Chapter 17
Societal Perspective in Risk Management: Application of Life-Quality Index

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Abstract Risk can always be reduced but at some cost. Since disproportionate cost of risk reduction diverts societal resources away from other critical needs, efficiency argument has been enshrined in regulatory practices worldwide. This means the benefits of improved safety must be balanced against the cost of risk reduction. Aging and degradation of infrastructure facilities and systems have raised concerns over the safety of public, environment and economic productivity. Large investments are required to upgrade civil and industrial infrastructures in compliance with safety regulations. The chapter presents the Life Quality Index (LQI) formulation to assess the effectiveness of regulations and infrastructure projects that have major impact on life safety.

17.1 Introduction

"How safe is safe enough?" This basic question has inspired quantitative evaluation of risk to rationalize regulations and engineering standards that aim to reduce risk in society. Experience-based professional judgment has always been fundamental in public risk management, health care, and engineering. Professional practice is now moving towards objective, transparent and accountable management of risks at the societal level. In addition to scientific evaluation of risks, an understanding of acceptable level of risk is equally important—more so, because it provides a basis to prioritize and invest in risk management programs.

In order to establish a threshold of acceptable risk, the key issues that need to be addressed are how to (1) choose a standard of what the associated risks are worth and assure that it serves society; (2) allocate limited resources for life-saving

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purposes for the collective benefit of society; (3) ensure transparency of the decision-making process; and (4) maintain respect for societal values. There is a considerable body of literature that explores the principles of managing risk in public interest and basis for determining the acceptable risk, as reviewed by Murphy and Gardoni (2007, 2008). This chapter does not review different methods of determining the acceptable risk, rather it focuses on one particular approach that relies on the social indicator to assess the impact of risk on society and measures to mitigate such risks.

Inspired by the Human Development Index (UNDP 1990), a new social indicator, Life Quality Index, was developed which has two component, namely, the life expectancy and the gross domestic product (GDP) per person (Pandey et al. 2006). The LQI can also be interpreted as an ordinal utility function that quantifies the utility of income derived over the expected lifetime of a representative individual in the society. It comprises of economic, demographic and life-safety aspects of a society (Nathwani et al. 2009).

The chapter illustrates the derivation of a minimum acceptable limit of resources that the society should commit to risk reduction in a sustainable manner. The key idea is that the engineered safety should be determined on the basis of a balance between the cost of risk control measures and the benefits in terms of improving life safety. This approach is analogous to a cost-benefit analysis that relies on LQI. The chapter clarifies the underlying concepts, computational procedures and provides the interpretation of results so that engineers can apply this method to practical examples of risk management.

The LQI approach is applied to assess the benefits of the Quantitative Health Objectives (QHOs) adopted by the U.S. Nuclear Regulatory Commission to control the risk of radiation exposure. The other potential area of application is the allocations of resources to infrastructure renewal projects. The safe and efficient management of engineering infrastructure systems, such as power plants, pipelines, transmission lines, bridges, highways, water distribution and waste-disposal systems, directly contributes to economic well-being and quality of life in the society.

17.2 Life Quality Index

17.2.1 General Concept

Maximizing a utility function has been a traditional approach to optimizing decisions. This approach can be extended to societal risk management. Longevity and quality measured by social income are two key determinants of life quality, among many other possible attributes that matter to life quality. A societal utility function, referred to as Life-Quality Index, is postulated that consists of life expectancy and the gross domestic product (GDP) person.

LQI is an ordinal utility function that quantifies the utility of income derived over the potential lifetime of a representative individual in the society (Pandey and Nathwani 2003a, c, 2007). The LQI has been derived as (Pandey et al. 2006)

$$L = cg^{q}e \leq \tag{17.1}$$

where e, g and c are the life expectancy, GDP per person and a constant, respectively. The parameter q has especial significance as it reflects a trade-off that the society places between economic consumption and the value of the length of life. Using macroeconomics theories, the exponent was derived as (Pandey et al. 2006)

$$q = \frac{1 \quad w}{\beta(1-w)} \tag{17.2}$$

In this expression, β denotes the share of labor input (i.e., wages) to GDP and w is the work time fraction in a year. Although a formal derivation, interpretation and calibration of the LQI have been presented elsewhere (Pandey et al. 2006), an example of LQI calibration is presented in Sect. 17.3.

