The potential applicability of the Life-Quality Index to maintenance optimisation problems

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ABSTRACT: The Life-Quality Index (LQI) is a tool for the assessment of risk reduction initiatives that would enhance safety and quality of life. The paper evaluates the impact of road maintenance programs on the quality of life in the Netherlands using the LQI method. The LQI is calibrated using the specific economic and demographic data for the Netherlands. A preliminary cost-benefit analysis shows that the current road maintenance program is beneficial to the Dutch society. The paper also concludes that the LQI can be promising in supporting decisions for structure and infrastructure maintenance.

1 INTRODUCTION

The main aim of maintenance management of structures and infrastructures is to meet predefined user requirements while assuring safety. In setting standards, safety factors and maintenance levels have often been set arbitrarily and large safety factors are added by designers for the sake of being "conservative". However, there is a large cost associated with compliance to "strict" standards that are not commensurate with benefits in terms of enhanced life quality.

The Life-Quality Index (LQI) is a substantial improvement for rationalizing the process for setting safety standards (Nathwani et al., 1997; Pandey et al., 2006). It is a tool for the assessment of risk reduction initiatives that would support the public interest and enhance safety and quality of life. The LQI is equivalent to a multi-attribute utility function being consistent with the principles of rational decision analysis. It is further refined to consider the issues of discounting of life years, competing background risks, and population age and mortality distribution.

Rackwitz (2002, 2004ab) and Rackwitz et al. (2005) expanded the LQI framework and applied it to determine optimal safety levels in civil engineering infrastructures. Maes et al. (2003) applied LQI for optimising the life-cycle cost of structures. The LQI model has also been applied to the cost-benefit analysis of air quality standards and nuclear safety design practices by Pandey and Nathwani (2003).

The paper investigates the potential applicability of the LQI as a tool for the evaluation of safety and risk-reducing maintenance activities. The LQI is applied to quantify the societal willingness to pay – which is an acceptable level of public expenditure in exchange for a reduction in the risk of death that results in improved life quality – and to obtain an optimal balance of the costs of maintenance and risk. The feasibility of this approach is investigated using a realistic example as a case study. The influence of maintenance efforts on road-surface quality and traffic safety are assessed.

The outline of this paper is as follows. In Section 2, the basic maintenance level for structures and infrastructures in the Netherlands is discussed. The foundation and formulation of the LQI are given in Section 3. The case study is presented in Section 4 and conclusions are formulated in Section 5.

2 INFRASTRUCTURE MAINTENANCE IN THE NETHERLANDS

To optimise the maintenance of structures and infrastructures, the Netherlands Ministry of Transport, Public Works, and Water Management (Rijkswaterstaat) has defined the so-called Basic Maintenance Level (BML) that should be satisfied against lowest life-cycle costs.

2.1 *Basic Maintenance Level (BML)*

Usually, maintenance is defined as a combination of actions carried out to restore a structure to a specified condition in which the structure can perform its required functions. Rijkswaterstaat refers to this specified condition as the basic maintenance level (BML) for structures (Klatter, 2003). In defining the BML, Rijkswaterstaat identifies the following five functions (see also Klatter et al., 2006):

1. Mobility (structural reliability, availability, maintainability);
2. Traffic safety (probability of no harm – injury or death – to human beings);
3. Life quality (personnel safety, human health, well-being, environment, noise nuisance, sustainability);
4. User comfort (road surface, risk perception);
5. Aesthetics (design and colours of a structure, absence of graffiti).

In civil engineering, a failure is often condition failure (disability of a structure to perform its required functions within constraints of legal safety margins), whereas in mechanical engineering failure is often physical failure (breakdown). In structural engineering, condition failure generally means that the probability of a collapse is unacceptable high. Rijkswaterstaat is currently investigating the risks of a structure's disability to satisfy the BML during a pre-specified reference period.

In maintaining the BML against the lowest possible costs, the total costs should ideally be considered over the whole life of a structure or infrastructure. Generally, the following life-cycle phases can be identified: design, construction, use, and demolition. All costs should be considered, regardless of the funding source. Therefore, life-cycle costs should not only include the direct costs of construction, maintenance, and demolition, but also the indirect costs to the society and environment. In defining and maintaining the BML, the user benefits should be taken into account as well. Therefore, effective maintenance should also consider possible user benefits with respect to mobility, traffic safety, life quality, user comfort, and aesthetics. Unfortunately, as pointed out by Besseling et al. (2004) and Ruijgrok et al. (2004), the contribution of maintenance measures to the user benefits is largely unknown, because these costs are very hard to quantify. In the opinion of the authors, the Life-Quality Index has great potential to quantify the impact of life-quality related benefits of a maintenance program.

