Lifetime Engineering for Roads

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Abstract: Lifetime engineering is the concretisation of an innovative idea for solving the dilemma existing between in infrastructure as a long-term product and the short-term approach to its design, management and maintenance planning. Although lifetime engineering was originally developed for buildings and bridges, its principles can be readily utilised for roads. Sustainable road construction needs the assessment of Life Cycle Costs (LCC) of the structures, the encouragement of data collection for benchmarks, as well as public procurement and contract award incorporating LCC. The use of lifetime-oriented road management has become world-widely more and more widespread The possible high recycling rate in road construction is strived for. Several lifetime engineering elements (life cycle costing, pavement performance models, user cost calculation, internalisation of external road effects, evaluation of the actual effect of road maintenance to pavement performance etc.) already available in Hungarian road management are also introduced.

Keywords: lifetime engineering, road planning, decision making, maintenance, recycling, environmental impacts

1. Introduction

Our society is living through a period of great change, in which we can also see changes in the central goals and requirements of construction techniques. The challenge to the present generation is to lead rapid development of a global economy towards sustainability in relation to our entire society, economy, social welfare and ecology.

Buildings, and civil and industrial infrastructures are the longest lasting and most important products of our society. The economic value contained in buildings, and civil and industrial infrastructures are, to say the least, significant; and the safe, reliable and sound economic and ecological operation of these structures is greatly needed. In industrialised countries buildings and civil infrastructures represent about 80 per cent of national property. Construction plays a major role in the use of natural resources and in the development of the quality of the natural environment in our time. Consequently, building and civil engineering can make a major contribution to the sustainable development of society.

The sustainability of buildings and built environment can, in short, be defined as thinking in time spans of several generations. Sustainability includes social aspects (welfare, health, safety, comfort), economic aspects, functional aspects (usability for changing needs), technical aspects (serviceability, durability, reliability) and ecological aspects (consumption of natural resources such as energy, raw materials and water; air water and soil pollution, waste production; and impact on biodiversity), all related over the entire life cycle of the built facilities. It could be claimed that a built facility can only be as good as its design. The technical definition for sustainable building can be: "Sustainable building is a technology and practice which meets the multiple requirements of the people and society in an optimal way during the life cycle on the built facility" [11].

Design is an important part of construction: translating the requirements of owners, users and society into performance requirements of the structural system; creating and optimising structural solution which fulfil those requirements, and finally, proving through analysis and dimensioning calculations, that these requirements are fulfilled.

Monetary costs are treated, as usual, by current value calculations. Environmental costs are the use of non-renewable natural resources (materials and energy), and the production of air, water or soil pollution. The consequences of air pollution are health problems, inconvenience for people, ozone depletion and global warming. These impacts dictate the environmental profiles of the structural and building service systems. The goal is to limit the environmental costs to permitted values and to minimise them. Integrated lifetime design is an important link in construction: translating the requirements of owners, users and society into performance requirements of the technical systems; creating and optimising technical solutions, which fulfil those requirements; and proving through analysis and dimensioning calculations that the performance requirements will be fulfilled over the entire design service life. The adoption of these new methods and processes will increase the need for renewed education and training of all those involved. This new model of integrated life cycle design, also called lifetime design, includes a framework for integrated structural life cycle design, a description of the design process and its phases, and special lifetime design methods with regard to different aspects discussed above.

Quality assurance has been widely systematised under the ISO 9000 standards. An environmental efficiency procedure is presented in the ISO 14000 standards. The impact of life cycle principles in construction is in the application of life cycle criteria in the quality assurance procedure. Multiple life cycle criteria are also applied during the selection of products, although most of the product specifications have already been produced at the design phase.

Integrated life cycle design supports and improved quality approach, which can be called life cycle quality. All its areas are treated over the life cycle of structures, and controlled in the design by technical performance parameters.

The life cycle performance of structures is highly dependent on maintenance. The first important instructions for life cycle maintenance are produced during the design stage. The structural system of a building or civil engineering facility needs a users' manual, just like a car or any other piece of equipment. The manual will be produced gradually during the design process in co-operation with those involved in design, manufacture and construction. The usual tasks of the structural designer are: compiling a list of maintenance task for the structural system, compiling and applying operational instructions, control and maintenance procedures and works, checking and co-ordinating the operational, control and maintenance instructions of product suppliers and contractors, preparing the relevant parts of the users' manual, and checking relevant parts of the final users' manual.