17.2.2 Illustration of LQI Calibration

In this section, the calibration of LQI using the Canadian economic and demographic data is illustrated. For Canada, the time series for the period 1961–2003 were used and all economic data were standardized in constant 1997C$ (Statistics Canada, www.statscan.ca).

Figure 17.1 shows the trend of increase in the Canadian population from 18.2 million in 1961 to 31.6 million in 2003. The workforce increased from 6.4 to 15.9 million in the same period. The ratio of the workforce to population has increased from 35.6 to 50.5 % in this period. Figure 17.2 shows that the GDP per person (in 1997 CAD $) has increased from $13,456 in 1961 to 34,675 in 2003, whereas the GDP per worker has grown from $27,839 to $68,632 in the same period.

The historical trends of the labor or work time fraction per year per person (w) used in producing the GDP is shown in Fig. 17.3. The work time fraction for workers is calculated from the average number of hours worked per employed person/year, estimated from labor market surveys. The work time fraction at the population level is obtained as the total number of work hours divided by the national population.

According to Cobb-Douglas production theory, the ratio of wage to GDP is a measure of the share of labor coefficient, β, in the production function (Nathwani et al. 2009). This ratio is plotted in Fig. 17.4, which shows a stable trend for Canada within the limits of 0.5–0.55.

To calculate q, the work time fraction (w at population level) from Fig. 17.3 and wage to GDP ratio (β) from Fig. 17.4 were substituted into Eq. (17.2). The resulting

Fig. 17.1 Increase in the Canadian population and workforce (1961–2003)

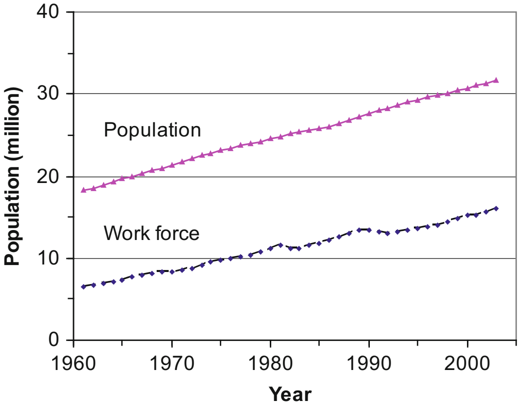


Fig. 17.2 GDP per person growth in Canada (1961–2003)

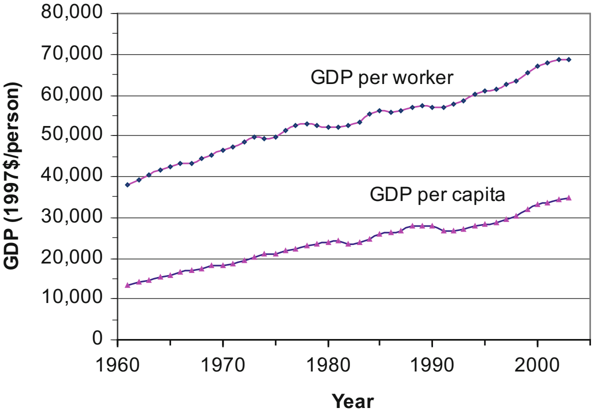
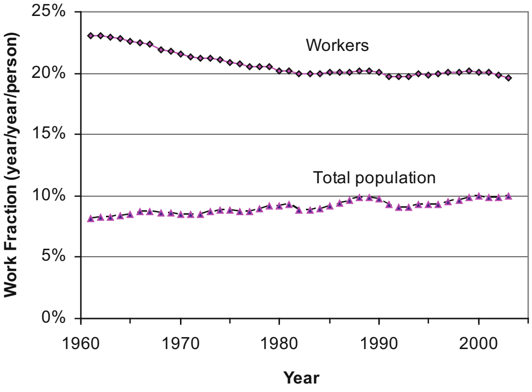


