program (CIWP) of the mid-1990s helped large cities cope with the prohibitive costs of modernizing waterworks, highways, and other large civil infrastructure projects essential for the quality of life in large metropolitan areas. Over the past decade, the old CIWP has been replaced by the Infrastructure Canada Program, the Canada Strategic Infrastructure Fund, the Municipal Rural Infrastructure Program, the Border Infrastructure Fund, and the New Deal for Cities and Communities Fund. The five programs have different initiation and termination dates, spanning collectively the period 2000–2013, and involve CAN$12.1 billion in projected spending, of which CAN$5 billion will be invested through the New Deal for Cities and Communities Fund.

Unfortunately, the large cities are no longer the priority in infrastructure spending. Although there is some overlap between the programs, the fine print shows a tendency to list priorities without giving them any relative weighting in importance, according to an editorial in *The Gazette* (2005). The editorial provided examples, such as tourism projects being considered as worthy as waterworks projects under the Strategic Infrastructure Fund rules; and the Infrastructure Canada Program has no restrictions on investment in "improving of community infrastructure" — it can mean anything. This situation is not surprising, because no politician would like to cut the ribbon for a sewage disposal project; they are "out of sight, out of mind". Arenas and parks are more visible to the voters; however, they are not as essential.

It is important to bring some rigour to all of Canada's infrastructure programs, which need to be overhauled, streamlined, and have their objectives prioritized. A higher priority needs to be assigned to the great challenges faced by the large cities, which were initially the spark plug for these programs. For too long, the municipal infrastructure in large population centres has been ignored, with serious results. For example, Canada leads the developed countries in dumping untreated human waste into lakes, rivers, and oceans. Over the past decade, there have been some problems with the drinking water in Walkerton and Kashechewan, Ontario; in North Battleford, Saskatchewan; and in some other communities. In particular, the isolated community of the Kashechewan First Nation has been on a Health Canada boil-water advisory over the past 2 years, and many such advisories have been issued over the past few decades. Because of the deadly *Escherichia coli* bacteria in the water supply, more than half of the local population has suffered from various stomach and skin diseases. The incorrect location of the water intake (constructed about 10 years ago), about 150 m downstream from the community's sewage lagoon, will continue to cause the drinking water to be contaminated with sewage. The advice of the local community on positioning the intake was ignored. These health and other socioeconomic problems of the community can be attributed to confusion over federal and provincial jurisdiction and to the lack of political will and government action to resolve the crisis. Only a comprehensive political solution, in partnership with the affected communities, can alleviate the serious socioeconomic and drinking-water problems faced by Kashechewan and at least another 100 native communities in Canada.

Recent natural calamities, such as Hurricane Katrina, the South East Asian tsunami, and the devastating earthquake in Pakistan and India, highlight the deficiencies in design, construction, and maintenance of infrastructure in these countries. For example, the devastation in New Orleans due to Hurricane Katrina could have been minimized considerably if the levees had been designed for a higher intensity hurricane. Moreover, the needed relief activities were slow, as a result of a lack of preparedness and competence and because of the tardiness of government action.

Politicians need to answer these questions with well-considered priorities. It is important to revert to the original core values in focusing the limited funds available on crumbling metropolitan infrastructure. These regions are the heart and lifeline of most economic activity in Canada. It would also be useful to fold all five programs into a single one with a short-term emphasis on the largest cities, which are the engines of Canada's economy.

As mentioned earlier, Canada's present infrastructure deficit is about CAN$125 billion. The small investments by the three levels of government will not return the badly deteriorated infrastructure to an acceptable level. The governments must seek other innovative sources of funding. If this investment is not made soon, the infrastructure, especially in large cities, will deteriorate at an accelerating rate, similar to any unchecked cancer in a human being. Would the cost of spending another CAN$2 billion or CAN$3 billion annually on our infrastructure be more significant in the long term than the cost of delaying the retirement of the accumulated federal and provincial deficits?

