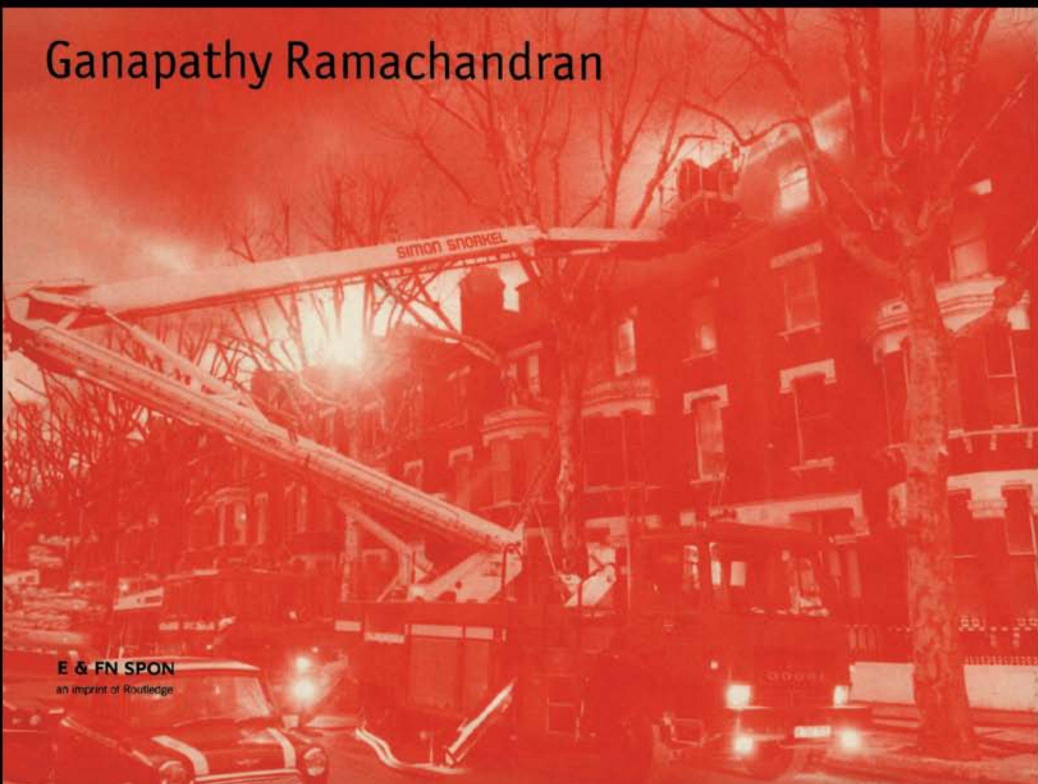
The Economics of FIRE PROTECTION

Ganapathy Ramachandran



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Retail prices index

Retail prices index, United Kingdom (all items)

Year	*Retail prices index*	*Year*	*Retail prices index*	*Year*	*Retail prices index*
1967	102.5	1977	299.8	1987	650.5
1968	107.3	1978	324.6	1988	700.1
1969	113.1	1979	368.1	1989	749.7
1970	120.3	1980	434.3	1990	821.4
1971	131.7	1981	485.9	1991	871.0
1972	141.0	1982	527.7	1992	898.6
1973	154.0	1983	551.3	1993	915.1
1974	178.7	1984	578.8	1994	937.8
1975	222.0	1985	611.9	1995	970.4
1976	258.8	1986	634.0	1996	993.8

Source: Annual Abstract of Statistics *published by the Office for National Statistics. Over the period 1966–96 the basis for the calculation of retail prices index was changed a few times.*

Note: *Mid-January 1966=100. Figures for 1965–82 are estimates based on mid-January values. Figures for 1983 and later years are estimates based on annual averages.*

About the author

Ganapathy Ramachandran, Ph.D, D.Sc, F.I.Fire E. is Visiting Professor in Fire Safety Engineering at the University of Hertfordshire, UK. From 1980 to 1988 he was the Head of Operational Research and Systems Studies Section at the Fire Research Station, Borehamwood, Hertfordshire. He currently practises as a private consultant, mainly in research problems concerned with fire risk evaluation, fire safety engineering and fire insurance specialising in statistical, probabilistic and economic aspects of these problems.

Preface

For over a century, the regulatory control of safety measures required to protect the occupants of a building from fire has mainly been achieved through a framework of prescriptive rules based on experimental data, scientific theories and case histories of major fires. These rules generally relate to the provision of passive measures such as fire-resistant compartments and means of escape facilities. They do not take sufficient account of the effectiveness of active fire protection measures such as sprinklers, which, although designed primarily for property protection, can provide some levels of life safety. Prescriptive rules, if enforced rigidly, can lead to costly over-design, particularly for some large and complex buildings.

Recognising these problems, a fire safety engineering approach has been developed in many countries during the past few years as a viable substitute for prescriptive rules. It is envisaged that the application of this approach would produce alternative fire protection strategies, including combinations of passive and active measures which can provide equivalent levels of safety for life and property. From among such strategies, a property owner may select one which is economically optimum in terms of the costs and benefits involved.

Selecting the most cost-effective fire protection strategy would be a simple task for an economist with experience of practical applications. It may, however, be a complex and confusing exercise for a fire safety engineer or property owner/manager confronted with several options that satisfy acceptable safety levels for life and property. Selected fire protection options should then be considered in combination with insurance options arising from appropriate levels of self-insurance (deductibles). An element of uncertainty is associated with each combination of fire protection and insurance options. This is due to the fact that the occurrence of a fire and the extent of the damage it can cause are random phenomena. Quantifying uncertainties by probabilities may be a simple task for a statistician but it may not be so for someone with an insufficient knowledge of statistical methods.

For these reasons, I decided to write a book on the economic aspects of fire protection for the use of practising fire safety engineers, owners/managers of industrial and commercial properties and others, such as those engaged in the development of fire safety codes, regulations and standards. This subject is an essential part of fire safety engineering and is being taught at undergraduate and postgraduate levels in some universities and colleges of further education around the world. The number of higher education institutions teaching fire safety is steadily growing and hence there is a need for a text book on fire protection economics, which may be met by this book.

The book attempts to explain how the theoretical concepts and models generally followed in a cost-benefit analysis can be adopted or modified to produce solutions to problems in fire protection economics. A few statistical and probabilistic techniques, requiring an undergraduate level of understanding, have had to be included to show how the uncertainty factor associated with the random variable, fire damage, can be quantified. Those discussed in Chapters 7 (Decision analysis) and 8 (Utility theory) are, perhaps, of post-graduate level but a practising fire safety engineer need not try to understand the mathematical techniques applied to derive the results. The statistical and probabilistic models discussed in the book are sufficient for all practical purposes but more advanced models can be applied, if necessary, for a critical evaluation of fire risk. Such advanced models are discussed in a book on probabilistic assessment of fire risk which is currently being prepared.

Chapter 1 provides a background to the economic problems encountered in providing fire protection and insurance cover, including the components of fire damage and the stages involved in fire risk management. This chapter also discusses methods of comparing fire damage in different countries. Chapter 2 is concerned with the enumeration of costs and benefits relevant to each decision-maker involved in fire safety problems, and Chapter 3 with different methods of expressing costs and benefits on an annual basis. Chapter 4 discusses methods such as benefit-cost ratio and the optimum level of fire safety which can be applied to select and compare alternative fire protection strategies. The selection process can be carried out systematically by following the decision tree approach (Chapter 7) if several options are available for fire protection and insurance cover. Chapters 3 and 4 contain simple mathematical formulae and equations whereas Chapter 7 presents some advanced statistical methods.

In Chapter 5, the theoretical concepts and models presented in Chapters 2 to 4 are applied to evaluate the economic value of individual fire safety measures. Due to lack of data, only a framework is provided in Chapter 6 to evaluate the interactions and trade-offs arising from combinations of passive and active fire protection measures and the interactions between these measures and fire insurance. This aspect has not so far been considered seriously in fire safety regulations.

As outlined in Chapter 6, the demand for fire cover to be met by fire brigades depends to some extent on the fire protection measures adopted in buildings belonging to different risk categories. This interaction would affect the number and size (manpower and equipment) of fire stations required for a geographical area and hence should be taken into account in economic problems concerned with fire brigade operation. These problems are not discussed in this book.

Using utility functions and some advanced statistical techniques, Chapter 8 presents a method for quantifying the attitude of property owners/managers to fire risk and the maximum amount they may be willing to spend on fire protection and insurance. This amount should be taken into account in calculating fire insurance premium rates for different risk categories and rebates on premiums for fire protection devices and self-insurance levels (deductibles). Chapter 11 provides some guidance on these and other statistical problems encountered by fire insurance companies. Chapter 9 provides background material to evaluate indirect/consequential losses caused by fires, an area in which little research has been carried out so far. Due to financial constraints on the amount of money available for fire safety activities, it is necessary to assign a monetary value to human life (Chapter 10), although it may be unethical to do so.

Chapter 12 is an expanded summary of the analytical methods and calculation procedures presented in the book. A practising fire safety engineer or student may find it useful to read this chapter first and then refer to the relevant chapter and section or equation for a detailed description of a method or procedure.

It should be emphasised that, due to the limited information available to me for analysis, I could include only some general examples to illustrate the application of the methods proposed in the book. For this reason, the results derived in these examples can only provide overall conclusions. Results and conclusions for particular cases would vary depending on several factors discussed in the various chapters of the book. They would also depend on the quantity and quality of data available to a decision-maker to perform a detailed economic analysis.

During the writing of this book, I received statistical data and other information and useful suggestions from many people and this is the place to thank them for their help. I would like to convey my thanks particularly to Tom Wilmot, Director of the World Fire Statistics Centre, London, for his timely help in providing me with up-to-date statistical tables on international fire cost comparisons which have been used in Chapters 1, 2 and 9. I am very grateful to the Society of Fire Protection Engineers, USA, for their kind permission to reproduce Chapters 8, 9 and 10 which I contributed to the second edition of the *SFPE Handbook of Fire Protection Engineering* published in June 1995. I should like to thank Eric Marchant for reading the manuscript and offering useful comments and suggestions.

The book contains several mathematical and statistical functions and formulae and therefore, typing the manuscript on a word processor was an extremely difficult task. Liz Tattersall coped admirably with this work and I thank her for this help. My wife, Radha, gave me considerable assistance during the preparation of the book by checking the typescript and the printed

page proofs and spotting mistakes to be corrected. I thank her for this support and for encouraging me to write other books which are planned for the next few years.

I wish to dedicate this, my first book, to my father Ganapathy Iyer and mother Venkatalakshmi who died a few years ago but are still inspiring me from heaven to continue with my academic activities.

G.Ramachandran

Chapter 1

Fire protection economics

Introduction and background

Components of fire damage

Fire in any one building is a rare event. But in a population of buildings in a country fires occur frequently and destroy life and property. In the United Kingdom, for example, public fire brigades attend more than 400,000 fires every year in which about 800 people are killed and 15,000 sustain non-fatal injuries. In addition, a number of fires occur which are not reported to the public fire brigades; some of these are dealt with by industrial fire brigades. Currently, fires in the UK cost more than £1,000 million per year in direct material damage to buildings and their contents. About 30 per cent of this total loss is in large fires, each costing £50,000 or more.

In addition to direct damage to life and property, some fires cause indirect/consequential losses, as discussed in Chapter 9. These losses associated with fires are incurred after the fires are extinguished and include, in the case of life damage, the distress and financial loss suffered by the family of an individual sustaining fatal or non-fatal injury. In the case of material damage, particularly that occurring in industrial and commercial properties, consequential losses arise due to loss of production, of trade, e.g. profits, of employment, of market share, of reputation and of exports and costs towards extra imports. Estimation of such consequential losses involves the application of complex statistical and economic techniques. For the reasons discussed in Chapter 9, if indirect losses and gains due to all fires occurring in a country are added together, their net contribution to the indirect loss at the national level is likely to be small. For example, this sum could have been about £90 million in the UK in 1993 when the estimated direct material loss was £900 million. This estimate of indirect loss is based on statistics produced by Wilmot (1996) (see also Table 2.1, p. 18).

Apart from direct and indirect losses, national fire costs (Fry, 1964) include those incurred by fire brigades run by government, for example, local authorities in the UK, and by major industrial firms, the administration costs of fire insurance companies and fire protection costs. The sum of all the costs mentioned above is defined as the total cost of fire. There are also other costs incurred mostly by government bodies towards the enforcement of fire safety and the formulation of safety standards, codes and regulations.

Fire damage in different countries

For purposes of international comparisons, direct and indirect fire losses and other fire costs are usually expressed as percentages of gross domestic product (GDP) and fire deaths per 100,000 persons. Table 1.1 contains the latest figures compiled by Wilmot (1996) of the World Fire Statistics Centre sponsored by the Geneva Association. For most of the countries for which complete data are available, the total cost of fire is more than three times the direct loss. Hungary has the highest number of fire deaths per 100,000 persons, followed in order by Finland, the USA, Denmark, Norway, Canada, Japan and the UK. Building size, design and constructional materials may be major factors affecting this ratio.

The trend in the annual direct fire loss expressed as a percentage of GDP during the period 1984–93 is shown in Figure 1.1 for a few countries for which data were available. For some of these countries the trend in this percentage for the period 1955–68 has been analysed by Ramachandran (1970a) and for 1965–74 by Appleton (1980). The variation in the percentage from country to country is, perhaps, a reflection of the economic state of the nation rather than of the fire losses. The chances of fire occurrence would generally increase with increasing industrial and commercial activities. However, this does not appear to be the case in Japan, where fire losses are increasing at a slower rate than the GDP.

GDP is not a satisfactory measure of the total burnable value at risk; it is only the total value of goods and services produced during a year. Gross fixed capital stock (GFCS) appears to be a better denominator for expressing fire costs as percentages although it only includes fixed assets i.e. buildings, plant and machinery, and not consumer durables. It is very difficult to estimate GFCS, whereas annual information on gross fixed capital formation (GFCF) is available for some countries. Ramachandran (1970a) compared direct fire losses in various countries during 1963–8 by expressing the loss as a percentage of GFCF. The trend in this percentage during 1984–93 is shown in Table 1.2. The ratio of loss: GFCF is somewhat high for Belgium. It has not increased significantly over the years for most of the countries but has varied from country to country due, perhaps, to differences in the economic conditions.

Analysing the data for the fourteen-year period 1955–68, Ramachandran (1970a) corrected the direct losses in various countries for inflation using consumer price index numbers and expressing them at 1955 prices in sterling (£) equivalents. He also calculated corrected losses per fire for the period 1961–8 which did not show any significant increase in most of the countries. According to this analysis, inflation and the increasing frequency of fires were major factors contributing to the increasing fire losses during 1955–68. The need for more

Table 1.1 International fire costs comparisons

Country	*Direct fire losses (%)*[a]	*Indirect fire losses (%)*[a]	*Costs of fire fighting organisations (%)*[a]	*Costs of fire insurance administration (%)*[a]	*Costs of fire protection to buildings (%)*[a]	*Total cost of fire (%)*[a]	*Fire deaths per 100,000 persons (%)*[b]
Austria	0.21 (79–80)	0.029 (79–80)	N.A.	0.14 (79–80)	N.A.	N.A.	0.74
Belgium	0.40 (88–89)	N.A.	0.18 (87–89)	0.28	0.21 (87–88)	N.A.	1.47
Canada	0.24	N.A.	0.16 (85)	0.21 (80–81)	0.34	N.A.	1.58
Denmark	0.26	0.034	0.09 (87–88)	0.08 (87–88)	0.40 (86–88)	0.864	1.64
Finland	0.17 (88–89)	0.021	0.18 (85–86)	0.05	N.A.	N.A.	2.18
France	0.23	0.037	N.A.	0.16 (79–80)	0.18	N.A.	1.26
Germany, West	0.20	0.037	N.A.	0.09	N.A.	N.A.	1.17
Hungary	0.12 (86–88)	0.028	N.A.	0.01 (87–88)	0.42	N.A.	3.31
Japan	0.08	0.016 (85–86)	0.27	0.11	0.27	0.746	1.52
Netherlands	0.19	0.03	0.16 (87–88)	0.04 (87–88)	0.32	0.740	0.63
New Zealand	0.20	N.A.	0.18	0.22	0.12	N.A.	0.92
Norway	0.24	0.005	0.12	0.11	0.28	0.755	1.60
Spain	0.12 (1984)	N.A.	N.A.	0.05 (86)	N.A.	N.A.	0.86
Sweden	0.25	0.009	0.21	0.06	0.12	0.649	1.35
Switzerland	0.23 (1989)	0.095	N.A.	N.A.	0.29	N.A.	0.53
UK	0.19	0.019	0.27	0.11	0.14	0.729	1.49
USA	0.15	0.013	0.29	0.06	0.30	0.813	1.95

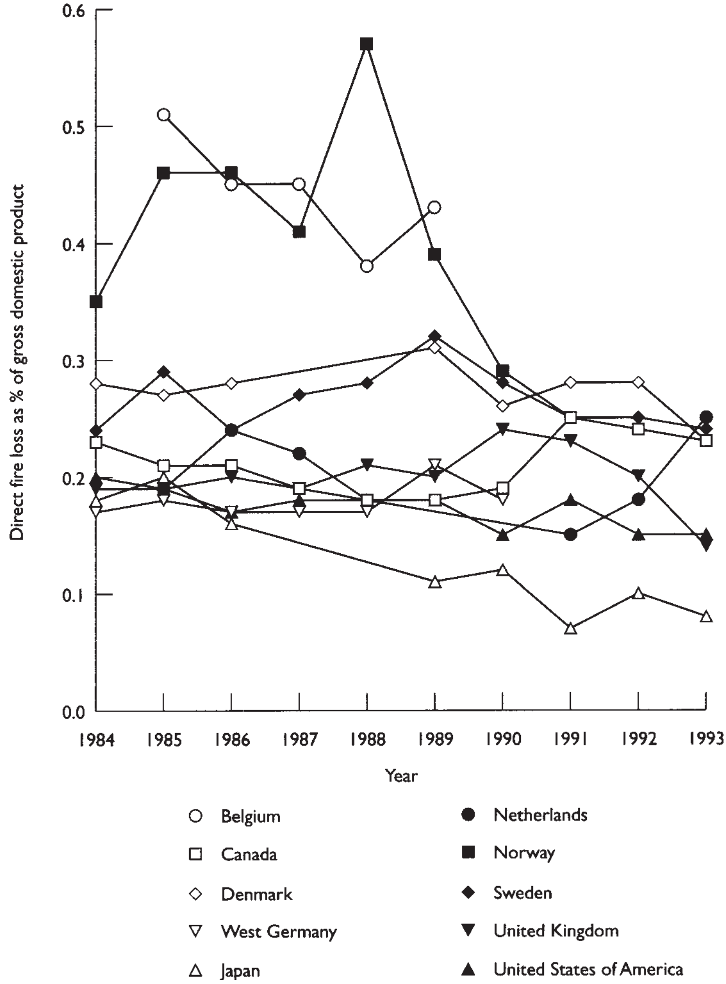
Notes

[a] Average percentage of gross domestic product (1991–3)

[b] 1991–3

N.A. = estimate not available

The years are indicated in brackets wherever they are not 1991–3.



Country	*1984*	*1985*	*1986*	*1987*	*1988*	*1989*	*1990*	*1991*	*1992*	*1993*
Belgium	n.a.	0.51	0.45	0.45	0.38	0.43	n.a.	n.a.	n.a.	n.a.
Canada	0.23	0.21	0.21	0.19	0.18	0.18	0.19	0.25	0.24	0.23
Denmark	0.28	0.27	0.28	n.a.	n.a.	0.31	0.26	0.28	0.28	0.23
France	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.24	0.23	0.21
W. Germany	0.17	0.18	0.17	0.17	0.17	0.21	0.18	n.a.	n.a.	n.a.
Japan	0.18	0.20	0.16	n.a.	n.a.	0.11	0.12	0.07	0.10	0.08
Netherlands	n.a.	0.19	0.24	0.22	0.18	n.a.	n.a.	0.15	0.18	0.25
Norway	0.35	0.46	0.46	0.41	0.57	0.39	0.29	0.25	n.a.	n.a.
Sweden	0.24	0.29	0.24	0.27	0.28	0.32	0.28	0.25	0.25	0.24
UK	0.19	0.19	0.20	0.19	0.21	0.20	0.24	0.23	0.20	0.14
USA	0.20	0.19	0.17	0.18	0.18	0.18	0.15	0.18	0.15	0.15

Note: n.a. = not available

Figure 1.1 Direct fire loss as a percentage of gross domestic product

Table 1.2 Direct fire loss/gross fixed capital formation (%)

Country	*1984*	*1985*	*1986*	*1987*	*1988*	*1989*	*1990*	*1991*	*1992*	*1993*
Belgium	N.A.	3.24	2.89	2.83	2.12	2.25	N.A.	N.A.	N.A.	N.A.
Canada	1.18	1.06	1.03	0.87	0.81	0.79	0.88	0.94	1.33	1.18
Denmark	1.64	1.45	1.34	N.A.	N.A.	1.73	1.51	1.72	1.80	1.52
France	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	1.13	1.17	1.10
Germany, West	0.84	0.94	0.88	0.88	0.88	1.03	0.86	N.A.	N.A.	N.A.
Netherlands	N.A.	0.96	1.15	1.08	0.84	N.A.	N.A.	0.72	0.88	1.28
Norway	1.36	2.09	1.61	1.46	1.97	1.45	1.53	1.38	N.A.	N.A.
Sweden	1.28	1.50	1.31	1.41	1.38	1.48	1.32	1.28	1.49	1.70
UK	1.05	1.11	1.26	1.11	1.11	1.02	1.23	1.36	N.A.	N.A.
USA	1.02	0.98	0.88	0.92	0.99	1.00	0.88	1.13	0.94	0.89

Note: N.A. = estimate not available

fire prevention activities was apparent, although fire protection and fire fighting efforts were generally successful.

The conclusion mentioned above may be true with regard to fire losses in various countries during recent years. Table 1.3, for example, relates to the United Kingdom, for which data were readily available for analysis. Figures for direct losses are based on the statistics published by the World Fire Statistics Centre. Indices for retail prices are based on the figures for 'all items' given in the *Annual Abstract of Statistics, 1995* (p. 336, Table 18.7). Figures for number of fires in occupied buildings have been obtained from *Fire Statistics United Kingdom,* which is an annual publication of the Home Office. It has been assumed that most of the monetary losses occurred in occupied buildings, although there may have been some contribution to the losses from outdoor and 'secondary' fires such as those in road vehicles, on grassland and heath-land and in chimneys. Apart from a sharp jump in 1989, the frequency of fires, both total and in occupied buildings, has not increased significantly between 1983 and 1993. Hence, inflation appears to be the major factor contributing to the increasing fire losses in the UK during recent years.