Fig. 17.3 Annual work time fraction in Canada (1961–2003)



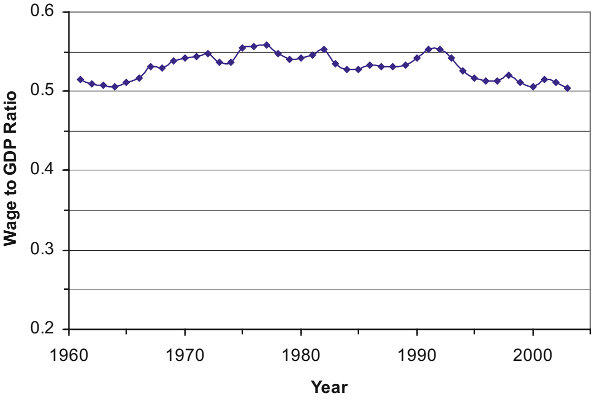


Fig. 17.4 The ratio of wage to GDP in Canadian economy

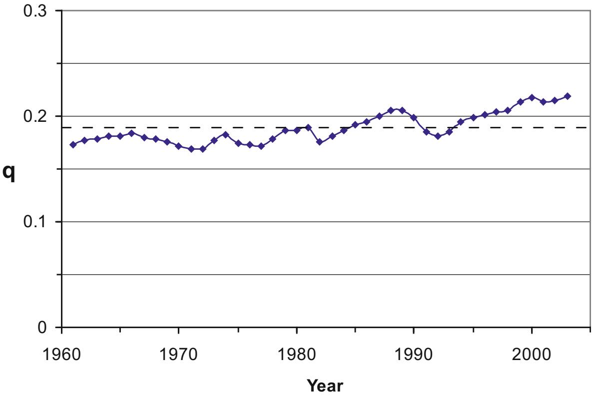


Fig. 17.5 The historical trend of the LQI exponent (q) based on the Canadian data

time series plotted in Fig. 17.5, shows that q varies in a narrow range of 0.17–0.21 with an average value of 0.19.

Given a small fluctuation in q, a mean value of $q = 0.2$ can be used in practical applications. The constant of proportionality, c, is not relevant to cost-benefit analysis. The LQI coefficient was also calculated for several OECD countries, which showed that q varies between 0.15 and 0.2 (Pandey et al. 2006).

The calculation of LQI can be illustrated using some practical data. The life expectancy at birth in Canada for example is 77.5 years. Assuming a value of the real GDP per capita as $g = 30{,}000$ \$/person/year, the LQI is computed as $(30{,}000)^{0.2} \times (77.5) = 609$ utils (note that utils are arbitrary units of the utility function which has no physical meaning).

17.2.3 Life Expectancy and Related Concepts

Define the probability density function of the lifetime, T, as $f_T(t)$, and use a concise notation to denote it as $f(t)$. In general, the life expectancy (i.e., the expected time of remaining life from the present) at birth is defined as

$$e = \int_0^{a_u} t f(t) dt = \int_0^{a_u} S(t) dt \tag{17.3}$$

where a_u is some maximum value of the human lifetime ($\approx$110 years) and $S(t)$ is the probability of survival up to age t, which can be defined in terms of the lifetime density and mortality rate, $m(t)$, as

$$S(t) = \int_0^{t} f(\tau) d\tau = \exp\left[- \int_0^{a} m(\tau) d\tau \right] \tag{17.4}$$

Survival probabilities for different ages are described in an actuarial life table for a country. The current survival and hazard (or mortality) curves for Canada are shown in Fig. 17.6.