2.2 *Costs and benefits of the infrastructure users*

In general, the longer the maintenance is postponed, the lower the BML and the higher the user costs. In this respect, the following user costs are important to consider (Besseling et al., 2004): mobility (the lower the BML, the higher the unavailability and the more restrictions on vehicle weights and speeds), traffic safety (the lower the BML, the larger the probability of a traffic accident), life quality (the lower the BML, the rougher the road surface and the more fuel consumption, tire wear, and noise nuisance), user comfort (the lower the BML, the less comfortable the driving and the higher the risk perception), and aesthetics (the lower the BML, the higher the risk perception). On the other hand, maintenance can increase user costs in itself. Major road maintenance works can cause traffic jams and increased risk of fatal accidents. They concern both traffic safety and personnel safety.

The current BML in the Netherlands is relatively high. The Dutch roads are among the safest among the European Union and are becoming safer, despite the increased car traffic. Furthermore, restrictions on vehicle weight and speed (in addition to legal limits) due to a backlog of maintenance are exceptions. In 2002, the number of traffic fatalities was 1,066, which decreased by almost 30 percent since 1996 (Rijkswaterstaat, 2004). On the other hand, the number of emergency repairs increased from 400 in the year 2000 to 750 in the year 2002 (Besseling et al., 2004). Unfortunately, a quantitative relation between the state of maintenance and the traffic safety cannot be derived using available data.

3 LIFE-QUALITY INDEX

To avoid failure, preventive maintenance is performed. In order to determine an appropriate maintenance strategy, we need to balance the costs of maintenance and failure. The consequences of failure can be subdivided into monetary and non-monetary losses (Maes et al., 2003). Monetary losses deal with direct and indirect economic losses, such as damage, repair, loss of assets, production losses, loss of appearance, loss of service, user delay or inconvenience, and impact on growth and employment. The costs associated with such consequences are relatively easy to value. Non-monetary losses represent losses suffered by individuals or groups of individuals. They include death, maiming, injury, loss of long-term income, emotional distress, loss of valuables, social disruptions, and environmental damages. The "costs" associated with these consequences are much harder to estimate. Non-monetary cost can be dealt with using the Life-Quality Index. If maintenance improves the life quality, it must be quantifiable in terms of money or life years and it can be included in the LQI. On the other hand, if the improvement is purely abstract ("feel better kind of thing"), then the LQI or any other measure is of no help. An advantage of the LQI is that a direct estimation of the value of human life is avoided. Instead, the LQI focuses on wealth, long life in good health, and leisure.

3.1 *General*

The Life-Quality Index at the societal level is defined as

$$L = G^q E \,, \tag{1}$$

where G is the gross domestic product (Euro/person/year), E is the life expectancy in the country, and q is the ratio of average work to leisure time available to members of society. The components of the LQI relate to the key human concerns: creation of wealth, duration of life and the time available to enjoy life in good health. The derivation of LQI is formally described below.

3.2 *Derivation*

The general idea is that a person's enjoyment of life or utility in an economic sense arises from a continuous stream of resources available for consumption over the entire life. Therefore, income required to support consumption and the time to enjoy are two determinants of the life quality. For a person at age a, the lifetime utility can be interpreted as total consumption incurred over the remaining lifetime.

Define the probability density function of the lifetime, T, as $f_T(t)$, and use a concise notation to denote it as $f(t)$. The probability of surviving up to age a is given as

$$S(a) = \int_a^{a_u} f(t)dt \,, \tag{2}$$

where a_u is some maximum value of the human lifetime (≈110 years). Survival probabilities for different ages are described in an actuarial life table for a country. The conditional probability density function of the lifetime of a person surviving up to age a is given as

$$f_T(t \mid T > a) = \frac{f_T(t)}{P[T > a]} = \frac{f(t)}{S(a)} \,. \tag{3}$$

The remaining life expectancy of a person of a age is $E[T - a|T > a]$

$$E[T - a \mid T > a] = \int_a^{a_u} (t-a)\frac{f_T(t)}{P[T > a]}\, dt = \int_a^{a_u} (t-a)\frac{f(t)}{S(a)} dt = \int_a^{a_u} \frac{S(t)}{S(a)} dt \,. \tag{4}$$

Denote the consumption rate at some age τ as $c(\tau)$ (Euro/year), and assume that a valid function, $u[c(\tau)]$, exists that can quantify the utility derived from consumption. The lifetime utility for a person is equivalent to integration of $u[c(\tau)]$ from the present age a till age at death t, which is a random variable,

$$U(a,t) = \int_a^t u[c(\tau)]d\tau . \tag{5}$$

The net present value of life utility of consumption can be determined as

$$U(a,t) = \int_a^t u[c(\tau)]e^{-r(\tau-a)}d\tau , \tag{6}$$

where r is the discount rate, also referred to as the rate of time preference for consumption.