Per capita loss was increasing in most countries during 1961–8 (Ramachandran, 1970a) and 1965–74 (Appleton, 1980) and varied from country to country, due perhaps to differences in living standards. Some allowances for these differences can be made by dividing loss per head by the average hourly earnings in manufacture (see Fry, 1964).

Ramachandran (1970a) commented that figures for different countries are not

Table 1.3 Direct fire loss per fire, adjusted for inflation, United Kingdom

Year	*DFL (£ millions)*	*Retail price index (all items)*	*DFL corrected for inflation (£ millions)*	*Number of fires in occupied buildings '000*	*Adjusted DFL per fire (£)*
1983	575	100	575	98	5,900
1984	575	105	548	102	5,400
1985	670	111	604	105	5,800
1986	680	115	591	106	5,600
1987	820	118[a]	695	104	6,700
1988	1000	127[b]	787	106	7,400
1989	1050	136	772	110	7,000
1990	1300	149	872	108	8,100
1991	1300	158	823	107	7,700
1992	1200	163	736	107	6,900
1993	900	166	542	109	5,000

Notes
a January 1987
b Estimated

Fire losses include explosions following fires but exclude explosion loss, where no fire occurred, for example, some acts of terrorism.

strictly comparable due to differences in methods of collecting and classifying fire loss data. For instance, major databases in most countries record only those fires attended by public fire departments and exclude small fires extinguished by industrial fire brigades, sprinklers and portable fire extinguishers. Types of fires reported to authorities can vary significantly from country to country: some countries exclude chimney, brush, rubbish or forest fires while others include them; some countries include all losses except those occurring in government properties. There are also wide differences in the values of the properties involved in fires. Methods of estimating fire losses are also likely to vary from country to country. Fluctuations in exchange rates do not help matters.

Some of the points mentioned above were considered by Rardin and Mitzner (1977) in a detailed investigation supported by the US National Fire Prevention and Control Administration, National Fire Data Center. The authors systematically reviewed the various hypotheses and theories which have been advanced to explain fire loss differences between nations. The additional factors enumerated by them fall into three broad categories. First, there are differences between countries in human factors: economic and technological development, social and cultural patterns. Second, there are physical differences relating to building construction, contents and utility systems of buildings, weather, etc. A third major class of theories centres on variations in the organisation and functioning of the professional fire communities in different countries. There are other minor factors which include the severity with which fire safety codes are enforced and the influence of fire insurance on fire protection planning.

Management of fire risk

In order to reduce the national wastage due to fires, individuals, organisations and the government in any country have a clear duty to manage or control the risk posed by fires. Major industrial and commercial firms in many countries have developed plans for managing fire risk which involves three main phases: before the fire, during the fire and after the fire. The first task in the first phase is concerned with the identification of potential sources of ignition likely to initiate fires. These include human sources, such as the careless disposal of matches and smokers' materials, and non-human sources, such as defective wiring to electrical appliances and mechanical heat or sparks in industrial buildings. The second task in the first phase is concerned with the identification of combustible materials or objects which can contribute to a rapid spread of fire, smoke and toxic gases. Examples of such materials are polyurethane-upholstered seats, materials used in the construction and lining of roofs, walls and ceilings, and the construction and covering of floors.

The next stage in the fire risk management of a property relates to risk evaluation; this is the third task in the first phase. In this stage, fire risk is evaluated qualitatively and, if possible, quantitatively by assessing the number of fires due to different ignition sources likely to occur in the property during, say, a year and the probable damage in each fire. Several mathematical models have been developed for this purpose. These include probabilistic and other non-deterministic techniques which take into account the random nature of the fire phenomenon (see Ramachandran, 1988, 1991a).

If the annual loss likely to be incurred in fires is of an unacceptable level, possible removal of most of the ignition sources should be considered as the first step in a risk-reduction or loss-control procedure. This task is executed by adopting fire prevention measures such as providing smoking lobbies, issuing notices to make people aware of fire risk due to smoking materials, periodically checking electrical appliances, and electrical rewiring, if necessary. Since it may be difficult to eliminate all the sources of ignition, it would be prudent to install in a building appropriate fire protection measures which, in the event of a fire breaking out, would reduce the extent of damage and enable the occupants to evacuate the building rapidly and safely. These measures, apart from building design and structural fire protection, include automatic fire alarms and detectors, sprinklers, smoke control systems, portable fire extinguishers and fire doors. All the fire safety measures mentioned above should be maintained in good order such that they perform satisfactorily if a fire occurs.

When fires do occur in spite of all fire prevention measures, it is necessary to initiate appropriate actions to provide all necessary assistance to occupants to reach a place of safety inside or outside the building. These actions are part of a fire emergency plan (FEP) and include tasks such as informing the fire brigade, attacking the fire and assisting the fire brigade. An FEP which has to be executed during the fire (second phase) should be prepared well in advance. The staff of a large establishment may be trained in carrying out the FEP satisfactorily. Occupants of a building should be trained for evacuation by staging fire drills periodically.

The third phase is concerned with actions to be undertaken after the fire. These include salvage operations, repairs to damaged parts of the building and restarting as soon as possible the industrial, commercial or other form of activity interrupted by the fire incident. During this phase, the financial damage is assessed and a claim is made to obtain insurance compensation. There is no need to emphasise the importance of having adequate fire insurance to cover direct and indirect/consequential losses. A large fire might seriously disrupt or even bankrupt a business or industrial activity.

Economics of fire protection

As discussed in the previous section, property owners, organisations, the government and society at large should adopt fire prevention and protection measures and other fire risk management activities in order to control the risk posed by fires. But these measures and activities involve considerable amounts of money being spent at all levels of a national economy. The questions, therefore, arise: How much control and at what cost?

With advances in fire science and engineering, it may be possible to reduce fire control costs by improved techniques of building construction, efficient sprinklers and detectors with optimum spacing between heads and so forth. The problem, however, is not merely to minimise fire protection costs but to improve their effectiveness in economic terms. The tenet that an investment should produce a profit applies equally as well to fire control as to general business ventures. For economic justification, the income or revenue from a project should exceed the expenditure or investment. In a broader sense, benefits from a project, direct and indirect, tangible and intangible, should be greater than the costs involved. Although this is a simple criterion to follow, a few problems arise when it is applied to fire safety measures. These problems are discussed in the next chapter.

Cost-benefit analysis

The first step in an economic analysis of different investment projects is concerned with the enumeration of relevant costs and benefits associated with each project (Chapter 2). Fire loss is an uncertain (probable) cost which will be incurred only if a fire breaks out (pp. 11–12) whereas fire protection costs and insurance premiums will certainly be incurred whether a fire occurs or not. During the next step, the costs and benefits are reduced to an annual basis using one of the methods discussed in Chapter 3.

An investment project can be economically justified if the aggregate value of annual benefits exceeds that of the annual costs. In other words, the ratio between the aggregate values of annual benefits and costs, known as benefit-cost ratio (see pp. 31–2), should exceed unity. This ratio is generally used for the selection and comparison of alternative investment projects.

A benefit component due to a fire protection device is assessed as the difference in the corresponding cost components for the two cases: with and without the device. For example, the reduction in the fire insurance premium due to the installation of the device is a benefit. If each case is considered separately, the insurance premium is a component of total cost. Hence, the fire protection strategy which minimises the total cost provides the economically optimum level of fire safety (see pp. 34–7). Watts (1988) has discussed briefly the techniques mentioned above.

Chapter 5 discusses the application of cost-benefit analysis to a few fire protection measures which have been considered effective in reducing fire risk or enhancing fire safety. These measures are considered individually with regard to their economic value. A combination of two or more measures can be expected to provide more safety than one alone but it may not be cost-effective. This aspect, which has not so far been investigated seriously in fire science literature, is discussed in Chapter 6. There is also an interaction between fire protection and insurance, and this is the subject matter of the last section of Chapter 6.

Other topics

A decision-maker is confronted with various fire protection measures from which he/she has to choose a measure or a combination of measures which minimises the total cost. This selection process can be carried out systematically by applying the decision tree technique (see pp. 116–19). Probability estimates considered in this exercise can be updated in the light of further information. The method generally used for this purpose is known as Bayesian technique (see pp. 127–30).

The amount of money property owners will be willing to spend on fire safety and insurance depends on factors such as their attitude to and assessment of fire risk and value of assets. If property owners are 'risk-neutral', they will use the actual monetary values of the costs and benefits in a cost-benefit analysis or decision tree approach. Such people put equal weight on each pound of loss or gain; this 'expected value' approach can lead to an incorrect decision, particularly with regard to fire insurance premiums. But most property owners would be keen to avoid the risks posed, particularly by large fires, and adopt a risk-averse attitude. Such risk preferences can be quantified by assigning greater weights to large losses and applying utility theory (Chapter 8).

In deciding the amount of money to be spent on fire safety and insurance, an industrial property owner would and should also consider seriously the indirect/consequential losses due to fires in addition to direct damage to the building and contents. Consequential losses at this economic level are not difficult to estimate and can be covered by insurance. But an evaluation of these losses at the national level is a complex problem, as discussed in Chapter 9. Consequential losses can seriously affect the activities not only of a fire-hit firm but also of its customers and suppliers.

Safety of life plays a vital role in the economic assessment of alternative fire safety strategies at the national level. In this context, it is necessary to assign a monetary value to each fire death. Different methods of estimating the value of human life are discussed in Chapter 10 together with some examples illustrating the application of this value in fire protection problems.

Actuarial techniques are well developed in the field of life insurance but not in the case of fire insurance. For example, most companies transacting fire insurance business use outdated or inaccurate schedules for calculating rebates on premiums for fire protection devices such as sprinklers and for different self-insurance levels (see Chapter 8). The rebates need to be estimated more accurately, also taking into account the maximum amount a property owner may be willing or is able to spend on fire insurance. This actuarial problem has been investigated by Ramachandran (1994) and is discussed in Chapter 11.

Chapter 2

Costs and benefits

Enumeration, decision-making and uncertainty

The theoretical concepts and principles underlying cost-benefit analysis are simple to understand since they stem from common sense. But a few difficulties arise when they are applied to a practical problem such as fire protection. These difficulties can be resolved by identifying major decision-makers involved in adopting, promoting or enforcing fire safety measures and enumerating the costs and benefits relevant to each decision-maker. Evaluation and comparison of different fire protection strategies with regard to cost-effectiveness have to consider the uncertainties (randomness) in the occurrence of fire, the damage caused, the behaviour of occupants of a building and the reliability of safety measures.

Decision-makers

Several decision-makers are generally involved in any sphere of economic activity. A fundamental problem is concerned with the definition and enumeration of costs and benefits relevant to each decision-maker: a cost to one may be the revenue of another in the same economic complex. For example, an insurance premium is a cost or expenditure for the insured but a benefit or income for the insurer; and the cost of a fire protection device is expenditure for a property owner but income for the manufacturer of the device.

Only certain costs and benefits are relevant to a particular decision-maker. It is therefore necessary to analyse the costs and benefits of fire control at different levels of decision-making. There are essentially five levels: the owner of a property; the fire brigade (department) or local (municipal) government; national or central (federal) government; the insurance firm; and the manufacturer of the fire protection device considered. The same criterion of balance between total costs and total benefits governs the economics at each of these levels but the basis for action differs. The objective common to all levels is the reduction of national wastage due to fires.

Costs such as installing and maintaining a fire protection device and benefits such as tax allowances and savings in fire insurance premiums are incurred or realised with ‘certainty’. But damage sustained in a fire is an ‘uncertain’ quantity whose ‘expected value’ and associated statistical parameters depend on the probability of fire occurrence and probable damage if a fire breaks out. The probable reduction in damage due to a fire safety measure is a benefit. Factors causing uncertainties in the occurrence and spread of fire are discussed briefly in the last section of this chapter.

Property owners

A property owner has to spend money to comply with certain basic fire safety requirements specified in fire regulations, codes and standards. These are ‘passive’ fire protection measures which include mostly the provision of compartments with prescribed levels of fire resistance, the selection of building materials, and methods to reduce the risk of fire spread and limit the size of the fire. At the same time, the building design should incorporate features of layout and means of escape facilities, such as protected staircases. Provision of fire doors and smoke extractors may be necessary for some buildings.

According to a recent study (Building Research Establishment, 1996), the cost of meeting Building Regulations fire safety requirements expressed as a percentage of building cost ranges from less than 1 per cent for dwellings and single-storey industrial sheds to over 9 per cent (but less than 10 per cent) for shopping complexes. At 1993 prices, the cost of fire safety requirements ranges from £1/m^2 for single-storey industrial sheds to £50/m^2 for high-rise atrium offices. These figures are based on thirty-one example buildings, forming seven purpose groups subdivided to give seventeen archetypes. The report lists typical costs for individual items of fire protection, either as complete measures or as component parts of a larger measure.

Fire safety regulations do not generally require the installation of ‘active’ fire protection measures such as automatic fire detectors and sprinklers. It is left to individual property owners to protect their buildings with active measures. However, through national and local legislation fire and building authorities in some areas, e.g. London, may require multistorey or high-rise commercial buildings to be protected by sprinklers. The fire authorities in some cities in the USA and Canada insist on the installation of sprinklers in large apartment buildings mainly for the safety of occupants. In England and Wales, 63 per cent of domestic dwellings are currently equipped with smoke alarms (Marriott, 1995) while the installation of these devices in residential buildings is mandatory in almost all the states in the USA.

The costs associated with some passive and active fire protection measures are discussed in detail in Chapter 5. The benefits to a property owner of adopting or installing fire safety measures are mainly in terms of reduced fire insurance premiums, tax allowances and government grants in some cases. These benefits are substantial in the case of sprinklers. Another benefit which is ‘uncertain’ is the probable reduction in fire damage for which a property owner is responsible if he/she has agreed to some level of self-insurance, i.e. deductible in the fire insurance contract.

According to Silcock (1967), the protection costs mentioned above can constitute 5 per cent of the building cost for a shop and 1.4 per cent for an office block. Nakamura (1984) made a detailed analysis of the costs of fire protection in 'electrical and mechanical works' for eleven occupancies, and estimated the fire protection investment rate, number of storeys and gross floor area and the correlations between these variables. The fire protection investment rate, the ratio of the fire protection cost to estimated entire construction cost, varied widely from one occupancy to another, the lowest rate (0.64 per cent) being for detached homes and the highest (3.26 per cent) for shops. Nakamura did not find any correlation between the number of storeys or the gross floor area and the fire protection investment rate for any occupancy.

In a later investigation, Nakamura (1986) presented an investment model of fire protection equipment for an office building. He discussed the results of a 'canonical correlation analysis' that describes the relations between the characteristics of a building and the cost indices of fire protection equipment. The building characteristics included variables such as number of storeys, building area, architectural area, number of spans/ridge direction, span length, number of structural bays and number of external and internal columns. He found that variate pairs between these characteristics and the cost indices of fire protection equipment are highly related. He showed how the model can be applied to a trade-off problem. According to him, designers evaluate the installation of sprinkler systems against the width within the buildings and decide to emphasise the installation of dry risers or sprinkler systems by comparison between the width and service cost index of the buildings.

Public fire services

Public fire protection provided by the fire brigades in the UK, fire departments in the USA and similar organisations in other countries has improved substantially in the last hundred years. Conflagrations such as those that swept London (Great Fire) in the UK, Hamburg in Germany, and Chicago, San Francisco and Baltimore in the USA have become rare. The gradual disappearance of solid fuel heating and oil heaters has led to a significant reduction in serious fires in homes and in the deaths caused by such fires.

Another reason for the improvement in fire safety in many countries is the introduction of rules to avert conflagrations. The provision of wide streets and boulevards and the nature of external cladding were considered to be useful remedial measures. Over the years, such rules have been supplemented or replaced by fire safety by-laws, acts, regulations, codes and standards. When fires do occur, fire fighters employed by public fire services can, at present, usually rely on municipal water supplies, powerful motor-driven vehicles, high-volume pumps, hydraulically operated ladders, aerial elevating platforms, self-contained breathing equipment and radio communication.

Internationally, significant fire safety problems still exist. In some countries fire is still the leading cause of catastrophic accidents in which five or more people die. With the increase in commercial and industrial activities, property losses have increased significantly. These losses, some also involving fatalities, occur in spite of large amounts of money spent on public fire departments, structural (passive) fire protection and installed (active) fire protection systems.

Moreover, some of the underlying problems are becoming more serious. Technological changes have created new fire risks. Risk to life has increased due to the greater use of synthetic materials both in the contents of buildings and for furnishing purposes. Some of these materials produce significant amounts of toxic and narcotic products which can lead to the incapacitation and death of occupants of a building. Socioeconomic factors are also affecting fire risk, as was investigated by Chandler (1979).

For the reasons mentioned above, the demand for public fire protection is increasing. Simultaneously, money is becoming scarcer. Subject to financial constraints, the public fire service has to perform effectively the various fire safety activities in which it is involved. These activities include the provision of fire cover, and publicity campaigns aimed at fire prevention, and the inspection of hazardous equipment, goods and structures. The second type of activity includes visits to schools and community groups, leaflet distribution, posters, television advertisements and fire prevention weeks. Optimum allocation of financial and other resources to these activities is a major problem facing the public fire service.

Fire brigades or departments are required to conform to standards of fire cover specified in response times to fires in different risk categories. The safety levels provided by these standards can be evaluated in terms of damage to life and property. These levels need to be maintained at their current values or reduced by efficiently deploying fire fighters and fire fighting equipment. These benefits from fire cover are enjoyed by the protected community.

Apart from the protection of members of the community, benefits to a municipality may include avoidance of tax and payroll losses and costs associated with assisting fire victims. Early detection of fires due to the installation of automatic detection systems enables fire fighters to arrive at the scene of a fire while it is still small. This enables them to bring the fire under control quickly and to extinguish it. Thus, fire fighters spend less time at the scene of a fire than would be required if detection were delayed.

Sprinklers can save life although they are designed primarily to reduce property damage. They frequently extinguish fires completely; otherwise they reduce the time taken by fire fighters to control a fire because they restrict the spread of the fire until the fire fighters arrive. In an American city, Fresno, the provision and satisfactory maintenance of sprinklers in most of the buildings led to the closing down of a fire station.

For the reasons discussed above, installation (and satisfactory maintenance) of efficient detectors, alarms and sprinklers in buildings could reduce the operating costs of a fire brigade to a significant extent. However, some of these systems can produce frequent false alarms; also fire brigades must deal with malicious calls to non-existent fires.

Potential benefits to a municipality from fire protection systems are considerably greater than those enjoyed by property owners. However, as pointed out by Watts (1988), the community may ignore some external effects of fire incidents. For example, the 1954 automobile transmission plant fire in Livonia, Michigan, affected the automobile industry in Detroit and various automobile dealers throughout the USA. However, there was little incentive for the community to consider such potential losses in their evaluation of fire fighting strategies since they would pertain to persons outside the community. It could be concluded, therefore, that the wider the decision-maker's boundary, the more likely it is that all relevant costs and benefits will be included, in particular social costs and benefits.

National level

At the national level of decision-making, a state (or local) or central government is concerned with the development and enforcement of fire safety codes, regulations and standards. Economic justification is necessary to enforce a safety measure on any type of building.

The total costs involved in these activities concerned with any safety measure together with the cost of compliance should not exceed the total benefits likely to be produced. At the national level, the probable reduction in total fire damage due to a safety measure is the only benefit that needs to be evaluated. Benefits such as reductions in insurance premiums and tax allowances are not relevant for a cost-benefit analysis at this level.

The total benefit at the national level should be based on reductions expected to be achieved in all the components of fire damage: direct damage to properties and their contents, loss of life and injury, social costs including hurt, and the cost wrought by public anxiety. Consequential losses such as loss of profits, of production and of foreign trade are certainly relevant at the private-sector level but not necessarily at the national level (see Chapter 9).

Insurance

A large loss from a single fire can cause consequences considerably more severe than the equivalent total loss from a number of small fires. A property owner may easily absorb in his or her budget the loss expected from a small fire but a large loss could be ruinous. So people join groups or 'pools' to share their risks. Each contributes a small amount regularly to mitigate the financial strain on a few members of the group unlucky enough to be involved in large losses. This is the principle underlying fire insurance; the contributions are the 'premiums'. Fire insurance is essentially a means of redistributing losses, in which the fortunate subsidise the unfortunate.

The loss expected from a fire is the average loss from all fires in a group or risk category of buildings. This average is known as the 'risk premium' to which an insurer usually adds two loadings: a safety loading and a loading to cover the insurer's operating costs which include profits, tax and other administrative expenses. The part of the premium constituting the expected loss and safety loading is generally reduced for a building equipped with fire protection systems. The insurer can be expected to pay out smaller sums in the case of protected properties than those claimed for fires in unprotected ones. The reduction in the premium is substantial for buildings with a sprinkler system installed.

As a further inducement to enhance fire safety, insurance firms encourage property owners to accept deductibles (self-insurance) in their insurance contracts. Under this arrangement, insured people take extra precautions to reduce the fire risk since they will have to bear all the losses up to the deductible amount. For a loss greater than this amount, the insurer will pay the insured the difference between the loss and the deductible. With a deductible the insured is given the advantage of a reduced premium, which is a loss to the insurer. However, when a deductible is applied, the insurer does not have to pay out for small losses and this relieves the company of a considerable amount of work. The reduced premiums offered for deductibles do not appear to reflect realistically the effectiveness of fire safety measures, particularly sprinklers (see Chapter 11).

By collecting insurance premiums, an insurance firm can run a profitable business, provided it has charged the insureds premiums at a level which ensures sufficient profits. A few catastrophic losses can ruin an insurance business. To assess the probability of ruin and to calculate appropriate premiums, actuarial risk theory has been well developed in many insurance fields except fire insurance.

The insurance industry's evaluation of a community's fire protection requirements is exclusively related to protecting the insurance industry's interests. The fire protection needs of a community will usually be different from those of the insurance industry. For example, safety of life is the primary concern of the community while the insurance industry is mainly concerned with property protection; thus the insurance industry may recommend different fire prevention and protection activities from those identified by the community.

Manufacturers of fire protection systems

By selling a fire protection system, a manufacturer receives benefits in the form of profits. To run this business successfully, the manufacturing cost of the system should be low but the selling price of the system should cover adequately the cost of manufacture, salaries and other administrative expenses and profits. To reduce the cost, some research and development work is necessary and this is usually undertaken by major manufacturers. Part of this work should be concerned with the evaluation of the effectiveness and reliability of the fire protection system in performing its design function satisfactorily.

It is difficult to sell a system which does not perform satisfactorily. To evaluate effectiveness and reliability, statistics may be available for fire protection systems such as sprinklers which have been installed in industrial and commercial buildings in particular over the past several decades. Insurance and fire protection organisations and associations and major manufacturers collect and analyse statistics on the performance of sprinklers.