Education

Civil engineering curricula at most universities deal with the basics and the design and construction of new infrastructure facilities. However, maintenance, repair and rehabilitation, and rational management of the existing deteriorating infrastructure hardly receive much attention (Mirza 2004). This is reflected in the current role of engineers: they specialize in one of design, construction of new facilities, or management of infrastructure, which involves maintenance, operation, and repair and rehabilitation. The latter group has developed this specialization on the basis of experience and judgment, without much formal training during undergraduate years. The needs and challenges of civil engineering practice have focused emphasis on environmental protection and amelioration, requiring a reorientation of technology. The development of these curricula and related details should be aimed basically at protection and restoration strategies sensitive to local practice.

Consideration of all technological options involves looking at ethical responsibilities and socioeconomic and environmental impacts, and it must lead to holistic decisions without any negative impact on health and safety of people. The emphasis should be on cleaner technologies with highly efficient resource and energy use and waste minimization. Implementation of the principles of sustainable development (involving socioeconomic, environmental, and other concerns) requires the engineer to reduce, reuse, recycle, and above all rethink — a practice adopted by the Canadian Society for Civil Engineering and the American Association of Engineering Societies. Engineering practice for a sustainable future would require a greater degree of involvement in political, environmental, economic, technical, social, and management issues. This sustainability can be achieved by changing the current practice of designing for the first cost (design and construction) and focusing on the life-cycle costs of infrastructure subjected to a variety of aggressive environments and by adopting the cradle-to-cradle philosophy, instead of the cradle-to-grave system that currently prevails. In addition, sustainable infrastructure would require minimization of the energy embodied in the processing and use of construction materials, and as well as the energy embodied in construction processes.

Dealing with the present infrastructure crisis and the need for sustainable development requires broad thinking and a multidisciplinary education, well beyond the conventional engineering courses. This broader education would include courses on sustainable development, financing, politics, law, management, sociology, and work-orientation skills. Multidisciplinary partnerships will be needed to address cultural, social, and environmental issues. The current basic design concepts will have to be revised considerably to incorporate sustainable development. Basic civil engineering education must provide a solid understanding of environmental and socioeconomic issues, evaluation of the risk and potential impact of every decision and action in terms of time and space, and the subsequent effective management of these risks and impacts. There would also be a basic need for courses in deterioration sciences, assessment technology, renewal engineering, and institutional effectiveness and productivity (Mirza 2004).

The focus would have to be shifted from the design of new structures to the rehabilitation, retrofitting, and management of structures with serious deterioration; to revised use; and to anthropogenic threats. Significant changes in education are needed to prepare engineers for the new technology and practice aimed at sustainable development. The present curricula are compartmentalized, without adequate interdisciplinary content, and lack synthesis; the universities are teaching too much content and not enough process and open-minded problem-solving.

The above philosophy was used partially in significantly revising the curriculum at McGill University in the 1990s; details are available in a committee report (McGill University 1993). The Canadian Engineering Accreditation Board of the Canadian Council of Professional Engineers (CCPE) must take cognizance of the major changes in professional practice, which in turn should be reflected in major changes in undergraduate civil engineering curricula.

National infrastructure policy

Aside from combating Canada's rapidly growing infrastructure deficit, the infrastructure renewal programs shared by the three levels of government have accelerated economic growth and created jobs in all regions of the country. Canada's population is concentrated mostly in cities and townships just to the north of the United States; this unique geographical feature has led the federal government to assume responsibility since 1867 for major national development projects, such as the Canadian Pacific Railway and the TransCanada Highway. For similar reasons, it is appropriate that the federal government assume leadership in the renewal of Canada's infrastructure. Of course, the provincial, territorial, and municipal governments would be key partners in this important venture.

The FCM and NRC, with the strong support of Infrastructure Canada, have developed the national InfraGuide network, which provides guidance on best practices in the amelioration of infrastructure in Canada. Use of the appropriate InfraGuide best practices can result in significant savings in expenditure on repair and rehabilitation of infrastructure; these savings are estimated to be between CAN$1 billion and CAN$2 billion annually. Other learned and professional organizations, such as the Canadian Society for Civil Engineering, the Canadian Council of Professional Engineers, the Association of Consulting Engineers of Canada, and the Coalition to Renew Canada's Infrastructure, have expressed very strong support for the new infrastructure programs.