The realization of life-time utility, $U(a, t)$, is conditional upon person's living up to age t. So the expected value of utility is given as

$$E[U(a,T)] = L(a) = \int_a^{a_u} U(a,t) f(t \mid T > a)dt . \tag{7}$$

Substituting from Eq. (3) into Eq. (7),

$$L(a) = \int_a^{a_u} \frac{f(t)}{S(a)} U(a,t)dt . \tag{8}$$

Substituting for $U(a, t)$ from Eq. (6) into (8) results in

$$L(a) = \int_a^{a_u} \frac{f(t)}{S(a)} \int_a^t u[c(\tau)]e^{-r(\tau-a)}d\tau dt . \tag{9}$$

Assuming $f(t)$ and $u[c(t)]$ to be continuous functions, the order of integration can be changed that leads to

$$L(a) = \int_a^{a_u} u[c(\tau)]e^{-r(\tau-a)} \left(\int_\tau^{a_u} \frac{f(t)}{S(a)} \right) dtd\tau . \tag{10}$$

Note carefully that the integration limits are changed to $a \le \tau \le a_u$ and $\tau \le t \le a_u$. Previously in Eq. (9), the limits were $a \le t \le a_u$ and $a \le \tau \le t$. From the definition of survival probability given in Eq. (2), Eq. (10) can be further simplified to

$$L(a) = \int_a^{a_u} \frac{S(\tau)}{S(a)} u[c(\tau)]e^{-r(\tau-a)}d\tau . \tag{11}$$

The quantity $L(a)$ in Eq. (11) can be interpreted as present value of expected utility of uncertain remaining lifetime of a person of age a. For the sake of simplicity, the consumption rate is assumed to be time invariant, so that $u[c(t)] = u(c)$ can be taken out of the time integral in Eq. (11)

$$L(a) = u(c) \int_a^{a_u} \frac{S(t)}{S(a)} e^{-r(t-a)}dt = u(c)e(a) . \tag{12}$$

Note that the discounting factor applied to utility of consumption is now merged in Eq. (8) with the survival probability integral. This integral is referred to as "discounted life expectancy", denoted by $e(a)$. Finally, Eq. (8) can be written in a compact form:

$$L(a) = u(c)e(a) . \tag{13}$$

The discount rate is related with the mortality rate in the following way. Denote by $m(t)$ the mortality rate (hazard rate), i.e., probability of dying at age t, and write the survival probability in terms of $m(t)$ as

$$S(t) = \exp\left[-\int_0^t m(\tau)d\tau\right]. \tag{14}$$

From Eq. (12), the discounted life expectancy is given as

$$e(a) = \int_a^{a_u} \frac{S(t)}{S(a)} e^{-r(t-a)} dt\,. \tag{15}$$

The ratio of survival probabilities can be expressed in terms of the mortality rate as

$$\frac{S(t)}{S(a)} = \frac{\exp\left[-\int_0^t m(\tau)d\tau\right]}{\exp\left[-\int_0^a m(\tau)d\tau\right]} = \exp\left[-\int_a^t m(\tau)d\tau\right], \quad 0 \le a \le t\,. \tag{16}$$

Substituting Eq. (16) into (15) leads to

$$e(a) = \int_a^{a_u} \exp\left[-\int_a^t m(\tau)d\tau\right] e^{-r(t-a)} dt = \int_a^{a_u} \exp\left[-\int_a^t [m(\tau)+r]d\tau\right] dt\,. \tag{17}$$

Clearly, the mortality rate works exactly like a discount rate and both are additive. In early ages, the discount rate dominates because the mortality rate $m(\tau)$ is small. In advanced ages, the situation is reversed. A higher force of mortality makes a person to act more "impatiently" and to place less value on future prospects or utility of life.