National accounting

An aggregate or global view of the fire protection economic system can be described using the costs (expenditures) and benefits (receipts) at each of the five levels discussed in the previous sections. The five accounts may be called a social or national accounting scheme (Klein, 1962). Some entries in one account may have exact duplicates somewhere in the other four sets of accounts. Two examples in this respect have been given above (p. 11) according to which a cost to one decision-maker may be equal to the benefit of another.

Apart from the balancing items mentioned above, some items cannot be recovered or compensated in a national accounting scheme for fire protection. For example, fire damage (direct and indirect) is a national wastage which cannot be recovered; it is merely redistributed among the property owners through insurance. Similarly, money spent on insurance administration and fire services activities are expenditures which are not compensated within the fire protection economic system although people employed in these organisations derive benefits in the form of salaries, and so on. A similar consideration would apply to the cost of fire protection, the gross amount of which may be considered in national accounting. The tax allowances and grants given by a government towards fire protection are not recovered within the economic system considered.

As argued above, a simple national accounting scheme for fire protection would consist of the following costs: fire damage (direct and indirect); insurance administration costs; expenditure on fire services; fire protection costs; and administrative expenditure incurred by manufacturers of fire protection systems. Global estimates for the first four items are available from the international fire statistics collected by Wilmot (1996). Estimates for the average annual costs during the period 1991–3 are given in Table 2.1 for the UK and the USA. The total annual cost of fire is currently of the order of £4,300 million for the UK and $50,000 million for the USA. These figures represent respectively 0.73 per cent and 0.81 per cent of the gross domestic product of the two countries (see also Table 1.1). Costs of fire casualties, particularly deaths, can be included in the national accounting scheme by assigning a monetary value to human life (see Chapter 10). The national object is to minimise the total cost of fire.

Table 2.1 The total cost of fire (average annual cost for 1991–3)

Components of total cost	*UK (£ million)*	*USA ($ million)*
Direct loss	1,100	9,200
Indirect loss	100	800
Fire fighting organisations	1,600	17,800
Fire insurance administration	600	3,700
Fire protection to buildings	900	18,100
Total annual cost	4,300	49,600

Notes
1 The average figures are estimates unadjusted for inflation.
2 The figures for indirect loss are adjusted estimates after making 50 per cent deductions for the difference between actual indirect losses and losses affecting the national economy.
3 The figures for fire fighting organisations are adjusted estimates after making additions for private fire brigades and deductions for non-fire work carried out by brigades

Uncertainties

Arson fires may have multiple ignition points but an accidental fire generally starts randomly from a single point somewhere in a building. The source of ignition can be human, e.g. the careless disposal of a smoking material, or non-human, e.g. an electrical appliance. The nature and number of ignition sources vary from one part of a building to another.

The spread of fire in a building is also a random phenomenon (Ramachandran, 1988). Apart from changes in environmental conditions, e.g. temperature, humidity, wind velocity, the spread is governed by physical and chemical processes evolved by a variety of burning materials arranged in different ways in different parts of a building. Multiple interactions among these processes at different times cause uncertainties in the development patterns of fire, smoke and other combustion products. Deterministic (scientific) and non-deterministic models have been developed in fire science literature, in particular to predict the spread of fire. The second type of model takes account of uncertainties explicitly in terms of probabilities and can be classified into two broad categories: probabilistic and stochastic (Ramachandran, 1991a).

The behaviour of the occupants of a building during a fire is also a random phenomenon to some extent (Canter, 1980). It depends on many factors such as the location of an occupant with reference to the location of the fire, the mobility and mental condition of the occupant, the presence or absence of alarms, detectors or other communication systems, and the escape routes available. An occupant must escape to a place of safety within or outside a building before the escape routes are blocked by excessive levels of heat, smoke and toxic gases. This interaction between the movement of occupants and the movement of combustion products is a complex probabilistic phenomenon.

The reliability of systems for fire detection, suppression and confinement are also sources of uncertainty. The successful operation of these systems and their effectiveness depend on several factors such as their design characteristics, the location of the fire with reference to the location of the system, e.g. the sprinkler head, the rate of increase of heat, smoke and other combustion products, and the maintenance of the systems in good condition. The structural boundaries of a room with a given fire resistance can ‘fail’ due to several causes and allow the fire to spread beyond the room.

For the reasons discussed above, the concept of fire safety itself is one of uncertainty; there is no such thing as absolute safety. Risk implies uncertainty and, hence, fire risk can only be evaluated in probabilistic terms. The object of fire protection and fire fighting is to reduce this risk to a minimum level acceptable to a property owner and to society at large. Absolute safety from fire is practically unattainable or prohibitively expensive. An economic analysis of a fire protection system, therefore, involves uncertainties which need to be taken into account by assigning appropriate probabilities.

Chapter 3

Annual costs and benefits

Methods of calculation

An economic analysis of fire protection measures is concerned with finding the least expensive way to fulfil regulatory and insurance requirements for the safety of life and property. This involves the selection and comparison of different fire protection strategies and identifying the strategy that minimises the sum of expected values of costs associated with self-insured fire loss, fire insurance premiums and fire protection. The usual practice in such an analysis is to reduce the relevant losses and costs to an annual basis. For this purpose, various methods have been developed, which are discussed in this chapter and explained with examples.

Fire losses

Consider first fire losses, most of which, except a small deductible amount, can be recovered from an insurance company if a property and its contents have full insurance coverage. In this case, a property owner is unlikely to take into consideration the direct losses due to fire and the uncertainty associated with these losses in determining the economic desirability of installing a fire protection device in his or her building. The owner may, however, consider the uncertainty attached to indirect losses which cannot be adequately covered by a consequential loss insurance policy. Apart from consequential losses, tax concessions and reductions in insurance premiums and not saving in fire loss would influence the decision of a property owner to install a fire protection system such as sprinklers.

Suppose F_V is the annual probability of fire occurring in a property with financial value V at risk. If the owner of this property accepts self-insurance with a deductible D, he or she will be responsible for meeting an expected loss $\bar{x}_D$ in the event of a fire occurring (see equation (7.4), p. 122). The owner in this case should take into consideration an annual amount of $F_V\bar{x}_D$ towards fire loss in an economic analysis of fire protection strategies. F_V, the annual probability of fire occurring, has a 'power' relationship with the value V at risk in a building (see pp. 188–90).

If a property has no insurance at all, i.e. it is fully self-insured, the annual fire loss to be taken into consideration is $F_V\bar{x}_V$ where $\bar{x}_V$ is the *expected loss in* a property with financial value V at risk (see equation (7.3)). The values of F_V, $\bar{x}_D$ and $\bar{x}_V$ would vary over a period of years, but corrected for inflation they may be regarded as constants for practical purposes.

The annual loss $F_V\bar{x}_V$ would also be applicable in an analysis at the national level of decision-making. For this level, an estimate of the 'probable' annual benefit due to a safety measure is given by the difference between the values of $F_V\bar{x}_V$ in the two cases of a building equipped with this measure and a similar building without this measure. A fire prevention measure aimed at reducing the frequency of occurrence of fires will reduce F_V and not $\bar{x}_V$. On the other hand, a fire protection device designed to restrict the damage will reduce $\bar{x}_v$ and not F_V. In the analysis above, $\bar{x}_D$ or $\bar{x}_V$ relate to direct loss to which an appropriate value for consequential loss may be added if data are available to estimate this component.

If sufficient data are available, an appropriate probability distribution may be fitted to the data and its parameters estimated. Then statistical methods can be applied to estimate $\bar{x}_D$ and $\bar{x}_V$ (see equations (7.3) and (7.4), p. 122). An approximate value of $\bar{x}_V$ is also given by a 'power' relationship with value V (pp. 188–90).

Another method is to estimate the expected loss $\bar{x}$ approximately by assuming that the value at risk, V, is large and using the following equation:

$$\bar{x}=p_1\bar{x}_1+p_2\bar{x}_2+p_3\bar{x}_3;\ p_1+p_2+p_3=1$$

where, given the occurrence of a fire, p_1, p_2 and p_3 are the probabilities that the fire size is likely to be small, medium or large, respectively. The corresponding average losses $\bar{x}_1$, $\bar{x}_2$ and $\bar{x}_3$ may be estimated empirically from available data. An empirical estimate may also be made for $\bar{x}_D$.

Amortisation of capital cost

Insurance premiums are charged annually, hence reducing them to an annual basis presents no problems. To calculate the annual equivalent of an initial capital cost C of a safety device, a simple method generally used is based on the accounting theory of equated payments. This method has been widely adopted by banks and building societies for the repayment of mortgage loans for houses. Under this scheme, also known as 'amortisation', the capital, C, is recovered (or repaid if it is regarded as a loan) in y years through annual instalments each equal to a sum A.

For the *i*th year, the constant annual amount A consists partly of an amount C_i towards the capital and partly of an amount towards interest on the balance of capital outstanding at the end of the previous year. Calculations would show that

$$C_i = C_1(1+r)^{i-1} \tag{3.1}$$

where r is the rate of interest expressed as a decimal fraction, e.g. 0.06 for 6 per cent, and C_1 is the payment towards capital in the first year for which

$$A = Cr + C_1 \tag{3.2}$$

Since

$$C = \sum_{i=1}^{y} C_i$$

calculations based on equations (3.1) and (3.2) would show that the annuity A is given by the product CK where

$$K = [r(1+r)^y]/[(1+r)^y - 1] \tag{3.3}$$

Watts (1988) has tabulated the values of the capital recovery factor, K, for various interest rates, r, and the number of years, y. The values of K for selected interest rates and years are given in Table 3.1. For C=£10,000, for example, the annual cost A is £1,023 for y=40 years and r=0.1 since K=0.1023. For large values of y, say y=60, K is equal to r approximately.

The amortised annual cost A for the capital cost C, therefore, depends on the ‘payback’ or ‘planning’ period y and the interest rate r. For the period y for any fire protection system it would be appropriate to use the economic life of the building to be protected, assuming that the system would perform satisfactorily throughout the building’s life. However, it would be necessary to take into consideration the fact that parts of a fire protection system may have to be repaired or replaced every few years during the life of a building: normally considered to be a period of forty years. The interest rate r may be equated to the rate of return that might be expected from invested capital. The annual cost A would depend, to some extent, on the accounting procedure adopted.

Present worth

The cost involved in installing a fire protection system is an initial cost incurred at the beginning of an investment period. The annual equivalent of this cost has been discussed in the previous section. But costs for system maintenance are met annually over the period considered. Also, some cost may be incurred at any time before the end of the planning period for replacing part of the system or for repairing the system. The benefits due to a fire protection system are also spread over a period of time.

In the case of cost or benefit components such as those mentioned above, we are confronted with a stream of costs and benefits resulting from a fire

Table 3.1 Capital recovery factor (K)

	Rate of interest (r%)								
Number of years (y)	*2*	*4*	*6*	*8*	*10*	*15*	*20*	*25*	*30*
1	1.0200	1.0400	1.0600	1.0800	1.1000	1.1500	1.2000	1.2500	1.3000
2	0.5150	0.5302	0.5454	0.5608	0.5762	0.6151	0.6545	0.6944	0.7348
3	0.3468	0.3603	0.3741	0.3880	0.4021	0.4380	0.4747	0.5123	0.5506
4	0.2626	0.2755	0.2886	0.3019	0.3155	0.3503	0.3863	0.4234	0.4616
5	0.2122	0.2246	0.2374	0.2505	0.2638	0.2983	0.3344	0.3719	0.4106
6	0.1785	0.1908	0.2034	0.2163	0.2296	0.2642	0.3007	0.3388	0.3784
7	0.1545	0.1666	0.1791	0.1921	0.2054	0.2404	0.2774	0.3163	0.3569
8	0.1365	0.1485	0.1610	0.1740	0.1874	0.2229	0.2606	0.3004	0.3419
9	0.1225	0.1345	0.1470	0.1601	0.1736	0.2096	0.2481	0.2888	0.3312
10	0.1113	0.1233	0.1359	0.1490	0.1627	0.1993	0.2385	0.2801	0.3235
15	0.0778	0.0899	0.1030	0.1168	0.1315	0.1710	0.2139	0.2591	0.3060
20	0.0611	0.0736	0.0872	0.1019	0.1175	0.1598	0.2054	0.2529	0.3016
25	0.0512	0.0640	0.0782	0.0937	0.1102	0.1547	0.2021	0.2510	0.3004
40	0.0366	0.0505	0.0664	0.0839	0.1023	0.1506	0.2001	0.2500	0.3000
50	0.0318	0.0466	0.0634	0.0817	0.1009	0.1501	0.2000	0.2500	0.3000
60	0.0288	0.0442	0.0619	0.0808	0.1003	0.1500	0.2000	0.2500	0.3000

protection strategy. Such future cash flows are usually discounted to their present or base time values by using a discount rate i. This procedure enables the calculation of the present worth or net present value of cash flows occurring over a period of time.

If C_j is a cost or benefit in the jth year, its present worth or value is given by

$$PV=C_j/(1+i)_j \tag{3.4}$$

This formula can be used for calculating the present value of, say, cost C_j to be incurred in the jth year towards part replacement or repair of a fire protection system. For example, if C_j=£5,000, j=20 and i=0.1, PV=£743. In other words, it would only cost £743 to carry out now a repair that would cost £5,000 after twenty years. The values of the discount factor $DF=1/(1+i)^j$ for different discount rates i and years j are given in Table 3.2.

Discounting can be said to be the opposite or reverse of compounding. The compound interest formula is

$$F=P(1+r)^n$$

where

F=future value
P=present value
r=rate of interest in decimal form
n=number of years

Formula (3.4) can also be used to calculate the net present value (NPV) of a stream of future benefits B_j (j=1,2,…y). In this case:

$$NPV = \sum_{j=1}^{y} B_j / (1 + i)^j \tag{3.5}$$

If B_j is a constant B, NPV may be calculated to have the value given by the product BW where

$$W=[(1+i)^y-1]/[i(1+i)^y] \tag{3.6}$$

From equations (3.3) and (3.6), it may be seen that W is the reciprocal of the capital recovery factor K with interest rate i. For y=40 and i=0.1, K= 0.1023 and W=9.7752. For large values of y, say y=60, W is equal to (1/i) approximately.

A property owner may have to analyse the cash flows year by year if the costs (expenditure) and benefits vary from year to year. In this case the NPV is estimated as shown in the example in Table 3.3. In this table the net cash flow is given by benefit minus cost. It may be seen that the NPV of discounted cash flows at the end of the fifth year is -33.8 if the discount rate is 12 per

Table 3.2 Discount factor (DF)

	Discount rate (i%)								
Number of years (j)	*2*	*4*	*6*	*8*	*10*	*12*	*15*	*20*	*25*
1	0.9804	0.9615	0.9434	0.9259	0.9091	0.8929	0.8696	0.8333	0.8000
2	0.9612	0.9246	0.8900	0.8573	0.8264	0.7972	0.7561	0.6944	0.6400
3	0.9423	0.8890	0.8396	0.7938	0.7513	0.7118	0.6575	0.5787	0.5120
4	0.9238	0.8548	0.7921	0.7350	0.6830	0.6355	0.5718	0.4823	0.4096
5	0.9057	0.8219	0.7473	0.6806	0.6209	0.5674	0.4972	0.4019	0.3277
6	0.8880	0.7903	0.7050	0.6302	0.5645	0.5066	0.4323	0.3349	0.2621
7	0.8706	0.7599	0.6651	0.5835	0.5132	0.4523	0.3759	0.2791	0.2092
8	0.8535	0.7307	0.6274	0.5403	0.4665	0.4039	0.3269	0.2326	0.1678
9	0.8368	0.7026	0.5919	0.5002	0.4241	0.3606	0.2843	0.1938	0.1342
10	0.8203	0.6756	0.5584	0.4632	0.3855	0.3220	0.2472	0.1615	0.1074
15	0.7430	0.5553	0.4173	0.3152	0.2394	0.1827	0.1229	0.0649	0.0352
20	0.6730	0.4564	0.3118	0.2145	0.1486	0.1037	0.0611	0.0261	0.0115
25	0.6095	0.3751	0.2330	0.1460	0.0923	0.0588	0.0304	0.0105	0.0038
40	0.4529	0.2083	0.0972	0.0460	0.0221	0.0107	0.0037	0.0007	0.0001

cent per annum. On the other hand, if a discount rate of 10 per cent per annum is considered, the NPV at the end of the fifth year is 74.1, which is a positive quantity. For a specified period of years, the NPV decreases with increasing discount rate.

Internal rate of return

As discussed in the previous section, the NPV at 10 per cent discount rate is positive, but it becomes negative at 12 per cent. For a specified period of years, the NPV will be zero at a particular discount rate defined as the internal rate of return (IRR) or the marginal efficiency of capital. The IRR can be ascertained approximately by a graphical analysis, as described in Figure 3.1 for the example in Table 3.3. In this figure, a straight line has been drawn connecting the two points representing the two discount rates (10 per cent and 12 per cent) and their corresponding NPVs. The line cuts the horizontal axis at 11.4. Hence, the NPV is approximately zero at a discount rate of about 11.4 per cent; the IRR is, therefore, 11.4 per cent. To find the IRR, the NPVs should be calculated at several discount rates, including at least one negative NPV. Then, inter-polation may be used to find the discount rate at which the NPV is approximately zero. A more accurate value of the IRR may be obtained by using a computer program.

As discussed above, the internal rate of return is the annual rate at which invested initial capital is recovered through benefits accruing over a given period of years. It is the interest rate at which the net present value of benefits is equal to the initial cost C. This rate i or r is given by

$$BW=C \tag{3.7}$$

if the annual benefit Bj, is a constant B. The value of i or r is thus the solution

Table 3.3 Discounted cash flows

End of year	*Net cash flow (£'000)*	*Discount rate 12% p.a.*		*Discount rate 10% p.a.*	
		Discount factor	*Discounted cash flow (£'000)*	*Discount factor*	*Discounted cash flow (£'000)*
0	−1,500	1	−1,500.0	1	−1,500.0
1	−200	0.893	−178.6	0.909	−181.8
2	400	0.797	318.8	0.826	330.4
3	600	0.712	427.2	0.751	450.6
4	700	0.636	445.2	0.683	478.1
5	800	0.567	453.6	0.621	496.8
Net present value			−33.8		74.1

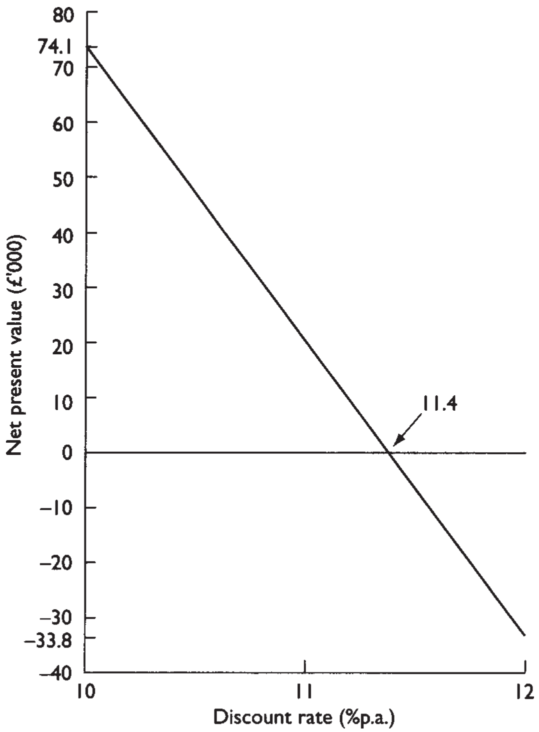


Figure 3.1 Internal rate of return

of

W=C/B or
K=B/C (3.8)

where W or K is given by equation (3.6) or (3.3).

Suppose, for example, the initial (capital) cost C of installing a certain fire protection device in a building is £10,000. Suppose also that the net annual benefit (B) due to this device, assumed to be a constant, is £3,000. This net amount, after subtracting the annual cost of maintaining the device, can be expected to be realised in terms of savings in insurance premiums and uninsured losses. Then, from equation (3.8), K is equal to 0.3 (=3,000/10,000).

The value of K mentioned above would be yielded by a number of combinations of the rate of return *r* and the planning period *y*. For example, from Table 3.1, K is approximately equal to 0.3 for r=0.08 and y=4. In other words, if the property owner were content with a rate of return of 8 per cent per annum, he or she can achieve this target over a period of four years. It would take longer to recover the capital cost at higher rates of return: about five years for 15 per cent, six years for 20 per cent, eight years for 25 per cent and so on. If such higher rates of return are expected within periods shorter than those specified, the property owner may decide not to go ahead with the installation of the fire protection device considered. An alternative device which might yield greater benefits for the same capital cost should then be selected.

The problem becomes somewhat complex and tedious if several benefit components with different rates of interest are involved in an investment project. In such cases, computer programs can be used to tabulate the cash flows year by year to find the internal rate of return for any specified period y which, as seen earlier, is the solution of

$$\begin{aligned} \mathrm{NPV} &= \mathrm{C} \quad \text{or} \\ -\mathrm{C}+\mathrm{NPV} &= 0 \end{aligned} \tag{3.9}$$

where NPV is given by equation (3.5)

Equation (3.9) can also be used to estimate the 'payback' period y for any given (internal) rate of return. This period is the length of time which is expected to elapse before the initial capital investment can be recovered from revenue at a given IRR. For example, for constant annual benefits with K=0.3, y is approximately 25 years for a rate of return of 30 per cent. A decision-maker may select an investment project whose benefits are such that the capital can be recovered within the shortest period at a desired rate of return.

Inflation and discount rate

As suggested by Watts (1988), provision for inflation may be made in two ways: (a) by estimating all future costs and benefits in constant prices and using a discount rate which represents the opportunity cost of capital in the absence of inflation; or (b) estimating all future benefits and costs in current or inflated prices and using a discount rate which includes an allowance for inflation. The discount rate in the first instance may be considered the real discount rate while the discount rate in the second instance is the nominal discount rate. An analyst should be careful not to use the current or inflated prices with the real discount rate or the constant prices with the nominal discount rate.

Additional reading

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DeGarmo, P.E., Sullivan, W.G. and Canada, J.R. (1984). *Engineering Economy,* New York: Macmillan.

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Chapter 4

Cost-benefit analysis

Based on annual costs and benefits as discussed in the previous chapter, alternative fire protection strategies can be selected and compared at different economic levels of decision-making. Different methods available for this purpose are discussed in this chapter and their application illustrated with examples. Two methods are discussed in detail since they are the most relevant to fire protection problems: the benefit-cost ratio and the optimum level of fire safety.