The federal government has shown some leadership in renewing Canada's infrastructure and has taken positive steps by creating a special department, InfraStructure Canada, with a designated minister to deal with all related issues. However, a national infrastructure policy is needed urgently, developed with federal leadership and input from all parties involved, to provide long-term direction on all infrastructure matters (Mirza 1997). Such a policy will result in several national benefits, including nation-building; development of appropriate technology and best practices (e.g., InfraGuide); economic benefits accruing from the international marketing of new technologies; economic benefits and opportunities for all regions of Canada (e.g., generation of new jobs resulting from infrastructure renewal investments and other related industries); and significant improvements in productivity, international competitiveness, and the overall quality of life of Canadians.

The national infrastructure policy should consist of long-term commitments and must address all issues of infrastructure in Canada under the jurisdiction of the federal, provincial, territorial, and municipal governments, as well as the issues of infrastructure in the private sector. The policy would address at least the following issues:

- The policy would acknowledge the present infrastructure crisis, its rapid growth over the near future, and its overall cost to Canadian society. The cost of extremely deteriorated and malfunctioning infrastructure includes the loss of investment, diminished economic growth, the loss of jobs, and decreased international competitiveness.
- All deteriorated facilities to be rehabilitated and all new infrastructure facilities should be designed, constructed, managed, operated, and maintained over a predefined life-cycle, with due consideration of all associated direct and indirect costs. These activities should incorporate the principles of sustainable development, accounting for all related socioeconomic, environmental, and cultural issues.
- The depreciation of these facilities should be incorporated into life-cycle accounting.
- All levels of government should develop strategic infrastructure programs (for all types of infrastructure for a period of at least 10 years) and provide sustainable funding for all related activities.
- The maintenance of any infrastructure facility should not be deferred under any circumstances.
- Provision should be made for safe drinking water, safe disposal of sewage and solid and hazardous waste, and pavement with a safe and comfortable riding surface. Other provisions could be added here.
- Managers and operators should have the required tools for properly managing infrastructure, and they should have

access to information on the best practices in all management, investment, decision-making, and technical areas related to infrastructure. This information is currently available from InfraGuide.

- In all major cities across Canada, centres of excellence should be established to undertake research and development on local, regional, and national topics of interest, besides providing advice to infrastructure managers, technical personnel, and decision-makers on the various best practices.
- The policy must ensure that each user pays appropriately for services and benefits received. The basic costs for services should be assessed on the basis of equity, economic efficiency, accountability, and transparency and should include appropriate administrative costs.

Where do we go from here?

Efforts to renew and rehabilitate ageing infrastructure should focus on prolonging the functional life of the facility's components and systems and ameliorating their safety. Of necessity, these activities must be performed in situ, and they must be economical and cause the least amount of disruption. Development of efficient and effective renewal technologies must by nature be interdisciplinary, and besides using traditional materials, engineers must adopt recently developed advanced and high-performance materials, protective systems, and joining methods. In addition, contrary to current practice, scientific design for renewal and reuse should be promoted. Urgent research is needed in these areas.

Summary and conclusions

The basic issues involved in infrastructure durability and sustainability have been reviewed, along with the future needs of the profession. Unlike the aircraft and automobile industries, the construction industry designs and builds infrastructure on the basis of first costs only, without explicit consideration of the maintenance and depreciation of the facility over its service life. The paper emphasizes the concepts of life-cycle performance and the associated costs, including depreciation of the facility over its service life. It is strongly recommended that life-cycle performance and management of infrastructure facilities deal with every facet of the service life — its conception, feasibility studies, design, construction, operation, maintenance, repair and rehabilitation, and finally decommissioning and disposal of the system after it has outlived its useful life. Every step of these considerations must be guided by overall socioeconomic and environmental concerns. These activities must be guided by the principles of sustainable development and must consider the energy embodied in materials and construction and in both initial and recurring maintenance.

The degradation of the performance of Canada's infrastructure over the past several decades has been reviewed, along with the consequences of proper or deferred maintenance and their impact on Canada's infrastructure deficit. The roles of the civil engineering profession, including education and training, and those of the public and private sectors were discussed briefly. Examples of recent technological advances have been summarily presented.

Finally, the paper emphasizes the need for a national infrastructure policy and attempts to answer the question, Where do we go from here?

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