3.3 *Life quality at societal level*

The life quality at the societal level is an aggregate of the values for all individuals in the society. To achieve this, the life-quality function, $L(a)$, for a person of age a with constant consumption rate c should now be integrated over distributions of population age and consumption rate.

As a matter of simplification, we assume a constant consumption rate equivalent to the real gross domestic product per person per year (G), a valid measure of average consumption in society. Integrating $L(a)$ over the population age distribution, $f_A(a)$, leads to

$$L = E[L(A)] = \int_0^{a_u} L(a) f_A(a) da = c^q \int_0^{a_u} e(a) f_A(a) da = G^q E\,, \tag{18}$$

where E denotes the discounted life expectancy averaged over the stationary age distribution of the national population. Note that the age distribution of a stationary population mathematically can also be derived by means of renewal processes (Baker, 2000).

3.4 *Societal willingness to pay*

Using the concept of a lifetime utility function, Pandey and Nathwani (2003) presented a derivation of the LQI in which the constant q in Eq. (1) is defined as the ratio of average work to leisure time available to members of society; that is,

$$q = \frac{c}{1-c}, \tag{19}$$

where c is a constant, denoting the annual fraction of work time per person required for producing G. In this formulation, the LQI can be written as

$$L = G^{\frac{c}{1-c}} E\,. \tag{20}$$

Obviously, the larger c, the larger q, and the larger L. This formulation links the LQI to concepts generally understood by practitioners in decision analysis, economic modelling, cost-benefit analysis and risk assessment.

One important goal in managing risks to life safety is to determine an acceptable level of expenditure that can be justified on behalf of the public in exchange for a small reduction in the risk of death without comprising the life quality. This value can be considered as a fair estimate of the Societal Willingness to Pay (SWTP) for safety. Suppose a small proportion of GDP, dG, is invested in implementing a project, program or regulation that affects the public risk and modifies the life expectancy by a small amount dE. The net-benefit criterion requires that there should be a net increase in LQI, which can be derived from Eq. (20) as

$$\frac{dL}{L} = \frac{c}{1-c} \cdot \frac{dG}{G} + \frac{dE}{E} \geq 0 \,. \tag{21}$$

For a population of size n, the SWTP is the acceptable level of expenditure that is justified in exchange for a small reduction of the risk of death. By assuming an equality sign in Eq. (21), the SWTP for a population of size n is defined as

$$n(-dG) = n \cdot G \cdot \frac{1-c}{c} \cdot \frac{dE}{E} \,. \tag{22}$$

The calibration of LQI is carried out in terms of the work time ratio (w) and the ratio of the total labor wages to the GDP (β). Then, using the labor-leisure tradeoff, the LQI exponent was derived as (Pandey et al., 2006)

$$c = \frac{1}{\beta} \cdot \frac{w}{1-w} \,. \tag{23}$$

4 APPLICATION OF THE LQI TO MAINTENANCE AND SAFETY

The potential application of LQI to the field of maintenance is explored using a specific example that assesses the effect of maintenance on the road surface quality and the number of accidents and fatalities. However, data on the relation between maintenance and traffic accidents are scarce. For this purpose, a case has been constructed using data from different sources and some simplifying assumptions. A Hollywood disclaimer stating “story based on real facts, resemblance of living persons is coincidence” would apply. Note that it was not possible to distinguish different effects for bridges and pavement.

The relations between the quality of the road surface and the occurrence frequency of traffic accidents and the costs of traffic accidents and maintenance are determined as follows.

The total number of injury traffic accidents was 37,947 in the year 2000 of which 4,101 occurred on the main road network. The number of traffic fatalities on the main road network was 155. An estimate of the fraction of traffic accidents related with the quality of the road surface is 7.5% (CROW, 2001). Applying the same percentage to the number of traffic fatalities on the main road network, 12 deaths are assumed to be related to the road surface quality.

The total costs of road accidents – *including* medical cost, loss of productivity, material cost, clearance cost, traffic-delay cost and *excluding* immaterial cost due to deaths – are estimated at 6,000 million Euro. This estimate is based on 1997 cost data taken from CROW (2001) converted to the 2005 price level with the civil engineering price index of Netherlands Statistics (2005). From these costs, about 50 million Euro is related to the surface quality of the main road network, which is obtained by multiplying the fraction of accidents on the main road network with the fraction of accidents related with the quality of the road surface. This provides an approximate estimate of the benefit of better maintenance.