Rate of return

The rate of return (RR) is the average annual profit or benefit expressed as a percentage of the original capital expenditure:

$$RR = \frac{\text{average annual profit}}{\text{capital investment}} \times 100 \tag{4.1}$$

Consider, for example, a capital investment of £100,000 and benefits in a subsequent four-year period of £40,000, £40,000, £30,000 and £30,000. The total benefit is £40,000 (=£140,000-£100,000) such that the average annual benefit is £10,000. The RR in this case may be seen to be 10 per cent $(= \frac{10{,}000}{100{,}000} \times 100)$.

The implication behind the RR technique is that higher the RR, the 'better' the investment. But the RR technique does not take into account the recovery of the capital over the life of the project. The RR is not comparable with a lending or a borrowing rate. The 10 per cent RR, for example, does not mean that if money has to be borrowed to finance the project at a rate higher than 10 per cent the project would be unprofitable.

The RR technique ignores the timing of the flows of benefits, as is illustrated in Table 4.1, in which two projects, both with an initial investment of £100,000, are compared. For both projects, the total benefit is £40,000 and the average annual benefit £10,000; the RR is 10 per cent. The RR criterion would mark both the projects equally; but most decision-makers would prefer Project B because of its larger benefits in the early years.

It would be better to describe the RR as discussed above as the 'crude rate

Table 4.1 Comparison of flow of benefits from two projects

Year	*Benefits (£)*	
	Project A	*Project B*
1	20,000	50,000
2	30,000	40,000
3	40,000	30,000
4	50,000	20,000

of return' in order to distinguish it from the internal rate of return (IRR) discussed earlier (pp. 26–8), which is based on the net present value (NPV) of discounted benefits. The IRR technique also does not consider the recovery of the capital over the life of the project. The benefit flows after the specified period of years are ignored.

Payback period

If a project requires an initial investment of £8 million and is expected to produce an average annual revenue of £2 million, the payback period (PP) is taken to be:

$$PP = \frac{£8\text{ m}}{£2\text{ m}} = 4 \text{ years} \tag{4.2}$$

The PP method gives, therefore, a measure of the period during which the initial capital is at risk. The rate of return is given by:

$$RR = \frac{£2\text{ m}}{£8\text{ m}} \times 100 = 25 \text{ per cent}$$

Thus, the RR is the reciprocal of the PP.

The implication behind the PP technique is that the shorter the PP, the 'better' the investment. But this method, just like the RR, ignores flows of benefits beyond the PP; it is biased in favour of short-term projects. As an extreme case, take two projects with an equal initial investment and an equal PP of five years. Suppose the first project lasts a little over five years while the second project lasts, say, eight years. Although, both projects have an equal PP, clearly the second project, which is longer lasting, is more desirable. Yet this is ignored by the PP criterion, which ranks both the projects equally. This criterion, just like the RR, ignores the timing of the benefit flows. A further disadvantage of the PP method is that it does not normally take into account the financing method used, because interest payment is ignored.

Nevertheless, the PP method can be of use but only as a supplementary analysis (not on its own) in situations where:

1 time risks are especially important;
2 the liquidity position is critical.

For example, if two projects appear to be equally profitable (as evaluated by a sounder technique than PP), it may be that the project with the shorter PP will be preferable, given that time risks and liquidity are important.

The PP method discussed above can be termed the ‘crude payback period’ in order to distinguish it from the payback period discussed previously (pp. 26–8), which is based on the net present value of discounted benefits. This latter PP also suffers from the disadvantages discussed in this section with regard to the crude PP.

Benefit-cost analysis

Benefit-cost ratio

As discussed earlier in this chapter, the rate of return on investment and the payback period, in either their crude or refined versions based on net present value, can provide only tentative guidance in determining the acceptability of an investment project or in comparing alternative projects. The drawbacks of these two methods can be rectified by calculating the net present value (NPV) of the benefits or the annual value of the initial investment cost (C) over a long period, such as the life of the fire protection device considered or the life of the building to be protected by the device.

Equation (3.9) expresses the balance between the NPV of total benefits and the initial cost over specified (long) periods and rate of return, i.e. specified values of y and i in equation (3.6). Generalising the criterion in equation (3.9), an investment project can be accepted if

$$\text{NPV} > \text{C}$$

or

$$(\text{NPV/C}) > 1 \tag{4.3}$$

or if

$$(\text{NPV-C}) > 0 \tag{4.4}$$

Equation (4.3) expresses the condition that, for any specified level of the rate of return and the payback period, the benefit-cost ratio (NPV/C) is greater than unity. Alternatively, equation (4.4) expresses the condition that the benefit-cost difference (NPV-C) is positive. If the annual value of the benefits is a constant B, not varying from year to year, and C is the initial cost, from equation (3.7) the condition for the acceptability of a project may be expressed as:

$$BW>C$$

or

$$(BW/C)>1 \tag{4.5}$$

Since, as mentioned with reference to equation (3.6), W is the reciprocal of K, the inequality (4.5), can be restated as:

$$B>CK \text{ or } (B/CK)>1$$

or as

$$B>A \text{ or } (B/A)>1 \tag{4.6}$$

As defined with reference to equation (3.3), K is the capital recovery factor (Table 3.1) and the product CK is the annual amortised cost A of the capital cost C.

The inequality (4.6) expresses the condition that the benefits occurring in future years at a constant annual level B should exceed the annual equivalent A of the capital cost C to be spent initially. The inequality (4.5), on the other hand, specifies the condition that the total value of future benefits discounted to the present or base time should exceed the initial capital cost C. Both the conditions would lead to the same conclusion if the discounting rate for benefits is assumed to be the same as the interest rate for capital recovery and the same payback or planning period is adopted in both cases. There can be no reason to adopt different rates and periods for the monetary values denoting benefits and costs, both of which should be expressed in constant or base time prices. The simple criterion in inequality (4.6) would be sufficient in any benefit-cost analysis of fire protection measures which involves constant annual benefits in terms of reductions in fire losses and insurance premiums.

The problem now is to select the best fire protection strategy from alternatives that fulfils the acceptability condition in inequality (4.3) or (4.6). A simple solution to this problem is to select the strategy likely to yield the highest value for the benefit-cost ratio (NPV/C) or (B/A). The economic usefulness of different strategies can be ranked or compared according to the value of this ratio.

Example

This example, based on hypothetical data, illustrates the application of the benefit-cost ratio technique. A relocation project is considered where, by heavy grading work on a new alignment, it is possible to reduce the length between two points on an existing highway by constructing a new route. The length between the two points is five miles on the existing highway and three miles on the proposed new route. The existing highway between the two points is to be abandoned after the construction of the new route. It is estimated that the average traffic for the next twenty years, the analysis period, will be approximately 2,500 vehicles per day, mainly passenger cars.

In problems of the type described above, the benefit is usually defined as the difference in road user costs (RUC). The annual value of section RUC is calculated according to the following formula:

$$RUC = 365 \,.\, A \,.\, L \,.\, U \tag{4.7}$$

where A is the predicted average daily traffic for the period of analysis and L is the section length in miles. U is the combined unit operating and time cost per vehicle mile for the type of highway and its operating condition.

For the example considered, A=2,500; L=5 miles for the existing highway and 3 miles for the new route; U has been estimated to be £1.40 for the existing highway and £1.20 for the proposed new route. The RUC per annum according to formula (4.7) can be calculated to be £6.39 million for the existing highway and £3.29 million for the proposed new route. The annual road user benefit due to the construction of the proposed new route is, therefore, £3.1 million.

The average annual maintenance cost on the existing route is £15,000 per mile or a total of £75,000, and that of the proposed route £12,000 per mile or a total of £36,000. The total estimated cost of construction of the proposed new route is £8 million. This cost is composed of £1.5 million for the pavement with an estimated life of twenty years and £6.5 million for grading, drainage and structures with an estimated life of forty years. At 10 per cent rate of interest per annum, the value of K from Table 3.1 is 0.1175 for twenty years and 0.1023 for forty years. The annual amortised investment cost of the proposed new route is hence

$$C=(1.5\times0.1175)+(6.5\times0.1023)$$

$$=0.18+0.66=£0.84 \text{ million}$$

Including the maintenance cost the total annual cost for the proposed route is £0.88 million, whereas the only annual cost for the existing highway is £0.08 million towards maintenance. Hence the additional annual expenditure to be incurred for the proposed new route is £0.8 million against which the annual road user benefit is estimated to be £3.1 million. Hence, the benefit-cost ratio for the new route is 3.9 (=3.1/0.8).

If the NPV method is followed, with forty years as the planning period and W=1/k=9.7752 for 10 per cent rate of interest, the NPV corresponding to an annual benefit of £3.1 million is £30.3 million. This method leads to a benefit-cost ratio of 3.8 (=30.3/8), which is approximately the same value obtained by considering the annual benefit and annual amortised cost.

An alternative strategy is to improve the surface of the existing highway; this will result in a reduction in the value of U to £1.25 per vehicle mile from the current value of £1.40 per vehicle mile. From equation (4.7) the value of RUC for the improved highway can be calculated to be £5.7 million. The annual road user benefit is hence £0.69 million (=6.39-5.70).

The total cost of the proposed surface for the alternative strategy is £0.8 million. With an estimated life of ten years for the improved surface, the value of K from Table 3.1 is 0.1627 for 10 per cent rate of interest. Hence the annual amortised value of the initial cost is £0.13 million. With an annual maintenance cost of £13,000 per mile or £65,000 for five miles, the total annual cost can be seen to be £0.20 million (=0.13+0.07). Since the annual maintenance cost for the existing highway is £0.08 million, the additional annual cost for the improved surface is £0.12 million against which the annual benefit, as calculated earlier, is £0.69 million. The value of the benefit-cost ratio for improvement to the surface of the existing highway is, therefore, 5.75 (=0.69/0.12).

Under the hypothetical figures used for the costs and other items, improving the surface of the existing highway appears to be more cost-effective than constructing a new route which reduces the distance between the two points considered. The proposed new shorter route may generate more traffic but this factor has not been taken into account in the analysis. Composition of the traffic (passenger cars, trucks, buses etc.), delay at intersections, if any, and motor vehicle accidents are also factors affecting road user costs (RUC).

Optimum level of fire safety

Minimum total annual cost

As discussed above, the acceptability of a fire protection strategy may be based on the value of the ratio between benefits and costs, which should be greater than one, or of the difference between benefits and costs, which should be greater than zero. The annual benefits B_p due to a strategy are essentially the savings in costs associated with uninsured or self-insured fire loss and insurance premiums compared with the costs for a 'basic' strategy that satisfies the requirements specified in a fire safety regulation or code. Represented algebraically, it is:

$$B_p=F\,(\bar{x}_0-\bar{x}_p)+(I_0-I_p) \tag{4.8}$$

where the symbols $\bar{x}$ and I refer to the expected uninsured loss in a fire and the annual insurance premium and the subscripts 0 and p refer to the basic strategy and the strategy under consideration, respectively. The parameter F is the annual probability of fire occurring, assumed to be a constant. In statistical terminology, Fx^- is the expected value of the annual uninsured loss.

A fire protection strategy other than the basic one may be accepted if its benefit factor B_p is greater than the difference (C_p-C_0) where the symbol C refers to the annual (amortised) cost of fire protection. Fire safety may be enhanced by adopting another strategy which is likely to reduce further the annual uninsured loss Fx^-. With a reduction in the annual insurance premium I, the value of the benefit factor B_q for this alternative strategy may be higher than B_p. But the 'marginal' or additional benefit (B_q-B_p) may not be significantly higher than the 'marginal' or additional cost (C_q-C_p) involved although the alternative strategy may have a higher value for the benefit-cost ratio. In principle, safety can be improved by spending more and more money on protection measures but a limiting stage may be reached at which the decreasing 'marginal' benefits are almost equal to the 'marginal' costs. Beyond this stage, the 'marginal' costs may exceed the 'marginal' benefits.

The phenomenon described above, characterised as the 'law of diminishing returns' in economic theory, has been depicted graphically in Figure 4.1. As shown in this figure, as the degree of safety is increased, the marginal benefit generally decreases from a high level, while the corresponding marginal cost

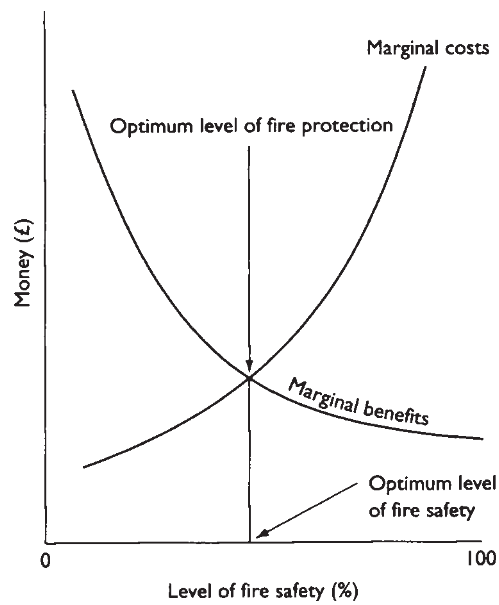


Figure 4.1 Marginal costs and marginal benefits

increases from a low initial value. The economically optimum level of fire protection is given by the point of intersection of the marginal cost and marginal benefit curves. At this point, the marginal benefit is equal to the marginal cost although the benefit-cost ratio may still be greater than one. Beyond this point, as is evident from Figure 4.1, the additional benefits from increased safety would be less than the additional costs involved in providing the extra protection.

As illustrated by Watts (1988) with an example, the fire protection strategy whose marginal benefits are equal to the marginal costs is the same as the strategy which minimises the total annual cost (see the example discussed below and illustrated in Figure 4.2). The fire protection strategy providing this minimum total annual cost is generally referred to as the optimum level of fire safety. The total cost for any strategy is given by:

$$T_p=F\bar{x}_p+I_p+C_p \tag{4.9}$$

As defined earlier, the symbols $\bar{x}$, I and C denote respectively the expected uninsured loss in a fire, the annual insurance premium and the annual amortised cost of protection plus annual maintenance cost; F is the annual probability of fire occurring.

Let us suppose that the strategy denoted by the subscript p has the minimum total annual cost T_p. For any other safer strategy, denoted by q, the total annual cost is T_q:

$$T_q=F\bar{x}_q+I_q+C_q \tag{4.10}$$

Since T_p is less than T_q:

$$F(\bar{x}_p-\bar{x}_q)+(I_p-I_q)+(C_p-C_q)<0 \tag{4.11}$$

In other words, the marginal benefit:

$$B=F\,(\bar{x}_p-\bar{x}_q)+(I_p-I_q)$$

is less than the marginal cost:

$$C=C_q-C_p$$

Consider now a strategy denoted by the subscript r which is less safe than that denoted by p. Its annual protection cost C_r may be less than C_p but the saving (C_p-C_r) will be less than the additional costs to be incurred towards uninsured loss and insurance premium:

$$C_p-C_r<F(\bar{x}_r-\bar{x}_p)+(I_r-I_p)$$

The result mentioned above follows from the fact that T_p is less than T_r given by:

$$T_r = F\bar{x}_r + I_r + C_r$$

General example

From the foregoing analysis it will be apparent that the total annual cost will attain the minimum for a strategy for which the marginal benefit is equal to the marginal cost of fire protection. Supporting this theoretical result, a hypothetical example is given in Table 4.2 in which safety, cost of protection and benefit are represented on relative scales. The safety level provided by basic fire protection measures is denoted by s_0; in this case only, say, 10 per cent of a building and its contents can be saved in the event of a large fire occurring. By adopting additional protection measures, the safety level may be increased to s such that, if

$$S = (s/s_0) = 2 \tag{4.12}$$

20 per cent of the building and contents may be saved in a large fire; 30 per cent of the property will be saved if S=3, 40 per cent if S=4, and so on.

If the building has no fire protection at all, s=S=0, in which case a major part of the property will be destroyed in a large fire with an expected annual loss of £100,000. If basic protection measures are adopted, $s=s_0$ and S=1 such that the annual cost (C) involved may be £4,000 as given by the following function (straight line):

$$C = 4S \tag{4.13}$$

with S=1. Compensating the protection cost there are annual benefits (B) in terms of reduced uninsured loss and insurance premium, which follow approximately the power function

$$B = 10S^{0.7} \tag{4.14}$$

For S=1, B=£10,000 and the total annual cost (T) including damage in a large fire is £94,000 is given by:

$$T = 100 + C - B \tag{4.15}$$

For safety levels higher than the basic, the cost of protection increases according to equation (4.13) and the benefits according to equation (4.14). Consequently, as shown in Table 4.2, the benefit-cost ratio (B/C) decreases from an initial value of 2.5. The marginal benefit, the difference between benefits at

Table 4.2 Optimum level of safety: minimum total cost

Safety level (S)	*Benefit (B)[a] (£'000)*	*Marginal benefit[b] (£'000)*	*Cost (C)[c] (£'000)*	*Marginal cost[d] (£'000)*	*Benefit–cost ratio*	*Total cost (T)[e] (£'000)*
0	0	–	0	–	–	100.0
1	10.0	10.0	4	4	2.5	94.0
2	16.2	6.2	8	4	2.0	91.8
3	21.6	5.4	12	4	1.8	90.4
4	26.4	4.8	16	4	1.7	89.6
5	30.9	4.5	20	4	1.5	89.1
6	35.0	4.1	24	4	1.5	89.0
6.5	37.0	2.0	26	2	1.4	88.9
7	39.0	2.0	28	2	1.4	89.0
8	42.9	3.9	32	4	1.3	89.1
9	46.6	3.7	36	4	1.3	89.4
10	50.1	3.5	40	4	1.3	89.9

Notes
All financial figures are annual values
[a] Benefit (B)=$10S^{0.7}$
[b] Marginal benefit=$7S^{-0.3}$ ds (where ds is the difference between two consecutive values of S)
[c] Cost(C)=4S
[d] Marginal cost=4
[e] T=100-B+C

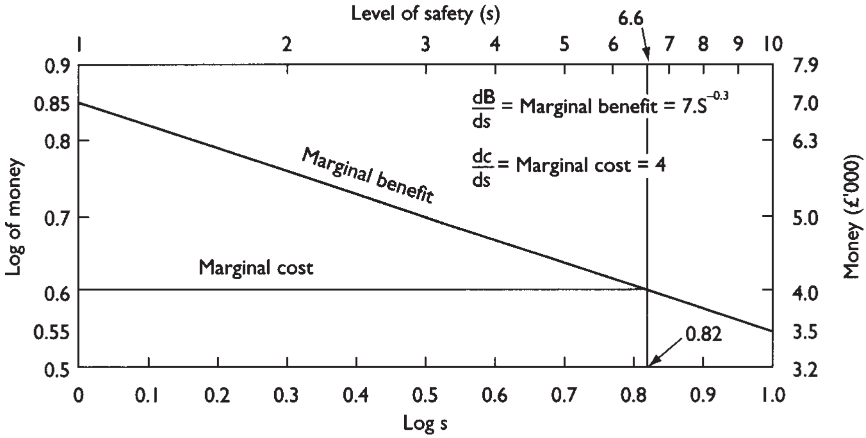


Figure 4.2 Optimum level of fire safety: example

two consecutive safety levels, decreases since the exponent in equation (4.14) is 0.7, a quantity less than one. Benefits are unlikely to increase proportionately with the level of fire protection adopted. If this level is doubled, for example, benefits will not necessarily increase by a factor of two. Since the cost function, equation (4.13), is a straight line, the marginal cost would remain at a constant value of £4,000.

As would be expected, the total annual cost decreases as the safety level is increased and reaches the minimum value of 88.9 when safety reaches a level corresponding to S=6.5. At this level of fire protection the marginal benefit is equal to the marginal cost, both being equal to about £2,000. This level can also be estimated by solving the following equation, which is obtained by minimising T in equation (4.15) with respect to S:

$$\frac{dB}{dS} = \frac{dC}{dS} \tag{4.16}$$

In equation (4.16), (dB/dS) is the derivative of B and (dC/dS) the derivative of C. From equations (4.13) and (4.14) the equation to be solved is:

$$7\ S^{-0.3}=4$$

such that for S=6.5, T will attain the minimum value. In the continuous case the marginal value of a function is given by its derivative. In the discrete case, the marginal value can be obtained by subtracting the actual values at two consecutive levels, as shown in Table 4.2.

For safety levels higher than S=6.5, the benefits continue to increase with a benefit-cost ratio still greater than one, but the marginal benefit is less than the marginal cost. Consequently, the total annual cost increases from its minimum value for S>6.5. There is, therefore, no economic justification for spending money to increase safety above the level denoted by S=6.5. This level, as defined in equation (4.12), is 6.5 times the safety level provided by basic fire protection measures and is expected to save 65 per cent of the building and its contents in the event of a large fire occurring.

Chapter 7 contains further analyses based on the total annual cost and Chapter 8 the application of utility theory. Costs and benefits of individual fire protection measures are discussed in Chapter 5 and the combinations of measures in Chapter 6.

Chapter 5

Cost-benefit evaluation of fire safety measures

Operation or performance of a fire protection system during a fire depends on several factors such as satisfactory maintenance of the system, location of the fire with reference to the location of the system, rate of growth of the fire or smoke, and environmental conditions. Statistics are available for some of these systems, e.g. sprinklers for estimating the probability of operation of the system in a fire. If the system operates in a fire, it can be effective in reducing the damage likely to be inflicted on life and property. This reduction in damage is a benefit due to the fire protection system at the national economic level which must to be compared with the total costs associated with the system. For a property owner, installation of a fire protection system provides benefits such as tax allowances and savings in fire insurance premiums. This chapter discusses the costs and benefits of individual fire safety measures to the extent that data and research results are available. Combinations of safety measures are discussed in the next chapter.

Structural fire resistance

Definition of fire resistance

Fire resistant compartmentation has long been the core of fire safety measures incorporated in codes and regulations concerned with fire. A building is regarded as being composed of compartments perfectly isolated from one another and the spread of fire as taking place by successive destruction (or possibly thermal failure) of the compartment boundaries (walls, floor and ceiling). If the boundaries are sufficiently fire resistant, it is argued, the probability of fire spread due to the 'failure' of the structural boundaries of the compartment will remain within acceptable limits.

The structural elements of a compartment would only be affected if a fire grew into a fully developed stage defined scientifically as 'flashover'. The severe heat generated during this stage can cause structural collapse or thermal failure. The probability that this undesirable event would occur depends also on the fire resistance of the structural element involved. Fire resistance is defined in terms of time, e.g. 30 minutes, 60 minutes, etc., during which a structural element can withstand a severe fire without violating performance criteria relating to stability, integrity and thermal insulation. The fire resistance period of a load-bearing element is usually determined by carrying out a standard fire resistance test in a laboratory. The period exhibited in the test should be equal to or exceed the period specified in a fire regulation or code for the risk category concerned and can be achieved by using an appropriate type of structural element, e.g. steel, concrete, timber, etc.