The active reduction of waste during construction, renovation and demolition is possible through the selective dismantling of structural systems, components and materials specifically for recycling. Selective dismantling includes detailed planning of the dismantling phases, and optimising the work sequences and logistics of the dismantling and selection process. The main goal is to separate the different types of materials and different types of components at the demolition phase in order to avoid multiple actions. The recyclability of the building materials and structural components depends on the degree and/or technical level of the desired reuse.

2. Lifetime engineering

Lifetime engineering is an innovative idea and a concretisation of this idea for solving the dilemma that currently exists between infrastructures as very long-term products and their short-term approach to design, management and maintenance planning [14]. The main elements of lifetime engineering are:

- lifetime investment planning and decision making,
- integrated lifetime design,
- integrated lifetime management and maintenance planning,
- modernisation, reuse, recycling and disposal,
- integrated lifetime environmental impact assessment and minimisation.

The integrated lifetime engineering methodology concerns the development and the use of technical performance parameters to guarantee that the structures meet throughout their whole life cycle the requirements coming from human conditions, economy, cultural, social and ecological considerations. Thus, using lifetime engineering, the human conditions (safety, health and comfort), the monetary (financial) economy and the economy of the nature (ecology) can be controlled and optimised tacking into account cultural and social needs.

For life cycle design, the actual analysis and design are expanded also to the levels of monetary economy and ecology. Life cycle expenses are calculated into present value or annual costs by discounting manufacture, construction, maintenance, repair, rehabilitation, reuse, recycling, disposal etc. expenses.

However, lifetime engineering was originally developed for buildings and bridges, its basic principles can be readily utilized for roads, as it will be shown subsequently.

3. Lifetime engineering development process

There is a clear need for a uniform approach for assessing, validating and operating infrastructures, buildings and industrial, facilities with the consideration of the generic requirements presented in Table 1 [10]

Table 1. Generic classified requirements of the structure

1. Human requirements • functionality in use • safety • health • comfort	**2. Economic requirements** • investment economy • construction economy • lifetime economy in: o operation o maintenance o repair o rehabilitation o renewal o demolition o recovery and reuse o disposal
3. Cultural requirements • building traditions • life style • business culture • aesthetics • architectural styles and trends • imago	**4. Ecological requirements** • raw materials economy • energy economy • environmental burdens economy • waste economy • biodiversity

Moving into lifetime technology means that all processes should be renewed. Furthermore, new methodologies and calculation methods are to be adopted from mathematics, physics, system engineering, environmental engineering etc. However, the need for strong systematic transparency and simplicity of design process has to be kept in mind in order to keep the multiple issues under control and to avoid excessive design activities. The adoption of new methods and process necessitates the renewal of the education and the training of all stakeholders.

Since the design for durability is an important element of lifetime engineering, its main principles will be briefly presented.

4. Design for durability

Durability design methods can be classified starting from most traditional and ending in most advanced methods as follows:

1. design based on structural detailing
2. reference factor method
3. limit sate durability design.

Durability design with structural detailing

Structural detailing for durability is a dominant practical method which is applied to all types of materials and structures. The principle is to specify structural design and details as well as materials so that both deterioration effects on structures, and the effects of environmental impacts on structures, can be eliminated or diminished. The first of these if typically dominant when designing structures, such as wooden buildings, which are sensitive to environmental effects. The second principle is appropriate for structures which can be designed to resist even stronger environmental impacts, such as concrete, coated steel or wooden structures.

The methods and details for durability detailing are presented in current norms and standards.

Reference factor method

The reference factor method aims to estimate the service life of a particular component or assembly in specific conditions. It is based on a reference service life – in essence the expected service life in the conditions that generally apply to that type of component or assembly – and a series of modifying factors that relate to the specific conditions of the case. The method uses modifying factors for each of the following:

- A quality of components
- B design level
- C work execution level
- D indoor environment
- E outdoor environment
- F in-use conditions
- G maintenance level.

Estimated service life of the component (ESLC):

$$ESLC = RSLC \times A \times B \times C \times D \times E \times F \times G$$

where RSLC is the reference service life of the component.

The reference factor method is always an additive method, because reference service life always has to be known. The reference factor method is most often needed because the environmental exposure (environmental load onto structure) usually varies over a wide scale. Many parametric methods including the values of parameters in different conditions already exist.

Limit sate durability design

Although this method is presented and applied in detail for concrete structures, similar methods can also be applied to steel, wooden and masonry structures. Deterioration processes, dictating environmental loads, degradation factors and degradation calculation models are different for different materials.