The life expectancy (i.e., the expected time of remaining life) changes with the age of the person. To illustrate this, the conditional probability density function of the lifetime of a person surviving up to age a is introduced as

$$f_T(t|T > a) = \frac{f(t)}{P[T > a]} = \frac{f(t)}{S(a)} \tag{17.5}$$

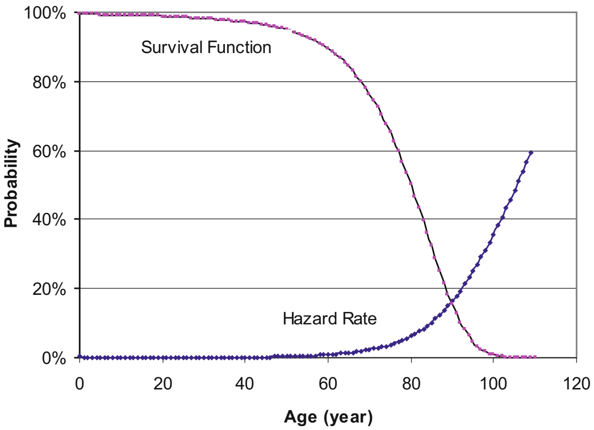


Fig. 17.6 Survival function and hazard rate of the human lifetime

The remaining life expectancy of a person of age a is denoted as $e(a) = E[T - a| T > a]$. This is equivalent to average remaining life of a person of age a.

$$e(a) = E\left[T - a\middle|T > a\right] = \int_a^{a_u} (t-a)f\left(t\middle|T > a\right)\,dt = \int_a^{a_u} (t-a)\frac{f(t)}{S(a)}dt$$

$$= \int_a^{a_u} \frac{S(t)}{S(a)}dt \tag{17.6}$$

The ratio of survival probabilities in Eq. (17.5) can be expressed in terms of the mortality rate as

$$\frac{S(t)}{S(a)} = \frac{\exp\left[-\int_0^t m(\tau)d\tau\right]}{\exp\left[-\int_0^a m(\tau)d\tau\right]} = \exp\left[-\int_a^t m(\tau)d\tau\right], \qquad 0 \le a \le t \tag{17.7}$$

Substituting Eqs. (17.6) into (17.5) leads to

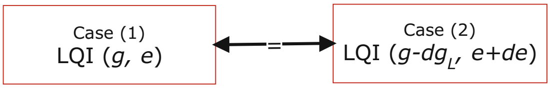
$$e(a) = \int_a^{a_u} \exp\left[-\int_a^t [m(\tau)]d\tau\right] dt \tag{17.8}$$

If the mortality rate is changed from $m(\tau)$ to $[m(\tau) + h(\tau)]$, it would modify the lifetime distribution. The modified distribution can be denoted by a new random variable T_1 and the mean lifetime can be obtained as

$$e_1(a) = \int_a^{a_u} \exp\left[-\int_a^t [m(\tau) + h(\tau)]d\tau\right] dt \tag{17.9}$$

The change in life expectancy is the average change in lifetime estimated as $de = \mathrm{E}[T - T_1] = (e - e_1)$. It should be noted that a change in mortality rate at any age $t \geq a$ will influence the remaining life expectancy, and the change in life expectancy is an average quantity that occurs over the lifetime of an individual.

Fig. 17.7 LQI invariance principle



17.2.4 Benefit-Cost Analysis Using LQI

One important goal in managing risks to life safety is to determine a minimum 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 compromising the life-quality. It can also be referred to as the societal capacity to commit resources (SCCR) and it can be obtained from the LQI invariance criterion as follows.