In order to minimise the probability of 'failure', the fire resistance, R, required for the structural elements of a compartment is set equal to a large level S_M of fire severity, S, likely to be attained in a real fire. The value of S_M would vary from one risk category to another, depending mainly on the combustion characteristics of materials or objects contained in the compartment. Hence the fire resistance required for the structural elements of a compartment would vary from risk category to risk category. Fire regulations and codes generally recognise that fire severity, S, is a random variable in a real fire but regard fire resistance, R, as a constant. Under this assumption, the probability of structural failure only depends on the probability distribution of S. Failure occurs if S exceeds the value of R pertaining to a structural element. Forms suggested for the probability distribution of S are exponential (Baldwin, 1975) and normal (Ramachandran, 1990). The probability of a fire spreading beyond a compartment due to structural failure is the product of the probability, F, of fire occurrence, probability, p_l, of severity reaching a high level S_M if a fire occurs and the probability, p_f of compartment failure if severity reaches the level S_M.

Cost-benefit analysis: national level

If L is the expected loss following structural failure and the probability of fire starting, F, is expressed on an annual basis, the expected value of the total annual cost at the national economic level is given by:

$$T_R = C_R + F.pl.pf.L.W \qquad (5.1)$$

where C_R is the cost of providing the fire resistance R, and W is the factor for calculating the NPV discussed above (pp. 22–6). The probabilities p_l and p_f have already been defined in the previous subsection.

As previously discussed (pp. 20–1), the annual probability, F, of the occurrence of a fire in a building with total floor area A can be estimated for any type of building. In an earlier study (North, 1973a), global values of F applicable to any building were estimated for some occupancies (see Table 5.1). Figures for 'destruction of element' in Table 5.2 (North, 1973b) denote approximate values for p_l. According to an analysis of more recent fire statistics (1984–7) on area damage carried out by Ramachandran (1993a), in the absence of sprinklers the

Table 5.1 The annual chance of a fire outbreak for various occupancies, UK

Hazard	*Number of buildings*[a]	*Number of fires annually*[b]	*Annual chance of fire outbreak*
Industry	183,377	8,075	4.4×10^{-2}
Houses	14,202,359	38,142	2.7×10^{-3}
Commercial – shops	664,817	5,574	8.4×10^{-3}
Commercial – offices	152,430	866	5.7×10^{-3}
Assembly – entertainment	12,540	1,446	1.2×10^{-1}
Assembly – non-residential	143,019	2,810	2.0×10^{-2}
Residential – clubs, hotels, etc.	36,609	1,352	3.7×10^{-2}
Residential – institutions	—	803	—
Storage	199,612	2,420	1.2×10^{-2}

Notes
[a] From *108th Report of the Commissioners of HM Inland Revenue,* reprinted in North (1973a).
[b] Fires during 1967.

Table 5.2 The maximum severity of damage as a proportion of all fires with known severities

Maximum severity[a]	*Occupancy group*						
	HFM[b]	*Residential*	*Offices*	*Shops*	*Assembly*	*Industrial*	*Storage*
Surface damage	0.24	0.29	0.24	0.23	0.30	0.24	0.11
Slight damage	0.39	0.41	0.45	0.35	0.35	0.30	0.29
Severe damage	0.29	0.25	0.21	0.29	0.24	0.26	0.54
Destruction of element	0.07	0.06	0.10	0.13	0.10	0.20	0.07
No. of fires included	983	69	29	111	99	127	28

Notes
[a] Those fires in which no structural damage was reported were excluded.
[b] HFM=private houses, flats and maisonettes.

probability of the entire floor area of a compartment being involved in a fire is 0.03 approximately for office buildings with an average room size of 100 m^2, assembly areas of retail trade premises (shops etc.) with an average size of 100 m^2 and hotel bedrooms of average size 50 m^2. Sprinklers would reduce this probability to 0.01. If the entire floor area of a compartment is involved in a fire, all the structural elements of a compartment will sustain severe damage or destruction, not just a single element.

An estimate of L can be obtained from fire statistics by considering life and property damage in fires which spread beyond the room of origin. Life losses can be converted to financial figures by assigning monetary values to fire deaths and injuries (see Chapter 10). Property damage in a fire spreading beyond the room of origin can be estimated by analysing data on large financial losses compiled by, for example, the Fire Protection Association in the UK and processed by the Home Office. Fire statistics collected by the Home Office include data on area damage, these figures can be converted to financial loss by using an estimate for loss per unit area, as obtained, for example, by Rutstein and Cooke (1979).

The benefit due to a specified level of fire resistance is the difference in the value of L for two types of rooms: one with fire resistant barriers and the other with no or low fire resistance. To estimate this reduction in L due to fire resistance, data are required which will enable buildings involved in fires to be classified into various fire resistance categories. Such detailed data are not available at present. Fire statistics available in the UK in the past contained some information for a crude classification into two broad categories: high and low fire resistance. This information has been used in an investigation concerned with the trade-offs between sprinklers and fire resistance (see pp. 97–8).

Estimating the cost of fire resistance is a complex problem. Silcock (1967) suggested a method based on the savings that can be estimated if a 'scaling down' exercise is carried out on an existing building built to normal fire standards. Assuming that the basic method of construction and design remains unchanged, the 'fire element' can be extracted by means of a series of omissions, reductions and subtractions applied to the building. These might take the form of items such as a reduction in the extra material cover thicknesses and the substitution of cheaper but otherwise equally suitable non-fire-resistant materials. The resultant savings may be expressed as a percentage of total building cost. Silcock estimated that for shops this percentage would be 0.83 for dry cladding in lieu of two-hour fire-resistant concrete cover on columns. According to a report by the Home Office (1980:139–40), the cost of fire resistance could be about 0.5 per cent of building cost.

In the context of an economic analysis, the cost of fire protection (C_R) must be estimated as a function of fire resistance. The cost increases as fire resistance increases, so ultimately the cost would exceed savings in fire damage thus setting a limit to the reduction in risk that can be achieved economically. According to Maskell and Baldwin (1972), a good approximation is:

$$C_R=\alpha+\beta R,\ R>0 \qquad (5.2)$$

where α and β are constants, a representing an operational penalty associated with installing fire protection independent of the amount of fire protection, β being the cost of increasing fire resistance per unit of time. In practice, concrete frames with zero fire resistance are not viable structures and hence $\alpha=0$. Unprotected steel frames are viable structurally but the cost α may be significant. The role of α in this case, in arguing for the use of unprotected steel structures, requires special analysis.

We can now consider the problem of estimating the structural 'failure' probability p_f which, if the randomness of fire resistance is ignored, depends only on the probability distribution of fire severity (S). This probability is given by:

$$\varphi_s\ (R)=1-F_s\ (R) \tag{5.3}$$

where $F_s(S)$ is the probability of severity being less than or equal to S. Equation (5.3) expresses the probability p_f of severity exceeding the fire resistance period R.

We can now rewrite equation (5.1) as follows:

$$T_R=\alpha+ßR+F._{pl}\ L.W\varphi_s\ (R) \tag{5.4}$$

According to Baldwin (1975), fire severity has an exponential probability distribution such that:

$$\varphi_s\ (R)=\exp\ (-R/S_0) \tag{5.5}$$

where S_0 is the mean severity. It is worth noting that the annual risk of failure is $F._{pl}.\ \exp\ (-R/S_0)$. Fire resistance reduces this risk by an order of magnitude for every 60 minutes resistance in office buildings. Ramachandran (1990) and Elms and Buchanan (1981) have suggested a normal distribution for severity. For this distribution, the mathematical expression for φ_s (S) cannot be written in a simple form since it involves the integral sign. But if the mean and standard deviation of S are known, tables of standard normal distribution can be used to estimate the probability φ_s (R) for any given value of R.

The value of fire resistance in minimising the total annual cost can be estimated by differentiating T_R in equation (5.4) with respect to R. This value (R_m) is the solution of:

$$ß=F.p_l.LWf_s\ (R_m) \tag{5.6}$$

where f_s (S) is the probability density function of S. This result follows from the statistical property that the density function is the derivative of the distribution function F_s (S) mentioned in equation (5.3). For an exponential distribution, the density function is $[(1/S_0)\ \exp\ (-S/S_0)]$ such that:

$$R_m = S_0 \log_e \left(\frac{F\, p_l.\ L.\ W}{\beta\ S_0} \right) \tag{5.7}$$

Suppose the severity S has the normal density function:

$$(1/\sqrt{2\pi}\ \sigma_s)\ \exp \left[-\ 0.5 \left(\frac{S - \bar{S}}{\sigma_s} \right)^2 \right]$$

where $\bar{S}$ is the mean and σ_s the standard deviation of S. In this case, it may be verified that R_m is given by the positive root of the equation:

$$\left(\frac{R_m - \bar{S}}{\sigma_s}\right)^2 = 2 \log_e \left(\frac{F \, . \, p_l.L.W}{\sqrt{2\pi}\,\sigma_s.\ \beta}\right)$$

According to Baldwin (1975), with an exponential distribution for severity, S_0=25 minutes for office buildings. For these buildings, Baldwin used a value of F=0.006 estimated by North (1973a) for the annual probability of fire starting. Baldwin *et al.* (1970) estimated that p_l=0.1 for the probability of a fire growing sufficiently large to damage building fabrics. With the values mentioned above, F.p_l=0.0006. Denoting building costs by the symbol I, Baldwin has assumed that ß/I=0.001 per minute. He has also assumed that the discount factor W has the 'typical' value of 10. If the values mentioned above are inserted in equation (5.7):

$$R_m = -35.68 + 25 \text{ loge } (L/I) \tag{5.8}$$

Since R_m must be positive, it can be seen from equation (5.8) that L/I should be greater than 4.17 to justify fire resistance.

Based on a graphical representation (see Figure 5.1, with D denoting L) of equation (5.8), Baldwin argued that a value of about 40–50 for D/I was necessary to justify a fire resistance of 60 minutes as required by UK building regulations at that time (for R_m=60, D/I=46). Such a high value for D/I would correspond approximately to a catastrophe. Hence, the requirements of the regulations for office buildings would have some economic justification only if structural failure caused catastrophic damage to life and property. Such damage can occur in a tall building with a large number of occupants.

In the analysis described above, fire severity S has been regarded as a random variable and fire resistance R as a constant. But R also is a random variable although, presumably for the sake of simplicity, fire safety codes and regulations treat it as a constant. Uncertainties (randomness) in the performance of fire resistant structural elements are due to weaknesses caused by penetrations, doors or other openings in the structural boundaries of a compartment. Another source of uncertainty is the fact that the fire resistance of a compartment is not necessarily the same as that of the structural elements. A fire resistant compartment is a fire protection system composed of structural elements as components. If both R and S are treated as random variables in equation (5.4), the total annual cost T_R should be minimised with reference to both of these variables. This is a complex mathematical problem which is beyond the scope of this book.

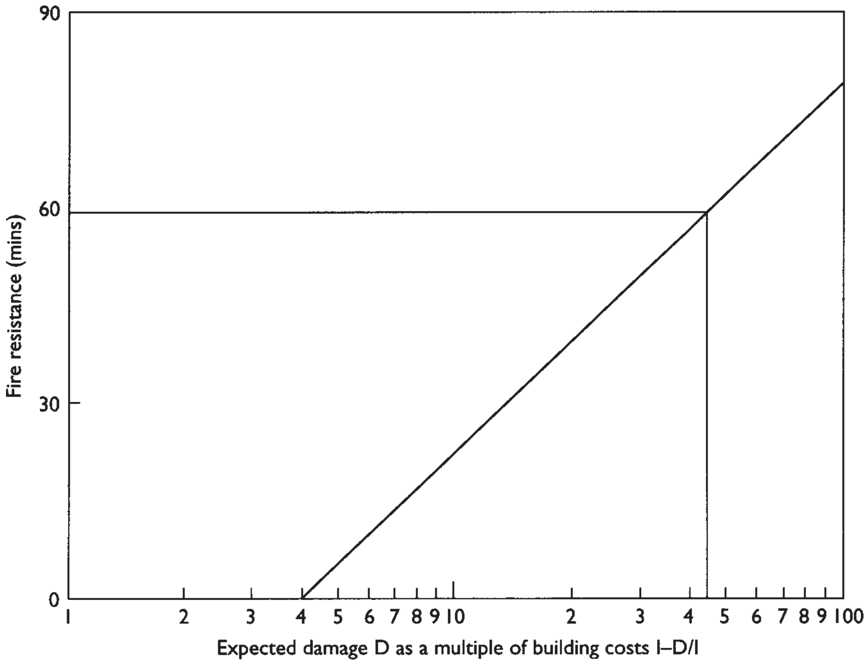


Figure 5.1 Variation of optimum fire resistance with expected damage (office buildings)
Source: Baldwin (1975)

Cost-benefit analysis: property owners

Since the fire insurance companies in the UK abandoned the tariff system and adopted a more competitive policy, they have been unwilling to provide information to the public on the fire insurance premium rates for different risk categories. It is doubtful whether the companies adopt any sound statistical approach when calculating appropriate premiums. They raise or lower the rates depending on their financial performance and on whether they are losing custom to competitors. Theoretically, the premium for any risk category should be equivalent to the 'risk premium' based on expected (average) loss for that category plus two loadings: one for safety and another to cover administrative costs, which include handling costs and profits.

Insurance companies are generally reluctant to provide insurance cover for a building without the level of fire resistance specified by them or required by fire regulations. If such a building is accepted for insurance, the premium rate for full insurance cover can be very high, e.g. £8 per £100 of insured value per annum for an uncompartmented warehouse. The provision of fire resistance and other fire precautions can reduce this rate to £2 per £100 of value per annum.

A quotation was sought from an insurance broker for a building not used as a warehouse or for any industrial or commercial activity; it might have been an office building. The broker was unwilling to disclose the risk category to which the quotation was applicable. For this category, the premium rate was about £1.95 per £100 of sum insured per annum if the rooms of the building did not have adequate fire resistance, and £0.65 per £100 of insured value per annum if the building had compartments with one-hour (60 minutes) fire resistance.

Consider, as an example, a single-storey property with a total floor area of 2,000 m^2 in the risk category mentioned above; its building cost or insured value is £1,000,000. The building cost is £500 per m^2 to meet normal fire safety standards. For this building, according to the rates quoted above, the annual premium would be £19,500 if the building had 30 minutes fire resistance, which may be considered inadequate by the insurer. It would be £6,500 if it had one-hour fire resistance. The annual saving in insurance premium or benefit would thus be £13,000 if the building were provided with the required level of fire resistance.

According to equation (5.2), with α=0, ß=0.001 and R=60, provision of 60-minute fire resistance would cost 6 per cent of the building cost (I) or value. Applying this percentage, the cost towards 60-minute fire resistance for this building can be seen to be £60,000 at a rate of £30 per m^2. Against this expenditure, the annual benefit is £13,000, the net present value of which at 10 per cent discount rate over a forty-year period is £127,000 (=13,000×9.7752). (From Table 3.1, the discount factor W=1/*k*=1/0.1023.) The value of the benefit-cost ratio is 2.12 (=127,000/60,000). The same value will be obtained by calculating the ratio between the annual benefit of £13,000 and the annual amortised cost of £6,138 (=60,000×0.1023).

The property owner may prefer to calculate the NPV of the benefit on a year-by-year basis. In this case, using the figures in Table 3.2 corresponding to 10 per cent discount rate, the NPV of the benefit at the end of each of the first seven years would be £11,820, £10,740, £9,770, £8,880, £8,070, £7,340 and £6,670. These seven figures add up to £63,290. The fire resistance cost of £60,000 can therefore be recovered in just over six years.

In the analysis discussed above the value of the contents of the building has not been taken into account; only the cost or value of the building has been considered. Insurers generally offer rebates on premiums for contents as well if a building has adequate fire protection. Hence, depending on the value of the contents, the benefit-cost ratio for this building will be higher than 2.12. The cost for the provision of one-hour fire resistance can be recovered in less than six years.

Fire loss has not been considered in the analysis discussed above since, if a fire occurs, the property owner will be compensated for almost the entire amount of the loss except a small deductible; this is because full insurance cover was obtained by the property owner. Fire loss will enter the economic analysis if the owner takes self-insurance, particularly with a large deductible.

Means of escape

Introduction

The main object of providing means of escape in a building is to ensure safe and rapid evacuation of all occupants to a place of safety in case of a fire. The escape routes should be available from all parts, remain safe and effective while they are needed, be clearly visible to all users, and be located and of a size to meet the needs of all occupants taking account of the use of the building. Means of escape should, therefore, be designed according to the number and characteristics (average age, mobility, etc.) of the occupants.

It is not known how many people are exposed to fires every year although statistics are available on the number of people who escape or are rescued. If assumptions are made about the average occupancy levels of different types of buildings, these levels can then be compared with the average number of people per fire who escape successfully. This method might give a rough idea of the effectiveness of escape routes. The consequences of inadequate means of escape have been highlighted in a number of incidents where the absence of properly designed routes, inadequate protection, failure of alarm or warning systems or some other shortcoming have resulted in serious loss of life.

Detailed data are not available to enable a cost-benefit analysis of means of escape to be carried out. Results of some research studies are presented in this section which provide some information on the economic value of escape routes such as protected staircases.

Number and widths of staircases

The provision of means of escape is important, particularly in multistorey buildings which require a sufficient number of adequately sized and protected escape stairs. In a multistorey building designed for 'total evacuation', the escape stairs should have the capacity to allow all floors to be evacuated simultaneously. For large buildings over 30 m high complete evacuation would be lengthy and difficult and the fire safety codes envisage evacuation of only part of the building, usually the fire floor and the floor above. This is referred to as 'phased evacuation' and is applicable to a building in which every floor is a compartment floor and which is fitted with an appropriate fire warning system. These criteria, together with data on numbers of occupants on different floors and their rates of passage through doorways, corridors, etc., determine the number and widths of staircases required to permit unimpeded flow of people.

The following formula has been suggested in British fire safety regulations and codes for total evacuation, assuming that one staircase is inoperative due to fire or smoke:

$$M=200b+50(b-0.3)(n-1) \tag{5.9}$$

where M is the maximum number of people who can enter a staircase of width b (in metres) serving n floors. Equation (5.9) has been derived by substituting the value of u given by:

$$u=50(b-0.3)$$

in the following equation, which assumes a uniform population density:

$$M=Nbt+(n-1)u \tag{5.10}$$

where the flow rate N is approximately 80 persons per metre width per minute. The parameter u is the number of people who can be accommodated on the stairway between one storey and the next. The parameter t is the 'design evacuation time', which is usually taken as 2.5 minutes and represents an acceptable period within which all the occupants of a floor should be able to enter a staircase after leaving their places of occupation. For buildings without compartmental floors between storeys, the recommended maximum number of people who can enter a staircase is $222b$. The minimum width of a stair designed for phased evacuation should be based on the formula [(P×10)-100] mm where P is equal to the number of people on the most heavily occupied storey.

Wider staircases may involve additional construction costs. However, according to Silcock (1967), the cost of measures of this type is likely to be small. It may, therefore, be assumed that the cost penalty of additional staircase width consists only in the loss of rentable floor space. This cost represents the value of the space to the building occupier; the cost to the society may be less. The amenity value of a building quantified by, say, the cost of normal circulation is unlikely to be affected significantly by a marginal change in staircase width not involving an increase in the number of staircases.

Melinek and Baldwin (1975) carried out a detailed analysis of the problem of estimating the total staircase width required to provide an adequate safe area for the evacuation of occupants in multistorey buildings. They calculated the staircase area as a function of the time allowed for travel to the entrance of the staircase and the number of floors required to be evacuated initially. For a typical staircase of width b they have assumed that the projected area of the staircase has dimensions $2b \times l/2$ ($=bl$). If the annual rent per unit area is R, then the annual cost of the staircase is C ($=Rbl$) per annum per floor. If the number of people to be evacuated from a floor is Q, the annual cost per person is C/Q. With $l=10$ m and R=£40 per m^2 per annum, C/Q has been estimated to be £$400b$/Q per annum, at 1975 prices.

Using the results mentioned above, Melinek and Baldwin (1975) have produced a graph (Figure 5.2) showing the variation of staircase width per person per storey, b/Q, with evacuation time t and the annual cost C/Q (=£$400b$/Q) per person. These curves, based on crowd movement data, are shown for three values of n, the number of floors to be evacuated. With $b/Q \leq 0.025$ m per

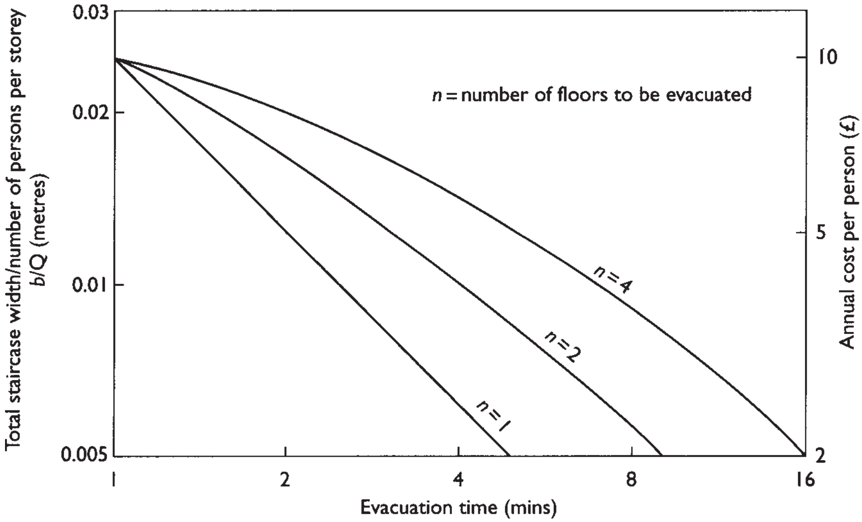


Figure 5.2 Variation of staircase width with required evacuation time, and the annual cost per person
Source: Melinek and Baldwin (1975)

person, C/Q≤£10 per person per annum. This is equivalent to a capital cost of approximately £100 per person at 1975 prices.

If the design evacuation time t=2.5 minutes is applicable to the evacuation of the fire floor and the floor above, with n=2, the annual cost of the staircase per person is about £6 at 1975 prices, according to Figure 5.2. The most obvious change that could be made in these requirements is to provide enough standing space on the stairs for all building occupants, corresponding to either t=1 minute or large values of n. In this case, from Figure 5.2, the annual cost would be about £10 per person, an additional £4 per person. According to the authors, if t=1, it would reduce the time for the general evacuation of the building by just over 40 per cent.

On the other hand, requirements may be relaxed such that only one floor, the fire floor, is evacuated or the fire floor may be evacuated within five minutes. These factors would reduce costs to about £3–4 per person per annum. But the time for general evacuation of the building would be about 30 per cent higher if only one floor were evacuated or 70 per cent higher if the design evacuation time were increased to five minutes.