A reduction of quality standards for the quality of the road surface – e.g., in terms of skid resistance and rut depth – by 20 to 40% leads to a 20 million Euro reduction of cost of pavement maintenance (DWW, 2001). The effect of this reduction on the number of fatalities and accident costs is roughly estimated as follows. A reduction of the skid resistance of 20% increases the risk of accidents with 50% on wet road conditions, which frequently occur in the Netherlands

(CROW, 2001) The increased risk will be less under dry road conditions. In addition to the increase of the number of accidents, the severity of the accidents also increases with decreasing skid resistance. However, an accurate quantitative relation is not yet available. In the example, we assumed that a decrease in risk for dry road conditions is in balance with an increase of severity of accidents for decreasing skid resistance. To conclude the consequences of reduced road-surface quality and associate savings of 20 million Euro are a 50% increase in both the number of fatalities (an increase of 6 to a total of 18 fatalities) and the cost of traffic accidents excluding fatalities (an increase from 50 to 75 million Euro).

Using the LQI, we can now determine the SWTP on the basis of Eq. (22). For this purpose, we use the 2003 life table for the Netherlands for both sexes (Human Mortality Database, 2003). The life expectancy at birth in the Netherlands is 79 years (see Table 1). As of November 2005, the population of the Netherlands is $n = 16.3$ million (Statistics Netherlands, 2005). The gross domestic product (GDP) per capita in purchasing power parity (PPP) US dollars for 2003 is $G = 29{,}371$ PPP US$ (UNDP, 2005). With a dollar-euro exchange rate of 1 US$ = 0.8 Euro, the GDP per capita is $G = 23{,}497$ PPP Euro. An analysis of the Netherlands historical economic data (1987 to 2001 from OECD, 2005) leads to the following results: The average work time fraction is estimated as $w = 0.0744$ year/year and the average wage to GDP ratio is $\beta = 0.51$, and therefore we estimate $c = 0.158$ from Eq. (23). For discount rates ranging from 0-8%, the SWTP of *not* reducing the maintenance and preventing 6 additional fatalities are listed in Table 1. It is advised to use the real interest rate as a discount rate, for the Netherlands this is $r = 0.04$ (Ministry of Finance, 1995). In this case, the discounted life expectancy computed with Eq. (15) is 23 years (see Table 1). Furthermore, the total benefit of current maintenance is the sum of SWTP (14 million Euro) and averted cost of traffic accidents (25 million Euro). Thus, the total benefit of 39 million Euro is much greater than the reduction in maintenance cost of 20 million Euro. In conclusion, the LQI method supports the decision of ongoing road maintenance.

Discount Rate For Life Years [-]	**Discounted Life Expectancy [Year]**	**Societal Willingness to Pay [Million Euro/Year]**	
		Preventing 6 Traffic Fatalities	**Preventing 426 Traffic Fatalities**
0%	79	17	1,200
1%	54	17	1,200
2%	39	16	1,150
3%	29	15	1,100
4%	23	14	1,000
5%	19	13	900
6%	16	12	800
7%	14	10	750
8%	12	9	650

Table 1. Discounted life expectancy and LQI estimates of Societal Willingness to Pay of preventing 6 fatalities due to road-surface related accident fatalities and 426 traffic fatalities for different discount rates.

As a second example, we investigate the objective stated in the Mobility Paper (Rijkswaterstaat, 2004) with respect to traffic safety. The Mobility Paper aims at reducing the total number of traffic fatalities (i.e., for all roads and causes) from 1,066 in the year 2002 to 640 in 2020. The SWTP for reducing traffic fatalities of 426 is 1,200 million Euro per year with no discounting and 1,000 million Euro per year with 4% discounting (see Table 1).

5 CONCLUSIONS

The application of the LQI to maintenance decision problems helps determining an optimal trade-off between the risk and consequences of traffic accidents and the reduction in maintenance efforts. In traditional life-cycle costing analyses of maintenance programs, the cost assessment is often performed quantitatively and the risk assessment qualitatively. A quantitative risk assessment looks promising from a conceptual point of view, which is accomplished in the paper using the LQI method. A preliminary cost-benefit analysis shows that the current road maintenance program is beneficial to the Dutch society. A decrease in the road quality standards would reduce the life quality in the society. A detailed analysis of the relation between the traffic accidents and the quality of road and maintenance actions is needed to refine the LQI analysis presented in the paper. In this respect, the use of geographic information systems can be helpful. The LQI framework can be applied to assess the impact of other investment in safety-related programs, such as road and bridge safety, in the Netherlands.

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