Suppose that a risk management program has a potential to improve the life expectancy from a reference or baseline level of e to $(e+de)$. A threshold value of the cost of the program, dg_L (in \$/year), can be calculated from the invariance criterion such that LQI in the reference case (g, e) is the same as in the new scenario $(g-dg_L, e+de)$, as shown in Fig. 17.7. This condition can be expressed as

$$\frac{dL}{L}=0 \Leftrightarrow \frac{dg_L}{g}+\frac{1}{q}\frac{de}{e}=0 \tag{17.10}$$

A threshold value of the cost rate can thus be derived as

$$(-dg_L)=\frac{g}{q}\frac{de}{e} \quad (\$/\text{person}/\text{year}) \tag{17.11}$$

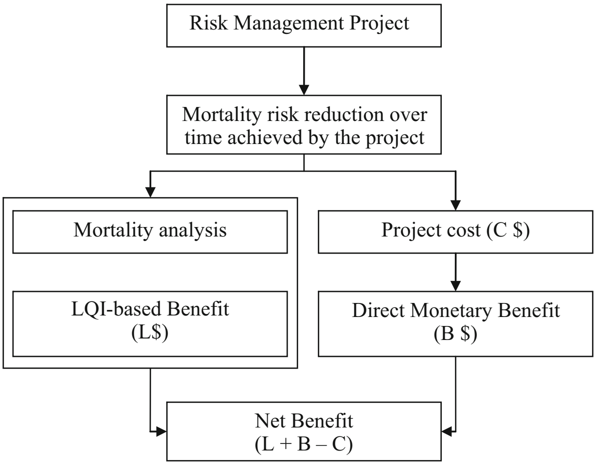
17.2.5 Societal Capacity to Commit Resources (SCCR)

A careful interpretation of all the terms in Eq. (17.10) is important. If the risk management program results in a gain in life expectancy, dg_L represents the maximum allowable cost per year to fund the program. In other words, if the actual program cost rate is less than dg_L, the program improves the LQI for the population under consideration. If a project results in loss of life expectancy, then dg_L represents minimum benefit that should be derived from the project. Otherwise, it will result in a decrease in the LQI.

It is noteworthy that $e \times dg_L$ is the amount per person that society should gain as a result of a risky project that imposes an additional risk that reduces person's life expectancy by de. Conversely, $e \times dg_L$ is the amount per person that society should spend in a project that improves the life expectancy by de. This threshold amount is referred to as the Societal Capacity to Commit Resources (SCCR) (Nathwani et al 2009). This value is specific to a society since it depends on the background mortality, demographics, and economic development.

The term de/e is in the unit of life years gained (or lost) per year of lifetime. The maximum cost of saving one life year can then be computed from Eq. (17.10) as

Fig. 17.8 Benefit-cost analysis using LQI method



$$\frac{(-dg_L)}{de/e} = \frac{g}{q} \quad \{(\$/\text{year})/(\text{life year}/\text{year}) \;=\; \$/\text{life year}\} \tag{17.12}$$

For $g = 30{,}000$ and $q = 0.2$, this value is 150,000 $/life year saved. This value is independent of the age of the person.

Another interesting quantity is dg/de, which is interpreted as the cost rate in $/year for saving one life year:

$$\frac{(-dg_L)}{de} = \frac{1g}{qe} \quad (\$/\text{year}/\text{life year}) \tag{17.13}$$

In summary, so long as the cost rate of implementing a program is less than that given by Eq. (17.10), the program can be considered to be beneficial from the LQI point of view.

A schematic of the LQI method is presented in Fig. 17.8. It should be recognized that a key input to LQI method is the change in mortality rates due to proposed project. Subsequently, it is important to quantify a change in life expectancy correctly. If a project has no impact on life safety, only an economic cost-benefit analysis is needed to judge its acceptability.

17.3 Applications

17.3.1 A Hypothetical Example

To illustrate the LQI method, we consider a hypothetical example of an infrastructure system to control environmental pollution. The inspection and surveillance data indicate that the system is experiencing increasing deterioration over next

40 years. If the system is not refurbished, it would pose a public hazard, which would increase the mortality rate in the exposed population. To deal with this situation, a refurbishment project is proposed to mitigate the impact of this hazard over a 40-year period. A key question in the decision-making process would be: what is the acceptable cost of this project? The LQI method can help answer this question.