As discussed above, a reduction in the design evacuation time would necessitate an increase in the width of the staircase. Alternatively, in a large building, the maximum travel distance to the entrance of a staircase may be reduced by constructing an additional staircase. The extra staircase is necessary since a reduction in t will reduce the maximum number (M) of people who can enter a staircase of given width b (see equation (5.10)). Both the courses of action mentioned above would involve additional costs but there would be benefits in terms of a reduction in life risk, quantified by the number of fatal and non-fatal casualties. An increase in the design evacuation time, on the other hand, would allow a decrease in the width of the staircase or fewer staircases to be built in a large building. In this case, there would be a gain in rentable floor space or reduction in the costs of staircases but the life risk will increase.

Change in life risk

The level of life risk will be affected if changes are made in fire regulations for means of escape or in building configurations. Estimating the change in the life risk is a difficult task but some light on this problem is thrown by estimating the extent to which the fatality rate per fire would increase for every minute of increase in the evacuation time. This increase in the fatality rate per fire, denoted by λ, can be evaluated approximately from UK fire statistics (Ramachandran, 1993b and see Table 5.3).

The rate for fires discovered at ignition is high due to the fact that a high percentage of fatalities were in the rooms of fire origin. Excluding this category, the overall (average) value of λ is 0.0008 for single occupancy dwellings and 0.0006 for multiple occupancy dwellings. With about 35,000 and 21,000 fires, respectively, per year a delay of one minute in the evacuation of these two types of buildings would increase the number of deaths by 28 and 13 per year,

Table 5.3 Discovery time and fatal casualties

Discovery time and occupancy type	*Number of deaths*	*Number of fires*	*Fatality rate (per fire)*
Single occupancy dwellings			
Discovered at ignition	445	76,243	0.005837
Discovered under 5 minutes after ignition	686	212,519	0.003228
Discovered 5–30 minutes after ignition	2,156	141,462	0.015241
Discovered more than 30 minutes after ignition	2,766	53,677	0.051530
Total	6,053	483,901	0.012509
Multiple occupancy dwellings			
Discovered at ignition	204	27,805	0.007337
Discovered under 5 minutes after ignition	334	123,648	0.002701
Discovered 5–30 minutes after ignition	1,281	110,078	0.011637
Discovered more than 30 minutes after ignition	1,703	28,125	0.060551
Total	3,522	289,656	0.012159

Source: *Fire Statistics United Kingdom*, London: Home Office, 1978–91 (published annually)

Notes

Single occupancy dwellings: $\lambda = 0.000801$

Multiple occupancy dwellings: $\lambda = 0.000596$

respectively. A delay of two minutes would increase the number of deaths by 56 and 26 per year, and so on. A similar analysis based on a number of years of statistical data on fires can be performed for other types of buildings with large numbers of occupants at risk, such as apartment buildings, flats, office buildings, hotels, hospitals, cinemas, department stores and shopping complexes. The number of deaths and injuries must be converted to monetary values, and that is the subject matter of Chapter 10.

Sprinklers

Types of sprinkler systems

In essence, an automatic sprinkler system is a fire fighting system designed to be operated by the fire itself so as to dispense water in areas where it is needed to ensure rapid suppression of the fire with minimum damage to property. The salient feature of the system is an adequate water supply which can be pumped through a network of pipes, usually at ceiling level, to a series of sensitive ‘sprinklers’ which are designed to respond to the thermal conditions created by the fire. Thus only those sprinklers which have been affected by the fire will operate and allow water to flow from them to be distributed in the form of a spray on to the fire below. Sprinklers are generally required to operate at an average temperature of 68°C but there are special requirements for certain occupancies.

Even in cases where water from sprinklers does not extinguish the fire, cooling by the water spray can protect the structural elements of a building and contain the fire until it can be extinguished by other means. This can lead to both lower fire temperatures and lower concentrations of smoke and other toxic products in the atmosphere; it can also retard the rate of growth of heat, smoke and toxic products. Since a sprinkler system has to detect a fire before it will operate, it also acts as an automatic detector system. The design functions of a sprinkler system such as the one described above are intended to give more time to the occupants of a building for escape, rescue or evacuation.

There are four basic types of sprinkler systems; they differ in terms of the most fundamental aspect: how the water is put into the area of the fire. Wet pipe systems and dry pipe systems use automatic sprinklers while deluge systems, instead of automatic sprinklers, use open sprinklers. The fourth type is similar to a deluge system, except that automatic sprinklers are used. There are many other types of sprinkler systems classified according to: the hazard they protect (such as residential, in-rack or exposure protection); additives to the system (such as antifreeze or foam); or special connections to the system (such as multipurpose piping); but all sprinkler systems can still be categorised as one of the four basic types. Fleming (1988) and Nash and Young (1991) describe the basic features of all sprinkler systems, the hydraulic calculations for determining water supply requirements and the performance of a system relative to a fire.

Performance of a sprinkler system

Several factors cause uncertainties in the activation and operating times of sprinklers in actual fires, although scientific (deterministic) methods have been developed to estimate the response time (see, for example, Evans 1985). The operating time can vary from 2.5 minutes for 'extra high hazard' occupancies to 16.8 minutes for 'light hazard', as estimated by Bengtson and Laufke (1979–80). The operating time of sprinklers in experimental fires has been estimated in several studies carried out in the UK, the USA and other countries.

In a building with a sprinkler system there is a chance that a fire may not produce sufficient heat to activate the system, so it is either self-extinguished or extinguished by first-aid means, e.g. portable fire extinguishers, buckets of water, etc. This chance associated with a 'small' fire is about 55 per cent, according to UK fire statistics which relate to fires attended by or reported to the fire brigades. In the remaining 45 per cent of fires requiring sprinklers, the system operates in 87 per cent of the cases and fails to operate in 13 per cent. The main cause of sprinkler failure (non-operation) is closed valves, i.e. system shut down (see Nash and Young, 1991; Miller, 1974). According to an investigation quoted by Rogers (1977), one-third of fires in buildings with sprinkler systems in the UK are extinguished by the system and not reported to the fire brigade.

If an allowance is made for 'small' and 'unreported' fires, calculations show that sprinklers operate in 94 per cent of fires (=89/95) in which their action is required. Rutstein and Cooke (1979) have estimated a figure of 2.2 per cent for sprinkler failure rate, which denotes a performance reliability of 97.8 per cent. Based on statistical data for Australia and New Zealand available for a hundred-year period (from 1886), Marryatt (1988) has estimated a success rate of over 99 per cent for sprinklers. The success rate for sprinklers in the USA is about 96 per cent (see Miller, 1974).

Effectiveness of sprinklers

The effectiveness of sprinklers in reducing property damage has been well discussed and established in fire protection literature. According to Rogers (1977), for example, sprinklers are very effective in reducing the average financial loss, particularly in multistorey industrial and commercial buildings, where they reduce losses by at least 50 per cent, i.e. by a factor of 2. The reduction can be as high as 85 per cent (in the textile industry), so the average loss in a building with sprinklers is 15 per cent of the average loss in a building without them. Rutstein and Cooke (1979) have estimated a reduction of 73 per cent due to sprinklers in average area damage in industrial buildings.

Fire loss data, compiled by the Factory Mutual Research Corporation in the

USA for the period 1980–9 for a wide range of production, warehouse and non-manufacturing occupancies, indicate that the average fire loss for a building without sprinklers is approximately 4.5 times greater than that of a building with sprinklers (Rees, 1991). An analysis of data for the period 1980–90, carried out by the National Fire Protection Association, USA, has shown that the reduction in the average loss per fire ranges from 43 per cent for stores and offices to 74 per cent for educational establishments (Hall, 1992).

Ramachandran (1993a) estimated that sprinklers reduce by a factor of 3 the probability of ‘flashover’ in office buildings, retail premises (assembly areas) and hotel bedrooms. According to Melinek (1993a), sprinklers would reduce the probability of area damage in industrial and commercial buildings up to 100 m^2 by a factor of 5. He also found that damage to the structure of a building would be reduced by a factor of 2.5.

Sprinklers have the potential to reduce the fatality rate per fire in multioccupancy dwellings to 0.0009 from the current level of 0.0122 (Ramachandran, 1993b). Comprehensive data from Australia and New Zealand covering 100 years up to 1986 show that, during that period, there were eleven deaths in 9,022 sprinklered fires (Marryatt, 1988). This represents a fatality rate of 0.0012 per fire, which is not much different from the figure of 0.0009 mentioned above. Hall (1992) quotes the results of an analysis of the likely effects of sprinklers on deaths in one- and two-family house fires, carried out by the National Institute of Standards and Technology, USA. This was based on laboratory test data, estimates from fire researchers and available statistics on the likelihood of certain scenarios and the life threat posed by them. According to this study, a 63–69 per cent reduction in death rates per thousand fires can be achieved if sprinklers are installed in dwellings that either do or do not already have smoke detectors.

Melinek (1993b) has estimated the number of casualties that would occur if all fires were sprinklered, assuming that the average number of casualties per fire depends only on the extent of its spread, and that the proportion of fires spreading, if all the buildings had sprinklers, would be equal to that in buildings with existing sprinklers. He has shown that the number of fatal casualties would be reduced by about half while the number of non-fatal casualties would be reduced by about 20 per cent.

Costs of installing sprinklers

The amount of internal water supply equipment will depend on:

- water pressure at building main;
- size and height of building;
- degree of fire hazard in the building;
- extensiveness of the sprinkler system;
- size of sprinkler pipes.

The more equipment necessary to support a sufficient water supply, the greater the cost. A special cost is a dual water meter, which is required for commercial buildings in some cities such as New York. It is dual in the sense that it meters both small flows (either domestic use or only a few sprinkler heads open) or large flows, when many heads operate. The cost of the meter varies widely depending on size of the sprinkler system. The water charges involved in most sprinklered incidents are likely to be small when compared to the meter costs.

Generally, a network of pipes is installed just below or above the ceiling on each floor of a building, with the sprinkler heads spaced a prescribed distance apart on the horizontal pipes. Sometimes, in higher-hazard buildings, a network both below and above the ceiling is required. Pipes vary in size according to the material of the pipe, the number of sprinkler heads and the size and height of the spaces. Concealed pipes are more expensive than exposed ones. This cost factor is especially important for installations in existing buildings.

Heat from a fire triggers the sprinklers to release water, and water will continue to be released until the main valve is turned off. Special heads can be obtained which automatically stop releasing water when the heat falls below the temperature set as the threshold. This feature is quite costly.

The frequency of the sprinklers along the pipes is an important cost factor; the greater the coverage per sprinkler, the cheaper the system. The recommended maximum coverage per sprinkler head is 12 m^2 for light and ordinary hazard occupancies, 9.3 m^2 for high-piled storage, and 8.4 m^2 for extra hazard occupancies. But the designer can select a design area and density appropriate for an occupancy according to area/density curves contained in, for example, the 1987 edition of NFPA13 (figure 2–2.1(b)) and the corresponding figures in NFPA231 and 231C (all of which are published by the National Fire Protection Association, USA). The designer may select a high density over a small area or a low density over a large area. In either event, it is expected that the fire will be controlled by the sprinklers within the design area without activating any additional sprinklers.

Rutstein and Cooke (1979) carried out a detailed analysis of the cost of a sprinkler system with the help of two major firms which manufacture and install them. They derived the following relationship between the cost (£) and the size (A) of the building expressed in floor area (m^2) (all costs at 1977 prices):

Extra low hazard:	Cost=500+0.77A
Ordinary hazard:	Cost=500+1.87A
Extra high hazard:	Cost=500+2.53A

The constant term represents the cost of the control valves, local alarm, etc., and the variable portion of the cost of the pipe work and sprinkler heads. These costs did not include connecting the system to a suitable water supply.

Rutstein and Cooke estimated the cost of water supply from figures made available to them for a number of new sprinkler installations at £1,500+1.3× number of heads, if no pumps were required. This cost was converted to a cost per m^2 of building floor space, using the Fire Offices' Committee standards for sprinkler spacings for the three types of hazards. For the case in which there were no pumps or extra water supplies, the authors estimated the total cost of sprinklers and the associated water supplies as:

Extra low hazard:	Cost=2,000+0.83A
Ordinary hazard:	Cost=2,000+1.98A
Extra high hazard:	Cost=2,000+2.67A

Pumps and additional water supplies may be required for extra high hazards or very tall buildings, so the cost of water supplies would increase considerably to £13,500+3.7×number of heads. For such buildings the authors estimated that the total costs=14,000+2.94A.

These costs are for the installation of sprinklers in buildings of a simple, open structure. If the building is divided into a number of small compartments or if the structure of the building is such that there are difficulties in installing the pipework, then the costs will be higher.

During the period from 1977 to 1995, in the UK retail prices for all items increased by a factor of 3 approximately. Hence, all the cost figures mentioned above should be multiplied by 3 to take account of inflation.

The annual maintenance cost of sprinklers is relatively small, about 1 per cent of the capital costs. Additional rates, i.e. property tax and water charges, must be paid but these are usually small costs.

In earlier studies, rough estimates of the cost of sprinklers were obtained in terms of cost per square foot of floor area. Burtner (1966), for example, estimated the capital cost to be \$0.32 per ft^2 for warehouses. This is equivalent to about £2.14 per m^2 at the current exchange rate of US\$ 1.6 to the £ sterling. Multiplying by 6 to account for inflation in the UK during 1966 to 1995, Burtner's estimate is equivalent to £13 per m^2 at 1995 prices. According to recent data obtained by the author, the cost of installing sprinklers in a department store with water supply from the mains varies from £13.6 to £17.4 per m^2 of floor area.

On behalf of the New York City Rand Institute, Wong (1973) carried out an interesting study of the costs of sprinklers and the savings in insurance premiums for commercial buildings in New York City. Including all components, Wong estimated the cost of sprinkler system per square foot for an existing building as \$0.90 for store, \$0.60–0.90 for loft building, \$0.50–0.60 for factory building, \$0.65–0.75 for warehouse, \$0.75–0.85 for garage and \$0.75–1.25 for office building. The figures were for a concealed system for store and office building and for an exposed system for the other four occupancies. The figures did not include any making good of floors, walls or ceilings which must be done as a result of the installation. The costs of sprinklers for fire-resistant structures did not differ much from those for non-fire-resistant structures. For the average size Manhattan building with five or six storeys a pump was necessary, at a cost of \$4,000. For taller buildings and for many six-storey buildings a gravity tank was necessary, at a cost of at least \$15,000.

Benefits of installing sprinklers

Let us now turn our attention to the benefits of installing sprinklers. Consider first a property owner who has certain benefits such as grants, tax allowances and reductions in fire insurance premiums. In the UK, for example, sprinklers are eligible for an investment grant of 25 per cent of the cost of sprinklers. If the building is in a 'developing area' the grant is 40 per cent. In the USA, instead of the grant, there is a federal income tax credit as a percentage of initial purchase and installation cost. In most countries, sprinklers are also eligible for tax relief on the balance of the cost after deducting the grant. In the USA, there is generally a municipal tax reduction in addition to a waiver of property tax.

Insurance companies offer substantial reductions on the premium for fire cover if a building is protected by sprinklers. Some UK sources put the savings in this respect for a building with high fire risk as much as 70 per cent of the premium charged for a building without sprinklers. This reduces to about 30 per cent if the building is of low fire risk. Higher percentage savings in insurance premiums have been quoted by Wong (1973) for certain types of commercial buildings in New York City; Burtner (1966) has quoted 75 per cent as the upper limit for the reduction in insurance rates for sprinkler installations. For a property owner or firm, benefits in terms of tax relief, grant and reduction in insurance premiums would usually be sufficient to recover the capital cost of sprinklers within a period considerably less than the life of a building or sprinkler system (see pp. 60–3). There is a possible further benefit in the event of a fire, due to a reduction in 'uninsured' loss if self-insurance has been accepted up to a stated level. Chapter 7 contains a detailed discussion of the determination of an economically optimum combination of fire protection and insurance.

The economic benefits mentioned above would be significant for a building with high levels of fire risk for which reductions in insurance premiums are generally considerable. In order to realise such benefits, the insurable value of the contents should be relatively high compared to that of the building. Size of building is another factor affecting the benefit-cost relationship. As discussed earlier in this section, the capital cost of a sprinkler system includes a fixed cost which is not dependent on the size of a building. Consequently, the cost per square metre decreases with increasing building size, although this parameter has been assumed to be a constant in some studies, as mentioned earlier. Fire insurance premiums are, however, usually calculated on the basis of premium per £100 of value. The benefit-cost ratio would, therefore, increase with building size. Installation of sprinklers may not be economically justifiable for small buildings or for buildings where the probabilities of fire occurrence and losses are low.

From this analysis it may be apparent that, at the level of the property owner or firm, the monetary loss due to a fire is not a major factor in assessing the economic desirability of installing sprinklers. This is because most of the insured part of the loss can be recovered from the insurer. Property owners' indifferent attitude towards fire loss may be one of the reasons for the low proportion of buildings with sprinklers in the UK (Ramachandran, 1970b). According to the later study by Rutstein and Cooke (1979), only 13 per cent of buildings in the UK had complete sprinkler coverage and a further 4 per cent partial coverage. Manufacturing industries such as textiles, paper, timber, chemicals, clothing and electrical engineering had the greatest number of sprinkler installations, covering a total of about 35 per cent of floor space.

Wong's (1973) study also revealed that commercial buildings in New York City were not sufficiently protected by sprinklers. He found that only 50 per cent of factories, 10 per cent of garages, 10 per cent of stores, 50 per cent of lofts, 10 per cent of offices and 30 per cent of warehouses were fully protected by sprinklers, covering about 3,000 out of a total possible 9,600 commercial buildings. Within each category, it was usually the more fire-resistant buildings than the non-fire-resistant buildings that were covered. Only about 5 per cent and 15 per cent of non-fire-resistant offices and stores, respectively, had sprinklers, although owners of many more of these types of buildings could have benefited financially from the installation of sprinklers. In some cases, e.g. warehouses and lofts, there were more sprinkler installations than would have been expected from insurance incentives alone.

Cost-benefit analysis: national level

From the national economic point of view, the probable reduction (gain) in fire loss due to sprinklers for any type of occupancy should be greater than the cost of sprinklers, with both gain and cost being expressed on an annual basis. This economic justification needs to be established if sprinklers are to be included as a mandatory requirement in a fire safety regulation or code. Benefits such as tax allowances and reductions in fire insurance premiums do not enter the national level of decision-making.

Installation of sprinklers would be economic in buildings larger than a threshold size. Rutstein and Cooke (1979) attempted to determine this size using the net present value technique. They assumed a discount rate of 10 per cent, a life of twenty years for a sprinkler system, and an annual cost of 1 per cent of the initial cost for maintaining it. According to Figure 5.3 reproduced from their study, the benefits of sprinklers would outweigh the costs in buildings larger than about 800 m^2 in manufacturing industries and 2,000 m^2 in shops. Sprinklers have no economic value in hospitals, offices, pubs, restaurants and schools. The results for storage buildings were somewhat inconclusive due to lack of data to allow the different types of storage premises to be identified and analysed separately; but in general, sprinklers can be economically justified in high-value storage buildings. Sprinklers appear to be of value in hotels larger than 1,600m^2.

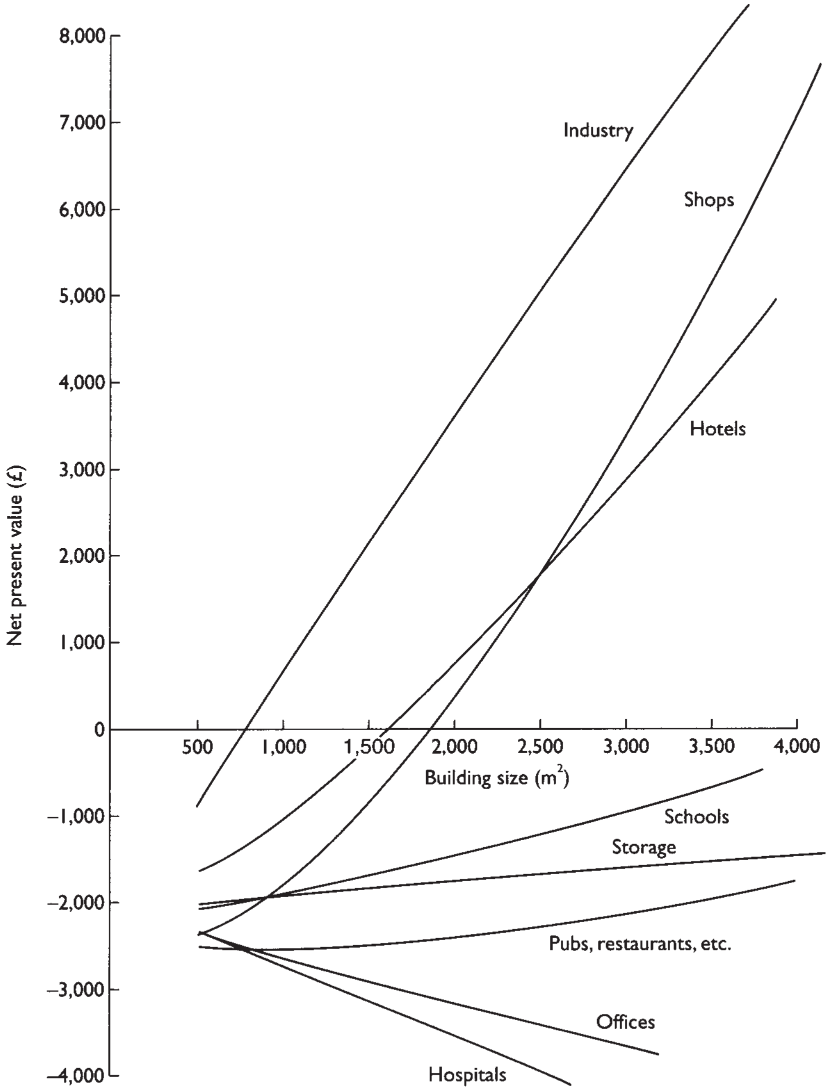


Figure 5.3 The value of sprinklers in various occupancies
Source: Rutstein and Cooke (1979)

Cost-benefit analysis: property owners

Rutstein and Cooke (1979) investigated the value of sprinklers for an industrial firm under the assumption that the property is fully insured against direct and consequential losses from fire. They used a discount rate of 15 per cent and a time horizon of ten years for the discounted cash flow calculations.

They also assumed that the annual costs of maintenance, additional rates and water rates would add up to 5 per cent of the initial costs. With the basic rate of tax of 52 per cent, they calculated that the net (discounted) cost after tax was equal to £0.48×(2,000+2B)×1.29 where B is the building size in terms of floor area (in m^2).