The simplest mathematical model for describing a "faliure" event comprises a load variable S and a response variable R. In principle the variables S and R can be any quantity and be expressed in any units, the only requirement is that they are commensurable. Thus, for example, S can be a weathering effect and R can be the capability of the surface to resist the weathering effect without too much visual damage or loss of the concrete reinforcement cover.

If R and S are independent of time, the "failure" event can be expressed as follows [10].

$$\{\text{failure}\} = \{R < S\} \tag{1}$$

The failure probability P_f is now defined as the probability of that "failure":

$$P_f = \mathrm{P}\{R < S\} \tag{2}$$

Either the resistance R or the load S or both can be time-dependent quantities. Thus the failure probability is also a time-dependent quantity. Considering $R(\tau)$ and $S(\tau)$ are instantaneous physical values of the resistance, and the load at the moment τ the failure probability in a lifetime t could be defined as:

$$P_f(t) = \mathrm{P}\{R(\tau) < S(\tau)\} \text{ for all } \tau \leq t. \tag{3}$$

The determination of the function $P_f(t)$ according to Equation 3 is mathematically difficult. That is why R and S are considered to be stochastic quantities with time dependent or constant density distributions. By this means the failure probability can usually be defined as:

$$P_f(t) = \mathrm{P}\{R(\tau) < S(t)\} \tag{4}$$

According to the Equation 4 the failure probability increases continuously with time.
At a given moment of time the probability of failure can be determined as the sum of products of two probabilities: 1) the probability that $R < S$, at $S = s$, and 2) the probability that $S = s$, extended for the whole range of S:

$$P_f(t) = P_f = \int \mathrm{P}\ \{R < S \mid S = s\}\mathrm{P}\{S = s\} \tag{5}$$

Considering continuous distributions the failure probability P_f at a certain moment of time can be determined using the convolution integral:

$$P_f = \int F_R(s) f_s(s) \mathrm{d}s \tag{6}$$

where $F_R(s)$ is the distribution function of R,
$f_s(s)$ the probability density function of S, and
s the common quantity or measure of R and S.

The integral can be solved by approximative numerical methods.

5. Sustainable road construction

Sustainable development is a matter of satisfying the needs of present generations without compromising the ability of future generations to fulfil their own needs [13]. Sustainable development means sustainability not only ecologically (= environmentally) and economically but also socially and culturally.

SBIS (Sustainable Building Information System) has been established in Canada to provide users with non-commercial information about sustainable building around the world, and to point or link the user to more detailed sources of information elsewhere.

The World's Largest Life Cycle Assessment – LCA database is available in Japan quantifying the products' impact on the environment throughout its life cycle.

The series ISO 15686 "Building and constructed assets – Service life planning" offers new tools for the life cycle planning of buildings or other constructed assets included roads.

The final report of EC-project "Life Cycle Costs in Construction" [9] has the following recommendations:

- adoption of a common European methodology for assessing Life Cycle Costs (LCC) in construction, encouragement of data collection for benchmarks, supporting best practice and maintenance manuals,
- public procurement and contract award incorporating LCC,
- life cycle cost indicators displayed in buildings open to public,
- life cycle costing at the early design stage of a project,
- fiscal measures to encourage the use of LCC,
- development of guidance and fact sheets.

The ways in which built structures are procured and erected, used and operated, maintained, repaired, rehabilitated and finally demolished (and recycled, reused) constitute the complete cycle of sustainable construction activities. The use of materials, energy and water, and mobility should be minimised [13].

6. Life cycle of road structures

Several countries including Finland [7] have developed lifetime-oriented road management. Usually firstly significant contributions to the research and development of long-term pavement performance are made. The long-term performance models are naturally never complete (final). Secondly, the procurement methods go through profound changes. Typically, the road maintenance responsibility after investment is included in the contract. The daily maintenance contracts therefore cover larger geographic areas with longer contract periods. The contractors and consultants need to learn how to evaluate the life cycle and the life cycle costs of roads. Empirical knowledge, careful observation of existing structures and competence are the keys to success. The client has to clearly describe the targets and the desired quality levels. Besides, the client has also to be in charge of collecting preliminary data to ensure that tenders can be submitted without unnecessary risks.

The life cycle of pavement depends on the bearing capacity – and in a lot of countries the frost susceptibility – of pavement structure. Nowadays, these factors are usually satisfactorily taken into account for main roads. At the same time, for secondary roads the relevant threshold values allow greater variation. As a result, more maintenance measures are required during life cycle.
Typically, rutting type defects due to the deformation of unbound base or sub-base layers need to be repaired. However, unevenness is also often the cause of major maintenance. The selection of rehabilitation methods depends on the factors causing the actual defect. Environmental aspects are also more and more considered by the recycling of road structural material.