17.3.1.1 Analysis

For the clarity of illustration, consider that only persons of age 50 years are affected by this hazard. The remaining life expectancy at age 50 is 29.9 years, which is estimated from a truncated remaining lifetime distribution, $f_{50}(x) = f(x)/S(50)$, as shown in Fig. 17.9.

Figure 17.10 illustrates calculation of the LQI as an integration of the utility of income derived over the remaining lifetime of a 50-year-old person:

$$LQI(50) = \int_{50}^{110} U(G) f_T\left(x \middle| x > 50\right) dx = \int_{50}^{110} G^q \frac{S(x)}{S(t)} dx = G^q e(50) \qquad (17.14)$$

Thus,

$$LQI(50) = (30{,}000)^{0.2}(29.9) = 235\,\text{utils} \qquad (17.15)$$

As stated earlier, the deterioration of infrastructure system increases the mortality risk, which is described as $m_{new}(k) = m_{old}(k)\ (1 + r(k))$, $50 \le k \le 90$. For illustration purposes, it is assumed that $r(k)$ increases linearly from 0.05 to 0.15 beginning from age 50 to 90 year. Note that an exaggerated mortality risk due to deterioration is considered for illustrative purposes only. In practical cases, very

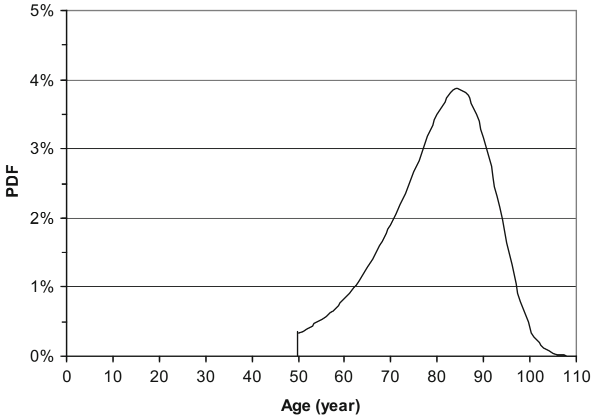


Fig. 17.9 The remaining lifetime distribution of the person of age 50 years

Fig. 17.10 Computation of LQI for the person of age 50 years

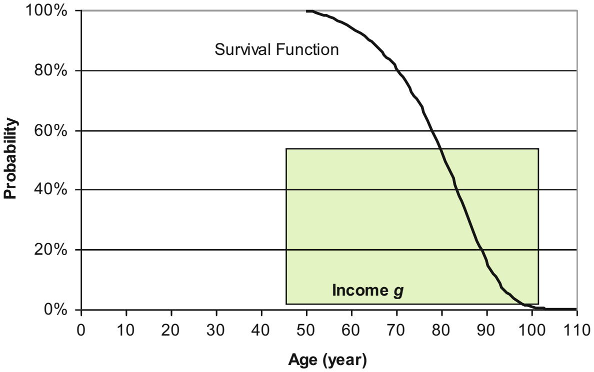
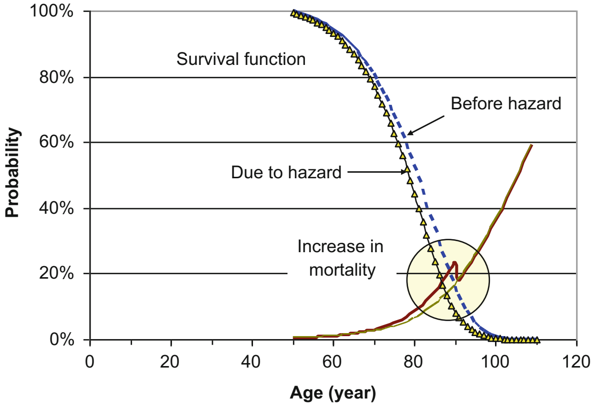