Against the cost component mentioned above, Rutstein and Cooke calculated benefits in terms of reductions in the insurance premium for direct loss and consequential loss. The premium reduction was estimated to be 4 (=2×2) times the expected reduction in direct losses if the total consequential loss premium was equal to the direct loss premium. The value of the premium reduction after tax was equal to 48 per cent of the actual premium reduction. Applying the net present value method, the authors concluded that only if an industrial building was larger than 600 m^2, was there a financial advantage to a firm in installing sprinklers. A higher threshold building size of 1,100m^2 was identified under an alternative assumption that the total consequential loss premium was equal to half the direct loss premium.

As discussed above, property owners are entitled to two major benefits when installing sprinklers in their properties: tax allowances and savings on insurance premiums. In the UK, tax allowances can be claimed on 25 per cent of the reducing capital cost involved in installing the sprinklers. In the first year, tax allowances are on 25 per cent of the total capital cost. In the second year, the allowances are applicable to 75 per cent of the total capital cost. In the third year, they are applicable to (1-0.25-0.25×0.75) or 56.25 per cent of the total capital cost, and so on. For industrial and commercial properties the corporate tax relief is at 33 per cent. Depending on the risk category, the insurance premium for a property with a full sprinkler system can be as low as 25 per cent of the premium for a property not protected by sprinklers, i.e. a saving of 75 per cent.

Consider, as an example, a major department store with total floor area 10,000 m^2. At an average rate of £1,500 per m^2 the property has been insured for £15 million to cover the building and the contents including stock. With water supply from the mains the capital cost for installing sprinklers in this property, including sprinkler tank and pumps, is £170,000; this is calculated at £17 per m^2 of floor area. Each sprinkler head would cover a floor area of 10 m^2. According to a leading commercial insurance company, the annual fire insurance premium for this property with high fire-resistant construction would be £0.30 per £100 of value at risk if sprinklers are not installed and £0.10 per £100 of value if equipped with sprinklers. The annual saving in insurance premium is hence £0.20 per £100 of value which, for the property valued at £15 million, is £30,000 per annum.

As mentioned earlier, for installing sprinklers tax allowances can be claimed on r (= 0.25), i.e. 25 per cent of the reducing capital (installation) cost denoted by C. The reduced capital cost is 0.75C in the second year, (0.75×0.75)C in the third year, (0.75×0.75×0.75)C in the fourth year, and so on. Generalising, the reduced capital cost in the nth year is $C(1-r)^{n-1}$. Over a period of n years the capital costs to which the percentage r is applied will add up to:

$$[1+(1-r)+(1-r)^2+(1-r)^3+\ldots(1-r)^{n-1}]C$$

$$=\left\{1+\frac{(1-r)\,[1-(1-r)^{n-1}]}{1-(1-r)}\right\}C$$

which, for a large value of n, is approximately equal to:

$$\left(1+\frac{(1-r)}{r}\right)C=\frac{C}{r}$$

Hence, over a period of, say, forty years, the total cost on which tax allowances can be claimed amounts to $[(C/r).r]$ or C, which is the installation cost. Hence, in forty years, the total benefit due to tax allowances is 33 per cent of C.

For the example discussed, over a period of forty years, tax allowances would total £56,100, which is 33 per cent of the capital cost of £170,000. The average annual benefit due to tax allowances is hence £1,403. Adding the annual saving in insurance premiums, the total benefit is £31,403 per annum. Over a forty-year period, at 10 per cent discount rate, the net present value of the total benefit is £306,970 (=31,403×9.7752). The benefit-cost ratio has, therefore, the value of 1.81 (=306,970/170,000). Following the alternative method, the annual amortised value of the capital cost is £17,391 (=170,000×0.1023) against which the annual benefit is £31,403. This method also gives a benefit-cost ratio of 1.81 (=31,403/17,391).

Calculations involved in a year-by-year analysis of discounted benefits are shown in Table 5.4. It may be seen that the net present value at the end of the seventh year exceeds the capital cost of £170,000. The NPV at the end of the sixth year is just below the capital cost. Hence, based only on tax allowances and savings in insurance premiums, the capital cost for installing sprinklers can be recovered in seven years. The recovery period would be about eight years if costs towards maintenance of the system and increases in general and water rates are taken into account.

The period for recovering the capital cost will be less than eight years if the value of the building and contents for material damage insurance exceeds £1,500 per m^2. This would certainly be true for major department stores. In such cases, the period for recovering the capital cost of sprinklers can be as low as three or four years. If the property is also insured for consequential losses (loss of profits, etc.), the rebate on fire insurance premiums for installing sprinklers would also be applicable to the value for which these losses are insured. In such a case the recovery period would be very short. It would be prudent to have insurance cover for consequential losses since a major fire can seriously disrupt or even bankrupt a business activity. However, the provision of adequate fire protection and insurance depends on the attitude of a property owner to fire risk apart from his or her assets and similar economic factors.

Due to inflation the value of a property would usually increase over a period of years. Consequently, the annual premium payable towards fire insurance would increase every year although the rate at which the premium is charged may not increase. Increasing annual premiums would produce increasing reductions in the premiums for installing sprinklers. The annual benefits in this respect would, therefore, increase gradually over a period. For example, the benefit from saving on insurance premiums shown in Table 5.4 would increase over the seven-year period although it has been kept at the constant level of £30,000.

Commissioned by British Automatic Sprinkler Association, Ove Arup & Partners (1995) investigated the costs and benefits of installing sprinklers in four types of buildings designed either in accordance with the sprinkler protection option offered by the England and Wales Building Regulations or alternatively without sprinkler protection. The building types were:

1 an eight-storey office building less than 30 metres high;
2 a similar office building with atrium;
3 a city-centre department store;
4 a large single-storey warehouse.

The analysis indicated that, for the first three types of buildings, installation of sprinklers would not increase the building costs significantly but lower insurance premiums would give a cost advantage for sprinklers. If the warehouse is built with sprinklers, the building costs would be higher but could be offset within five years by reduced insurance premiums.

Residential sprinklers

Ruegg and Fuller (1985) analysed the benefits and costs of fast-response residential sprinklers from the point of view of the owner of such a system. The authors selected nine hypothetical cases pertaining to new, single-family dwellings in the United States. The cases assumed an ‘average’ level of fire risk to the owner, as indicated by US fire statistics, and sprinkler effectiveness, based on the results of laboratory and field tests. The model used by the authors expressed the benefits of reduced fire losses in expected value dollars, reflecting the probability of fire occurring and of deaths, injuries and direct and indirect losses. Various components of system operating costs were also modelled as expected values, reflecting their functional relationship to the probability of fire occurring. The model also took account of savings in fire insurance costs, possible reductions in local property taxes and income tax adjustments. The net present value technique was adopted, with all benefits and costs expressed in dollars taken over the entire period during which the owner was expected to

Table 5.4 Sprinklers: net present value of benefits

Year	*Reducing capital cost (£)*	*Capital cost for tax allowance*[a] *(£)*	*Tax allowance*[b] *(£)*	*Saving in insurance premium (£)*	*Total benefit (£)*	*Discount factor*[c]	*Discounted benefit (£)*
1	170,000	42,500	14,025	30,000	44,025	0.9091	40,023
2	127,500	31,875	10,519	30,000	40,519	0.8264	33,485
3	95,625	23,906	7,889	30,000	37,889	0.7513	28,466
4	71,719	17,930	5,917	30,000	35,917	0.6830	24,531
5	53,789	13,447	4,438	30,000	34,438	0.6209	21,383
6	40,342	10,086	3,328	30,000	33,328	0.5645	18,814
7	30,256	7,564	2,496	30,000	32,496	0.5132	16,677
Net present value							183,379

Notes

[a] Capital cost on which tax allowance can be claimed is 25 per cent of reducing capital cost in the second column.

[b] Tax allowance is 33 per cent of the figure in the third column.

[c] The discount factor is based on 10 per cent discount rate.

have home sprinkler protection. The model assumed that homeowners are 'risk-neutral' although in actuality they exhibit varying degrees of risk preference (see Chapter 8).

Ruegg and Fuller drew several inferences based on their case studies. The following three results are of special interest:

1 the cost-effectiveness of residential sprinkler systems is improved if code changes allow the use of approved plastic pipe;
2 sprinkler systems are likely to be cost-effective for homeowners who are part of a community of sprinkler users;
3 sprinkler systems are likely to be cost-effective when used in situations where additional protection is needed, such as where the benefits of smoke detectors alone may not be attainable, e.g. when occupants are incapacitated and cannot respond to the alarm.

Several groups involved in the formulation of building regulations are now seeking public support for the mandatory adoption of sprinkler protection of all new buildings including dwellings. A few communities in the USA have adopted ordinances which promote the use of residential sprinklers: Scottsdale in Arizona, Montgomery County in Maryland, Greenburgh in New York and Cobb County in Georgia are leaders in this field. Fast-response sprinklers have been installed in apartment buildings in some cities, e.g. New York and Toronto.

Once a safety system is made mandatory, whether it offers a net benefit to the property owner is no longer of interest. The question to be addressed is whether it offers a net benefit to a community as a whole and to the citizens of an entire country. The problem is to establish the cost effectiveness of residential sprinklers from the national economic point of view. This problem was examined by Harmathy (1988) with reference to the economy of equipping all new single-family dwellings in the USA with fast-response sprinklers. He estimated the various components of the life cycle costs: the cost of the sprinkler system; the cost of its maintenance; and the cost of fires (loss of life, injury, property loss and indirect loss). These were estimated for two alternatives: not equipping any of and equipping all the newly built single-family dwellings with sprinkler systems. After carrying out a detailed analysis, Harmathy concluded that equipping single-family homes with sprinkler systems has no economic justification.

However, installation of sprinklers in flats and apartment buildings may have economic justification. They may be able to save some of the fatal and non-fatal casualties that occur in a flat or apartment in which a fire starts. Smoke and toxic gases pose a greater threat than fire (heat and flame) to the occupants of an apartment building who are in rooms or areas other than the one in which the fire starts. Sprinklers can enable these people to escape safely by extinguishing the fire or by retarding the rates of production and transport of smoke and toxic gases. This indirect benefit should also be considered in a cost-benefit analysis of installation of sprinklers in flats and apartment buildings.

Automatic detectors

Performance

Automatic detection systems are designed to detect heat and/or smoke from a fire in its early stages of growth, give an audible signal and call the fire brigade if directly connected to it. Such a signal would enable first-aid fire fighting to commence early so that the fire could be controlled quickly and prevented from causing extensive damage. Unlike sprinklers, which both detect fires and actively participate in fire fighting, detectors are passive and play no role in fire control. Custer and Bright (1974) have described in detail various types of detectors in a review of the state of the art in detector research. Problems concerned with the design of detection systems and fire alarm audibility have been discussed in detail by Schifiliti (1988).

Although it is possible to calculate from test results the response time of a heat/smoke detector under known conditions of ceiling height, detector spacing and fire/smoke intensity (total heat/smoke release rate), the time of operation of a detector head in an actual fire depends on many factors. The time when a fire product, heat, smoke or radiation, reaches a detector head depends on the rate of spread of the product, and this is controlled by the room/building configuration and environmental conditions. According to Bengtson and Laufke (1979–80), operating times for heat detectors range from 2 minutes in 'extra high hazard' occupancies (XHH) such as a plastic goods factory, to about 20 minutes for 'light hazard' (XLH) which includes flats and other residential premises. The operating times of smoke detectors range from 0.5 minutes (XHH) to 2.25 minutes (XLH) for wood materials and to 0.75 minutes (XLH) for polystyrene.

Statistical data are unavailable to evaluate the probability of a detector operating in a fire. Helzer *et al.* (1979), in assessing the economic value of different strategies for reducing upholstered-furniture fire losses, assumed that 80 per cent of detectors would respond effectively to a fire. Apart from other reasons, detectors would fail to operate if the heat or smoke generated is insufficient to activate the system.

According to *Fire Statistics United Kingdom 1991,* published by the Home Office, the proportion of fires discovered in less than five minutes in dwellings was 69 per cent for fires discovered by smoke alarms and 53 per cent for fires not discovered by smoke alarms or other detectors. In other occupied buildings, 78 per cent of fires that were detected by smoke alarms were detected in five minutes or less, compared to 45 per cent of other fires; this proportion includes fires discovered by other detectors.

Effectiveness: property protection

According to Baldwin (1971, 1972), the probability of fire spread or of a large fire could both be reduced by early detection or discovery. Furthermore, the probability of a fire which starts during the night becoming large could be reduced by two-thirds if detected promptly. Figures published in *Fire Statistics United Kingdom 1991* indicate that among fires in occupied buildings discovered by smoke alarms, 67 per cent of fires are confined to items first ignited and 0.2 per cent spread beyond the building. If smoke alarms are not installed in these buildings, only 36 per cent of fires would be confined to items first ignited and 2.5 per cent would spread beyond the building. For dwellings, the probability of a fire being confined to the item first ignited is 0.68 if the fire is discovered by a smoke alarm and 0.41 if not discovered by a smoke alarm or any other detector.

Cerberus, manufacturers of ionisation detectors, maintains a casebook of fires which have occurred in Switzerland in premises protected by their systems. Several items of information are recorded for each fire detected by the fire alarm system and which has led, or almost certainly would have led, to damage claimable from an insurance company. Fires not resulting in insurance claims are excluded from the calculation of the average insurance loss. The statistics include only fires which occurred in rooms monitored by automatic fire alarm systems. According to an analysis of these statistics for the period 1960–7, the average fire loss (premises and contents) in buildings in Switzerland monitored by Cerberus fire alarm systems was only one-third of the average loss in buildings without these systems.

Early detection of a fire through automatic detection systems would reduce the time period T_1 from ignition to discovery of a fire. This will also reduce the control time T_4 since a fire detected soon after ignition will be in an early growth stage when the fire brigade is called. Hence, the brigade can arrive at the scene when the fire size is small and control it quickly. Consequently, the total duration of burning, T, and area damage, A(T), will be reduced considerably. Represented algebraically, this is:

$$T_4 = a + b.T_A \tag{5.11}$$

where

$$T_A = T_1 + T_2 + T_3$$

$$T = T_A + T_4$$

T_A is the time period from ignition to the arrival of the brigade at the scene of a fire. T_2 is the time taken to call the fire brigade after discovering a fire and T_3 is the attendance or response time of the brigade.

The above equations were used in a pilot study (Ramachandran, 1980) on the economic value of automatic fire detectors in the textile industry. According to an exponential model used in this study:

$$A(T) = A(O) \exp(\theta T) \tag{5.12}$$

where A(T) is the area destroyed (in m^2) in T minutes since the start of the fire, A(O) the area initially ignited and θ the fire growth parameter. The following values were obtained for the parameters in equations (5.11) and (5.12):

θ = 0.0632
A(O) = 4.6852 m^2
a = 6.90
b = 0.83

The parameter *b* expresses the fact that the control time T_4 will increase by 0.83 minutes for every minute of delay in the arrival of the brigade at the fire scene. Table 5.5 shows the calculations involved in estimating the savings due to automatic detectors for the two cases: where the detector is not connected to the fire brigade and where it is. The savings are reductions in the damage in a fire not discovered at ignition. An average time of 1 minute was assumed for the operation of an automatic fire detector, 2.5 minutes for calling the fire brigade after the discovery of fire by human means, 15 seconds for the call time of a detector connected to the brigade and 5 minutes for the attendance time of the brigade.

The course of the fire is depicted in Figure 5.4, which shows the sizes of the fire at the times of fire brigade arrival and control for the three cases considered and the reduction in damage due to automatic detectors. In the absence of the fire brigade, a fire can burn for more than 54 minutes and damage exceed 140 m^2. The important time in a fire situation is the first five minutes when the occupants are attempting to escape. During this time, the heat of the fire will be low and hence the smoke temperature will be low and the buoyancy movement sluggish.

Table 5.5 is a general example illustrating the application of the exponential model of fire growth in assessing the economic value of detectors. The input figures in this table can be varied according to factors such as detector type, occupancy type, location of the nearest fire station and communication systems in a building. For example, instead of 1 minute, a different operating time based on experimental results may be assumed. The attendance time for a particular building may be less than or more than 5 minutes depending on the risk category assigned to it by the brigade. For a particular building, A(O) may be estimated by carrying out a fire load survey but the value of θ may remain the same for any risk category. With particular input values, a figure such as Figure 5.4 can be drawn for any building.

In a further application, Ramachandran and Chandler (1984a) applied the following expanded version of the exponential model:

$$A(T)=A(O)\exp[\theta_A T_A+\theta_B T_B] \tag{5.13}$$

where $T_B=T_4$. The parameter θ denoting the overall rate of fire growth has

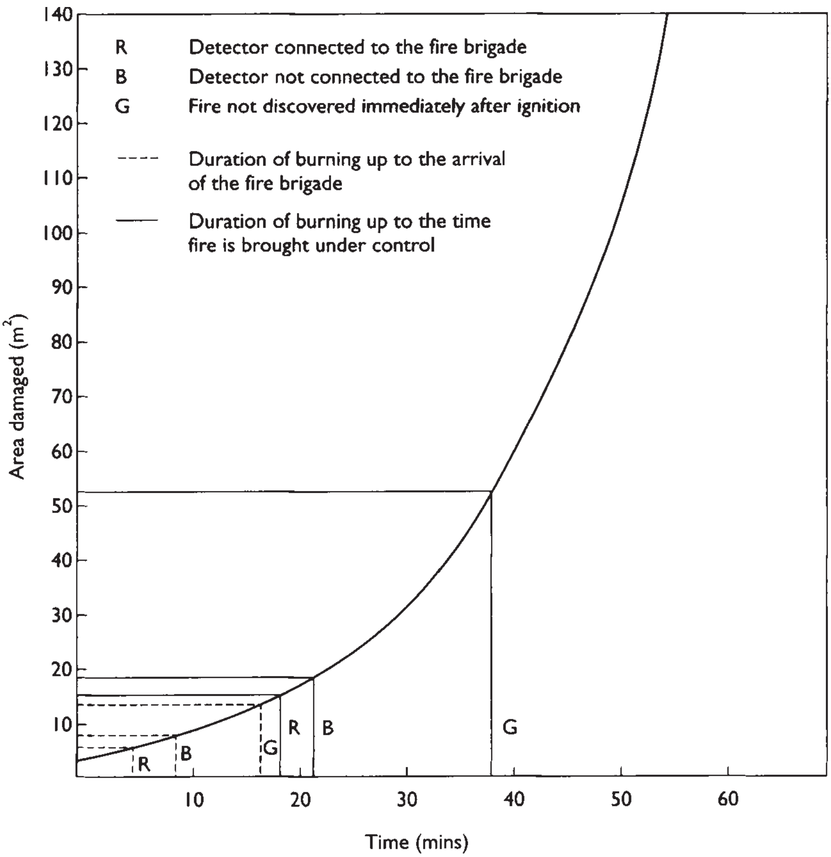


Figure 5.4 Average time and area damaged

been split into two parts: θ_A for the growth during the period T_A, and θ_B for growth during T_B. The relationship in equation (5.11) was also used with estimated values of *a* and *b*. A table similar to Table 5.5 was compiled for each group of industrial and commercial premises to estimate the savings due to automatic detectors connected to the fire brigade against a loss that might have been incurred if a fire was not detected or discovered at ignition. The results of this investigation revealed that detectors connected to the fire brigade only produce savings in fire damage marginally higher than savings due to detectors not connected to the brigade. The results also showed that economic benefits due to detectors would be particularly high for buildings with no provision for first-aid fire fighting.

Rutstein and Cooke (1979) used the following formula to estimate the average damage in an unprotected building:

Table 5.5 Savings due to detectors, textile industry, United Kingdom

Case	*Average time (minutes)*					*Average area damaged m^2*	*Direct loss per fire*[a] *(£)*	*Saving per fire (£)*
	Detection time (T_1)	*Call time (T_2)*	*Attendance time (T_3)*	*Control time (T_4)*	*Total duration of burning (T)*	*$A(T)$*	*L*	
Detector not connected to the fire brigade	1.00	2.50	5.00	13.96	22.46	19.37	4,358	7,448
Detector connected to the fire brigade	1.00	0.25	5.00	12.09	18.34	14.93	3,359	8,447
Fire not discovered at ignition	9.66	2.63	4.84	21.08	38.21	52.47	11,806	–

Notes

a At the rate of £225 per m^2 at 1978 prices.

$$p_1.C_1A^{ß}+p_2.C_2A^{ß}+p_3.C_3A^{ß} \quad (5.4)$$

where p_1 and p_2 were the proportions of fires which occurred when people were in the room of fire origin or the building (not room) of origin, respectively; p_3 was the proportion of fires which occurred when there were no people in the building. These proportions were according to the location of the nearest person. For a given value of ß the parameters $C_{1,}$ C_2 and C_3 were based on the expected damage estimated under certain assumptions. For industrial buildings, for example, values of 1.5, 1.9 and 3.9 were obtained for C_1, C_2 and C_3 respectively. For these buildings, with ß=0.45, p_1=0.55, p_2=0.18 and p_3=0.27, the value given by equation (5.14) may be seen to be $2.22A^{0.45}$

Assuming that the damage was reduced by 60 per cent in 'people in building' fires and by 55 per cent in 'people not in building' fires, the fire size in a protected building was estimated to be $1.44A^{0.45}$. This is equivalent to an overall reduction in damage of 35 per cent due to a detection system, whatever the size of the building in terms of floor area A (m^2). This reduction was applied to a local alarm system while a reduction of 45 per cent was estimated for a direct line system.

Effectiveness: life safety

While heat detectors are of economic value in reducing property damage in industrial and commercial buildings, smoke detectors are essential for dwellings, where most fire deaths occur. Smoke is the leading cause of death in fires occurring in these premises. Early detection of a fire would enable evacuation of a building to commence soon after the start of the ignition and would increase the chance of occupants reaching a safe place before escape routes became blocked due to heat, smoke or toxic gases. According to the parameter λ in Table 5.3, for every minute saved in evacuation time, the fatality rate per fire would be reduced by 0.0008 for single-occupancy dwellings and by 0.0006 for multiple-occupancy dwellings.

For fires in single- and multiple-occupancy dwellings in the UK, the average discovery times are 14 and 18 minutes, respectively. If automatic detectors reduced the discovery time to, say, 1 minute, there would be a saving of 13 and 17 minutes in the discovery time. Hence the fatality rate would be reduced by 0.01 for both the types of buildings according to the values of ? mentioned above. With about 55,000 fires per year in these buildings, 550 lives can be saved every year if in particular smoke detectors which operate within one minute are installed in these buildings. The reduction in life risk is sensitive to the value assigned to the operation time of a smoke detector. Proper maintenance of the system is necessary for its satisfactory operation in a fire.