Construction expenses are generally rather high compared to life cycle maintenance costs. The former expenditure can be reduced by the possibly maximum rate of recycling, the minimisation of using materials from outside.

There is no generally accepted methodology to calculate the residual value for road structures at the end of investigation period. One of the possible ways is to consider the construction costs during the planning period as increasing (positive) factor and the deterioration (wear) of structures as decreasing (negative) factor. The remixing of wearing course slightly changes the actual residual value. The residual value of a road structure can be higher than the asset value at the beginning of the period.

The increasing use of performance-based specifications in road project tendering and contracting also paves the way for the application of the principles of lifetime engineering [8].

7. Some lifetime engineering elements available in Hungarian road management

Although it is evident that the lifetime engineering as a science has not been utilised, usually not even known by the Hungarian road engineers, several of its elements have already been worked out and applied in road (pavement, bridge etc.) management systems and in practice [4], as follows.

- a.) Whole life (life cycle) costing is more and more used in the planning and design of major Hungarian road projects.
- b.) Pavement performance models have been developed for the forecasting of future behaviour of various road pavement types as a function of time or traffic passed [5].
- c.) The user costs (vehicle operating costs, time delay costs and accident costs) as a function of different pavement conditions levels were also estimated and utilised in the national economy level forecast of life cycle costs.
- d.) Considerable effort has been made for the internalisation of such external road effects as air pollution, traffic noise and vibration.
- e.) The actually effect of major road maintenance (rehabilitation) has also been evaluated using trial section monitoring information [1].

References

[1] Bakó, A.: *Optimization Model for Highway Pavement Maintenance. Proceedings of ISAPT II*, 2004, Kuala Lumpur, Malaysia. CD-ROM publication. 7 p.

[2] Ferreira, A., Antunes, A., Picado-Santos, L.: *Probabilistic Segment-linked Pavement Management Optimization Model*. Journal of Transportation Engineering. Nov-Dec. 2003. pp.268-277.

[3] Gáspár, L.: *Highway Pavement Performance Models. 9th International Conference on Asphalt Pavements*. Copenhagen, 2002. CD-ROM Proceedings. 6 p

[4] Gáspár, L.: *Lifetime Engineering.* Közlekedéstudományi Szemle. (Scientific Review of Transport). 2003/3. pp. 81-85. (In Hungarian).

[5] Gáspár, L.: *Útgazdálkodás* (Road management). Academy Press. Budapest, 2003. 361 p. (In Hungarian).

[6] Gáspár, L.: *Pavement condition before and after rehabilitation*. The International Journal of Pavement Engineering & Asphalt Technology, Volume 5, Issue 1, 2004. pp. 15-28.

[7] Kalliokoski, A., Kasari, T.: *Life Cycle of Road Structures in Road Construction in Practice. Proceedings of 2nd International Symposium* ILCDES 2003. Kuopio, Finland. pp. 349-354.

[8] Mäkinen, S.: *Pilot Project of Lifetime Design of Asphalt Concrete in Finnish Road Administration*. Proceedings of 2nd International Symposium ILCDES 2003. Kuopio, Finland. pp. 403-408.

[9] Roger-France, J.-F. et. al.: *Life Cycle Costs in Construction*. EC DG Enterprise, 2003. 68 p.

[10] Sarja, A, Vesikari, E.: *Durability Design of Concrete Structures*. RILEM Report Series 14. E&FN Spon: London. 1996. 143 p.

[11] Sarja, A: *A vision of sustainable materials and structural engineering.* In: Tuuti, K. (ed.) Selected studies from Scandinavia. Report TVBM-30-78. Lund University, Lund Institute of Technology, 1997. pp. 141-193.

[12] Sarja, A.: *A process towards lifetime engineering in the 5th and 6th Framework Program of EU*. Proceedings of 2nd International Symposium ILCDES 2003. Kuopio, Finland. pp. 7-12.

[13] Tupamäki, O.: *Total LCC and Sustainable Construction.* Proceedings of 2nd International Symposium ILCDES 2003. Kuopio, Finland. pp. 103-109.

[14] Work description of LIFETIME proposal no. CTC1-2001-43046 to Competitive and Sustainable Growth (GROWTH) Programme, Espoo, Finland, 2001. (Co-ordinator: Asko Sarja) 41 p.