Fig. 17.11 The impact of increased mortality rate for the person of age 50 years



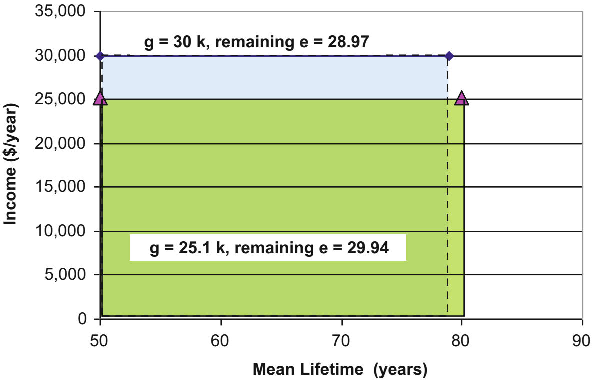
small changes in life expectancy are seen. Another remark is that the assessment of increased hazard and its mortality impact are not trivial tasks. Comprehensive scientific modeling and analysis are required to achieve this work. This information is a critical input to the LQI model.

An effect of increased mortality rate on the survival curve is illustrated in Fig. 17.11. The new survival curve is obtained by modifying the hazard rates between 50 and 90-year ages. In presence of the new hazard, the life expectancy is reduced to 28.97 years from the original value of 29.94 year. These calculations are done using a simple spreadsheet package and the Canadian life table.

The infrastructure refurbishment project is intended to remove the effect of deterioration. In other words, an anticipated gain in life expectancy due the project is $de(50) = 29.94 - 28.97 = 0.97$ year. The LQI threshold cost rate for this project can be estimated from Eq. (17.10) as

$$(dg_L) = \frac{g}{q}\frac{de}{e(50)} = \frac{30,000 \times 0.97}{0.2 \times 29.94} = 4860 \tag{17.16}$$

Fig. 17.12 Illustration of LQI invariance principle



In summary, there are two scenarios. First is "do-nothing" scenario in which life expectancy would reduce to 28.97 years, but the income would remain unaffected at $g = 30{,}000$ $/year. The other scenario is to restore LE to 29.94 years, but the income would change to $(g - dg) = 30{,}000\text{–}4860 = 25{,}140$ $/year. The LQI would remain the same in both scenarios, as shown in Fig. 17.12.

The cost rate per life-year saved is calculated as

$$\frac{dg}{de} = \frac{4860}{0.97} = 5010\ \$/\text{year}/\text{lifeyear saved} \tag{17.17}$$

The maximum total cost of this project is given as $L = 4860 \times 29.94$ year $= 145{,}508$ $/person. In other words, the project is beneficial from LQI criterion so long as its total cost is less than 145,508 $ per exposed person.

If the exposed population consists of persons of other age groups, this analysis needs to be repeated for each age group and the results have to be summed over the age distribution. In the calculations presented here, the discounting is not taken into account. For more details of these topics and LQI applications to structural engineering, readers are referred to Rackwitz et al. (2002, 2003, 2005).

17.3.2 Analysis of Radiation Safety Regulations

The qualitative safety goals adopted by the U.S. NRC (2001) are as follows:

Firstly, individual members of the public should be provided a level of protection from the consequences of nuclear power plant operation such that individuals bear no significant additional risk to life and health. Secondly, societal risks to life and health from nuclear power plant operation should be comparable to or less than the risks of generating electricity by viable competing technologies and should not be a significant addition to other societal risks. To achieve these objectives, NRC adopted two Quantitative Health Objectives (QHOs), which are analyzed in this section using the LQI framework.

17.3.2.1 QHOs of the U.S. NRC

The first QHO is related to prompt fatality and states that the additional risk should not exceed 0.1 % of the total prompt fatality risk to the population. The baseline risk of prompt fatality in the U.S. was estimated as 5×10^{-4} per year. Thus, the maximum risk imposed by the nuclear power plant is allowed to be 0.1 % of the baseline value, or 5×10^{-7} per year.

Using the life table analysis, reduction in life expectancy at birth due to this risk is estimated as $de = 13$ h. The LQI equivalent impact is estimated using Eq. (17.10) as $dg = 3.5$ \$/person/year (=260 \$/person). Impact of additional risk indeed appears to be insignificant.

The second QHO related to cancer fatality states that risk should not exceed 0.1 % of the total cancer fatality risk to the population from all other causes. The baseline risk of cancer fatality in the U.S. population is 2×10^{-3} per year per person. As per QHO-2, a maximum risk imposed by the nuclear power plant is allowed to be 2×10^{-6} per year. The loss of life expectancy at birth due to this risk is estimated as $de = 52$ h per person. The LQI equivalent monetary impact is estimated as $dg = 14$ \$/person/year (=1042 \$/person). This computation ignores the delayed onset of cancer mortality.

17.3.2.2 Dollar Per Person Rem

US NRC (1995) has recommended 2000 Dollar per person-rem as a threshold value for investing in radiation reduction equipment and program. Note that "rem" is a unit of effective absorbed dose of ionizing radiation in human tissue, equivalent to one roentgen of X-rays. The dollar per person rem limit means that if a program costs more than 2000 \$/person rem reduction, it does not pass the benefit cost efficiency test. This limit was estimated as a product of the value of statistical life (VSL) of \$3 million with the risk of death of 7×10^{-4} per person-rem.

It is not clear as to exposure being a single event, or it continues permanently over a longer period of time. A reduction in mortality risk of 7×10^{-4} per year over the entire life of a person is quite substantial, as it would increase the life expectancy by 2 years. It is not clear to us whether or not this is the implication of the regulatory limit.

This problem can be approached in a different way. Suppose, a 2000 \$/person investment is made in the risk reduction program. The LQI allows to impute a value of minimum risk reduction that ought to be achieved by this investment. The LQI equivalent reduction in risk of death should be 4.5×10^{-6} per person per year, which implies 117 h (about 5 days) of increase in the life expectancy at birth.

17.3.2.3 Fire Risk Reduction Program

In Browns Ferry nuclear plant, over $80 million were spent to reduce the fire risk causing the core damage (1988). Overall risk reduction achieved by this modification was estimated as 7.8×10^{-5} per year (McCullough and McCullough 1991). This program was effective for remaining 15 year of the plant life.

LQI analysis of this risk reduction can be carried out assuming that average age of the plant worker age was 30 years. Applying this risk reduction a life table analysis, the resulting increase in life expectancy was estimated as 16 days. The LQI equivalent monetary impact is estimated as $dg = 6602$ $/person/year, which is a rather significant amount. This analysis is also somewhat approximate as the underlying assumptions of core damage frequency analysis are not clear to us. Nevertheless, this example illustrates how one can evaluate the effectiveness of a risk reduction program using the LQI approach.

17.4 Conclusions

It is generally accepted that resources committed to mitigation of risks to the public should be utilized in an efficient manner. However, an absolute and objective definition of efficiency in societal risk management is hard to achieve, and, therefore, some normative guiding principles are needed. A basic goal in risk regulation should be to preserve life in good health and resources. To address this goal, an approach based on the Life Quality Index is proposed.

LQI is a "parsimonious" surrogate for the societal utility function including longevity, and social income are two key factors. The Life Quality Index (LQI) reflects the overall societal valuation of life time and economic activity. The chapter illustrates that the societal capacity to commit resources to risk reduction in a sustainable manner can be derived from the LQI. The chapter presents an exposition of the LQI-based benefit-cost analysis method that can be used to evaluate the impact of safety regulations and investments in risk reduction projects. The chapter derives a maximum cost or minimum benefit threshold to judge the acceptability of a project. The chapter clarifies input requirements, computational steps and how to interpret the results of the analysis in order to facilitate practical applications of the LQI method. The LQI analysis of the Quantitative Health Objectives used by the U.S. NRC is discussed along with the implications of the dollar per rem limit. Other applications of LQI to air quality management and flood risk reduction programs are already presented by the authors (Pandey and Nathwani 2003b; Lind et al 2009).

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