According to a US study (Bukowski *et al.,* 1987), detectors would reduce the fatality rate per fire in single- and two-family dwellings by 0.0042 (from 0.0085 to 0.0043). In this connection it is worth mentioning that, since 1977, every dwelling unit owned by the Ontario Housing Corporation, Canada, has been protected by at least one smoke detector. The statistics produced by this organisation clearly indicate that smoke detectors save lives. McGuire and Ruscoe (1962) analysed data on 342 residential fires in Ontario and estimated that smoke detectors could have saved 41 per cent of the victims.

False alarms

In practice, any level of sensitivity to fire, in particular to signals of combustion, can be achieved with existing technology. However, if sensitivity is set at a high level, a detector may pick up signals given by spurious fires from sources such as cigarette smoke and cooking, which are normal activities. On the other hand, a low level of sensitivity can increase the risk of genuine fires being undetected.

False alarms are a nuisance and waste time and money, particularly to fire brigades whose response to genuine fires may be delayed due to unnecessary call-outs. Apart from malicious calls, occupiers of homes and fire brigades may be responding to signals from cooking smoke, bathroom water vapours, tobacco smoke and other non-threatening sources of air-suspended particulates. Other causes of false alarms include dust, debris and insects in the sensing chamber. Apart from high sensitivity levels, location, type of detector and lack of maintenance can also be reasons for unnecessary alarms.

Reasons for nuisance alarms arising from smoke detectors in homes have been identified by the National Smoke Detector Project carried out by the US Consumer Product Safety Commission (1993). As pointed out in this report, power sources for a high percentage of smoke detectors in homes are intentionally disconnected because of nuisance alarms. Repeated false alarms from an organisation may cause a fire brigade to cancel connection facilities, thus exposing the organisation to increased fire risks.

The most comprehensive British study of false alarm statistics was that of Fry and Eveleigh (1975) who analysed data collected in a special survey on detector actuations carried out by fire brigades. Based on 5,930 reports of fire signals in 1968, only 489 were to genuine fires. There was thus a ratio of 11:1 between false and genuine calls. The ratio was highest with combined heat and smoke detectors, at 23:1. The ratio was 11:1 for heat detectors and 14:1 for smoke detectors. Alarms activated by sprinkler systems showed a false to genuine ratio of 10:1, with a ratio of 4.4:1 for manually operated alarms. Mechanical and electrical faults, especially defective wiring or heads, accounted for 46 per cent of 5,441 false calls. Ambient conditions, especially extraneous heat and smoke, accounted for 26 per cent of false calls, and 16.5 per cent were due to communication faults. The analysis also classified false calls according to occupancy and time of day. According to Davies (1984), 95 systems of a Swiss manufacturer gave 85 genuine alarms as opposed to 1,329 false calls (a ratio of

16:1); of the latter, 1,194 were described as 'fire stimulating events', e.g. blow lamps in reasonably normal use.

Cost-benefit analysis

The cost of purchasing and installing a detector system depends on the type of the system—heat or smoke, the number of heads required, and the sophistication of the control system. The cost also depends on the structure and geometry of the building as this will determine the length of wiring required and the size of the area which can be covered by a detector head. In an uncompartmented building or area, damage in a fire can be reduced by increasing the number of heads (hence decreasing the spacing between two adjacent heads), but this increases the cost of the system. As in the case of sprinklers, the problem of determining an economically optimum spacing between detector heads does not appear to have been investigated so far in the fire science literature.

Several investigators have attempted to obtain rough estimates of the cost of detectors. Doctor *et al.* (1971), for example, evaluated that if 14 million detectors were installed in New York City, the investment cost per detector would be \$86 (at 1970 prices) with an annual operating cost of \$11.80. These costs include the detectors, transmission system, installation, maintenance, etc. The authors emphasised that their estimates were substantially biased upward. The prices of detectors have come down over the past two decades due to advances in manufacturing technology and increasing use of detectors particularly in dwellings, in addition to industrial and commercial buildings. Helzer *et al.* (1979) quoted an average purchase cost of \$20 and installation cost of \$2 based on a \$20 installation cost for house-wired detectors. The installation cost is zero for a battery-operated detector. An annual maintenance cost of \$1.80 per detector has been assumed by the authors based on battery replacement costs or an equivalent amount of electricity for house-current detectors. Specialised detector systems are required to protect industrial and commercial properties. Costs associated with these systems would be much higher than for those installed in dwellings.

Although the cost of smoke detectors is greater than the cost of heat detectors, this is compensated by the fact that smoke detectors cover a larger area. Accordingly, Rutstein and Cooke (1979) estimated the costs of detector heads and associated wiring as £1.1 per m^2 for both heat and smoke detectors. This variable cost would be about £10 per detector head if each head covered an area of 9 m^2 as generally recommended. An industrial or commercial building would require control equipment and an annunciator which, according to Rutstein and Cooke, would cost about £1,500. If the system is connected to a central alarm station there will be a connection charge of about £250. The initial costs of detector systems are thus, for a local alarm system, £1,500+1.1A; and for a direct line system, £1,750+1.1A, where A is the building size in terms of floor area (in m^2). If the detectors are maintained and serviced by an outside contractor, the annual maintenance cost would be composed of a fixed charge of £50 plus a variable charge of £1.50 per detector head or 0.025 times building size (m^2). For a system connected to a central alarm station an annual rental charge of £200 has been assumed. All the cost figures mentioned above are at 1977 prices.

In assessing the economic value of detectors to a firm, Rutstein and Cooke have assumed a tax rate of 52 per cent such that the net cost to the firm of installing and maintaining a detection system is 48 per cent of the sums paid out. The authors have also assumed that both the direct loss and consequential loss insurance premiums are reduced by 20 per cent if a direct line detector system is installed. Accordingly, they have used the following formula for calculating the reduction in insurance premium:

0.2×4×expected annual direct fire loss in an unprotected building

The expected annual fire loss is given by the product of annual probability of a fire starting and the probable area damage in a fire together with the loss per square metre. After tax the net benefit to the firm will be equal to 48 per cent of the gross saving. The net annual premium savings and maintenance cost have been discounted by the authors at 15 per cent over ten years.

Following the method and assumptions described above, Rutstein and Cooke estimated the economic values to a firm of installing direct line detectors in ‘typical’ industrial buildings of varying sizes. They estimated net present values (£) of -1,280, -870, -470 and -85 respectively for buildings of sizes 500, 1,500, 2,500 and 3,500 (m^2). Based on these results the authors concluded that only in very large industrial buildings, larger than 4,000 m^2, would there be a financial incentive to firms to install direct-line detectors connected to the local fire brigade. Detectors would perhaps have economic justification only for certain parts of an industrial or commercial building, particularly in areas such as those used for storage.

For the four building sizes mentioned above, the authors assessed the value of detectors to the national economy, obtaining net present values (£) of -3,000, -1,300, 400 and 2,060. In calculating these values, a 45 per cent reduction in fire damage due to detectors has been assumed. These results suggest that, in the national interest, buildings larger than 2,000 m^2 but smaller than 4,000 m^2 should also be equipped with detectors and that a building of this intermediate size in a development area in the UK should attract a tax-free grant of 20 per cent of the capital cost of a detector system. This additional benefit would provide an economic justification to a firm to install a direct-line detector system in a building larger than 2,000 m^2 in a development area.

Only damage to property has been considered in the study discussed above, which is concerned with industrial and commercial buildings. Loss of life is an important factor in assessing the economic value of installing smoke detectors in particular in dwellings. This problem has been investigated at the national level by Helzer *et al.* (1979). These authors assumed that, if smoke detectors were made a mandatory requirement for all residences, 90 per cent of these buildings would be protected by the system by 1985. Thus for the years 1985 and beyond only operating and replacement costs would be required. The authors also assumed that most of the detectors would be battery-operated with no associated installation cost. They assigned a nominal value of $300,000 for each life for computing life and property losses.

Under the assumptions mentioned above, Helzer *et al.* evaluated three alternative strategies on a present value basis by discounting at 8 per cent future expected losses and costs for each of the years from 1977 to 2010. The sum of these present values for cost plus loss for the thirty-four years, was estimated to be $6.33 billion for the no-action alternative, $5.95 billion for the detector alternative and $5.96 billion for the proposed standard for upholstered furniture. On the basis of these results the authors concluded that the most attractive of the three alternatives was either the proposed standard or the smoke detector. A combination of these two strategies was found to be slightly more attractive than either strategy alone.

The present cost of purchasing a battery-operated detector for a residential building is small, about £10 in UK and $20 in the USA; the annual maintenance or battery replacement cost is negligible. Hence, from a national point of view, it may be worthwhile to install smoke detectors in particular free of cost in all dwellings. McGuire and Ruscoe (1962) analysed data on 342 residential fires in Ontario and estimated that smoke detectors could have saved 41 per cent of the victims. Statistics produced by the Ontario Housing Corporation, which, we noted above, protects every dwelling with at least one smoke detector, clearly indicate that smoke detectors save lives. Their installation in residential buildings is mandatory in most states in the USA.

Smoke detectors may not reduce property damage significantly, according to Hygge (1986) who analysed the effects of free distribution of these devices to all the policy holders of an insurance company in Sweden. It should be emphasised that automatic detectors are passive devices have no active role in fire fighting. They only reduce damage to life and property indirectly by enabling fire fighting to begin when a fire is at a very early stage. The effectiveness of automatic detectors can be fully realised only if early detection of a fire is followed quickly by rapid and successful evacuation of a building and fire fighting by first aid means, by sprinklers (if installed) or by the fire brigade.

If an automatic detector system is installed in an industrial or commercial property, insurance companies currently appear to give a reduction in fire insurance premiums of only about 5 per cent if the system is not connected to the local fire brigade and 10 per cent if connected. Tax relief can be claimed on the capital cost as in the case of sprinklers. Installation of detectors in small industrial or commercial buildings may not have sufficient economic justification except in storage areas where detection by people is generally absent; but it would be economically worthwhile in buildings such as hotels where a large number of people are at risk.

As mentioned earlier, the costs of installing a smoke detector in a dwelling are quite low. Hence, in this case, it is not necessary to establish any economic justification from the property owner's point of view, particularly because of the protection afforded to occupants although detectors may provide some level of property protection as well.

Addressable fire detection systems

Up until the early 1980s, when new-technology addressable systems (see below) were introduced, all automatic fire detection systems were of the conventional type, such as heat, smoke or ionisation detectors. These systems employed similar methods of transmitting signals between fire detectors and control equipment. Each conventional detector is a 'two-state' device in the sense that it is in either the normal state or the fire state. When one of the devices in a zone operates, the only information it gives is that there is a fire condition somewhere within that zone; the control panel cannot distinguish between one device and another device on the same zone operating, as the effect will be exactly the same.

With addressable systems, signals from each detector are individually identified at the control panel. Within the software of such a system, the device identity can be converted into a pre-programmed location which is then displayed, for example, on an LCD or vacuum fluorescent display. The majority of installed addressable systems are of the analogue type in which the detectors transmit to the control equipment a signal level representing the amount of heat, smoke or flame that is being sensed. A 'pre-alarm warning' is given if the signal exceeds a certain threshold level and a 'fire warning' if the signal exceeds a higher threshold level. At a very low threshold level, a fault signal may be given to indicate that the detector has become very insensitive. Some of the analogue addressable systems include sophisticated logging facilities.

The reliability of an addressable system in detecting a fire and not triggering a false alarm can be expected to be considerably higher than the reliability of a conventional system. Hence, such a system can drastically reduce life risk and the costs incurred in attending false alarms. Due to these enhanced benefits, an addressable system can be a cost-effective fire protection option, particularly for large buildings such as hospitals and hotels, although the cost of installing and maintaining such a system will be higher than the cost of a conventional system.

Fire brigade activities

Fire cover

The fire service in any country provides protection to life and property in the event of a fire occurring. The level of protection provided by a fire brigade or department depends on the time it takes to respond to a call, reach a fire scene and control the fire. This level, termed 'fire cover', therefore depends on the number, siting and strength of fire stations in terms of manpower and equipment (fire engines, pumps, ladders, etc.).

The standards of fire cover prescribed in terms of, say, time and equipment for first and subsequent attendance for various risk categories impose constraints on the planning of fire cover but do not provide a unique solution to the problem. Within the standards, many different combinations or systems of arrangement of stations and allocation of equipment are possible. The problem is to determine a system which minimises the total of all costs involved. The costs are: the fire stations; the men and equipment; and the loss of property and life caused by fires. The number of additional lives that could be saved by a faster brigade response is likely to be small and hence the optimal fire cover may not be sensitive to the monetary value of life assumed in the calculation.

Walker *et al.* (1979) have estimated some cost figures involved in the operation of a fire department. According to these authors, in most paid fire departments in the USA, manpower costs amount to more than 90 per cent of the total budget. To supply staff and operate one fire company—keeping the unit ready and running twenty-four hours a day, seven days a week—could cost $250,000–750,000 per year at 1979 prices, depending on manning levels and salaries. The authors considered, as an example, a fire fighting unit staffed by four fire fighters and an officer. They took into account paid vacation, holidays, sick leave, etc., and estimated the effective time per week on duty as 43.5 hours. Hence, 3.9 (=168/43.5) fire fighters should be actually on the payroll to fill a single full-time position. Two units each with five fire fighters on the appliance would thus require a total of 39 fire fighters on the payroll.

In many US jurisdictions, at 1979 prices the average total cost of a fire fighter (including officers and allocated support and administrative personnel) is roughly $20,000 per year. This includes salary, pension contributions and fringe benefits such as insurance. Hence, the personnel cost of a fire fighter unit staffed full time would be $390,000 (=20,000×19.5) per year. A fire station housing one such unit might cost $400,000 and last forty years. Amortised at 7 per cent interest, with normal maintenance, the annual cost of the unit is about $45,000. The fire apparatus and associated equipment might cost about $70,000 and have a fifteen-year life. Amortised, with maintenance, they would cost roughly $10,000 per year. Together, the fire house, apparatus and equipment, with maintenance, would cost about $55,000 per year. This figure is 12.4 per cent of the total cost ($445,000) of the unit if personnel costs $20,000 per individual per year, and 8.6 per cent of $640,000 if personnel costs $30,000 per individual per year.

The example described above provides an outline of the various components of the cost of operation of a fire fighting unit or station. A similar break-down of this cost is available for public fire brigades in the UK and for fire services in some other countries. In some areas in any country there may be some flexibility as major hazards change periodically (e.g. in office buildings at night and weekends), permitting modification of coverage at those times instead of full-time coverage. Also, alarm rates may be high enough to warrant additional units on duty at peak times.

Manning levels vary considerably from locality to locality, even on similar units handling similar hazards. Manning needs of any unit clearly depend on fire fighting tactics adopted, fire problems or risks faced by the unit (industrial, residential, etc.), fire fighting technology available, skills and experience of the fire fighters and the organisational and response strategies followed. Major opportunities for flexibility clearly exist, but they need to be considered in the context of the overall deployment of a fire department's resources. Walker *et al.* (1979) have discussed several approaches which can possibly improve the productivity of the fire fighting resources.

The performance of a fire service must be assessed by three criteria that reflect the essential social values underlying the service: effectiveness, efficiency and equity. Effectiveness is concerned with the provision of protection from fires while efficiency is concerned with the economical use of available or scarce resources. A fire department may be effective in providing excellent fire protection without being efficient; another department may be efficient, i.e. economical but not highly effective. The third criterion, equity is concerned with how fairly costs and benefits are distributed. For example, to locate fire stations to minimise the response time to actual fires, there would be a tendency to group them in the high alarm rate areas. This allocation would reduce coverage in the areas that call for service less often. Such a distribution might be considered inequitable or unfair to the people who have fewer fires. Equity is often called the 'political' criterion; it concerns the relationship between those who pay and those who benefit. Hence, the results of a benefit-cost analysis of the performance of a fire service may or may not be acceptable for political or social reasons.

The community served by a fire department is mainly concerned with the effectiveness of the department in reducing damage to life and property caused by fires. Assessing the effectiveness of a fire brigade is a formidable task. Three general approaches to this problem can be distinguished: engineering models; 'quantified intuition' models; and statistical models. The first is concerned with fire growth and spread in particular buildings, with factors representing fire department activities. These models are extremely complex and cannot be easily applied to a cost-benefit analysis of fire brigade activities. The second represents systematically the intuitive experience and feelings of senior fire officers. These models are useful in identifying important factors but their results cannot be correlated with property damage and life loss. The third is concerned with the statistical analysis of data on losses in and response times to actual fires which occurred in the past. The data are fitted to 'reasonable' mathematical representations of the major effects involved. This approach is best exemplified by studies carried out by the Scientific Advisory Branch of the British Home

Office, which has derived curves for loss versus response time for a number of occupancy types, using aggregate data.

Rutstein (1975) reviewed these relationships and other methods with reference to the problem of planning fire cover using cost-effectiveness criteria. Rutstein defined as optimal the solution for which the total costs are the minimum overall possible numbers of stations, station sites and allocations of appliances. The total cost included the cost of the fire stations, men and equipment and the expected property loss defined in terms of first attendance times. Life loss was not considered, for the reason stated at the beginning of this section.

Suppose, for example, that the nearest station to location *j* is five minutes away and has two appliances, the next station ten minutes away and has one, and the next fifteen minutes away with three. Based on a queuing theory model, the probabilities of 0, 1, 2 appliances being available at the nearest station are, say, 0.05, 0.10, 0.85. When none is available at the nearest station, the arrival times of the first attendance of three appliances would be 10, 15 and 15 minutes with a further appliance arriving at, say, 25 minutes. In this case the loss has been estimated to be £16,250. When one appliance is available at the nearest station, the arrival times would be 5, 10,15 and 20 minutes with an expected loss of £10,750. If two are available at the nearest station, the arrival times would be 5, 5, 10 and 20 minutes with an expected loss of £10,000. Weighting by the probabilities, the expected loss per fire at location *j* would therefore be:

$$(0.05\times 16{,}250)+(0.1\times 10{,}750)+(0.85\times 10{,}000)=£10{,}387$$

The expected total fire loss is obtained by summing over all fires, all fire types and all fire locations.

Using the method described above, Rutstein (1975) found that siting and manning procedures are separately optimal but this does not guarantee that an overall optimal solution will be obtained by using the two procedures sequentially. When station sites are being chosen in the siting programme, all stations have been assumed to have the same fixed costs, whereas the 'true' station costs will depend on the number of appliances at that station and any effect that station has on the number required at neighbouring stations. The 'true' fire losses will also be affected by the number of appliances at each station. However, the use of a series of siting solutions as the bases for manning studies should provide a good overall solution. It should only be necessary to look at a few different siting solutions with numbers of stations close to the optimal number as indicated by the siting routine.

The siting and manning procedures described by Rutstein were applied to several brigade areas which appear to have produced generally reasonable and sensible results. In some cases, however, the resulting curves of total costs versus number of units were surprisingly flat, revealing thus insensitivity to the number of units and stations over rather a wide range. Although this result may be somewhat unrealistic, it does seem to show that the best allocations of men and equipment are not extremely sensitive to the exact numbers used in the response time versus loss relations or to their exact forms. It should, however, be pointed out that the variation in time before detection and reporting is likely to mask the effects of the much smaller variations in response times. The loss figures will in any case have to be adjusted for specific buildings (skyscrapers versus shacks) to reflect relative variations. The Fire Cover Model of the UK Home Office does not consider explicitly the interactions between fire brigade and fire protection measures such as detectors, sprinklers and building design.

In further studies described by Dessent and Harwood (1986), the UK Fire Cover Model has been used to assess the resource implications of alternative standards of fire cover. One alternative was concerned with, for example, the dispatch of a second appliance to arrive within ten minutes to C risk areas—built-up areas of towns. This was found to require further appliances (and men) in some areas and to involve a considerable station building programme at extra costs which could not be economically justified. Another alternative related to a reduction from three to two appliances in A risk areas, comprising commercial and industrial city complexes. This would not mean that current resources would result in over-provision since, in general, the third appliance had a first attendance role in an adjacent station's area. The model showed that the resource implications of different fire cover standards varied from brigade to brigade depending on two major factors: the 'busyness factor' and the 'geographical factor'. The former reflects the rate of incidents while the latter pertains to road configurations, risk map definition and location of station and appliance.

Fire prevention publicity

In most countries, fire prevention activities are mainly carried out by fire brigades or departments, apart from some efforts by fire protection associations and insurance organisations. These activities aimed at reducing the number of fires are of two basic types: public education and inspection. Efforts under the first type include visits to schools and community groups, posters, television advertising, fire prevention weeks and other publicity campaigns. The second type is concerned with the inspection of hazardous equipment and structures.

Evaluating the effectiveness of public education in preventing fires is difficult since data collected for these activities are usually not amenable to proper statistical analysis. The available evidence suggests that efforts directed at a particular type of fire (e.g. grease or chip pan fires) are most likely to be successful. See, for example, the fire prevention campaigns in Kileen, Texas (US National Fire Prevention and Control Administration, 1975). Several public education programmes are discussed by Swersey *et al.* (1975).

Three examples of fire prevention campaigns carried out by the fire brigades in the UK have been analysed by Chambers (1969, 1970a, 1970b). The first deals with the effects of house-to-house visits in Worcester and the county of Worcestershire during the eleven-year period 1956–67. It was estimated that at the end of this period fires were occurring in dwellings at two-thirds of the expected national frequency. The second study was concerned with a short campaign for chip-pan safety in Exeter. The analysis showed a downward trend in fire frequency for about eighteen months, which was just on the borderline of statistical significance. The third study, concerned with an intensive publicity campaign in Leicester, did not reveal any significant effects.

The UK Home Office sponsored a television publicity campaign in 1976–7 on the subject of the prevention and extinction of chip-pan fires. One county (Yorkshire) had a high level of television advertising while a second (Lancashire) had a lower level of advertising. A third region (West Midlands) had no advertising and acted as a control area. One brigade in each region also organised further local publicity, including house-to-house visits giving away fire warning stickers, the use of local radio and press, and interviews on local television and radio.

The results of the television campaign mentioned above were analysed by Rutstein and Butler (1977). The problem considered was the effect of publicity on the number of chip-pan fires reported to the brigade. The past pattern of fire incidence in each brigade area was examined and a forecast made of the future number of fires, assuming a continuation of this established pattern. A seasonal effect was incorporated in the forecast. In all those brigade areas where there had been television publicity, the actual fire incidence clearly fell below the forecast levels. The fire incidence in areas which had brigade support activity was not significantly different from those areas in which this activity had not been carried out. In terms of change of attitude, the extinction message came across more strongly than the prevention message.

Following the success of the chip-pan fire publicity campaign, the UK Home Office sponsored a similar campaign in 1978 in the Yorkshire television area on the subject of space-heater fires. Advertisements were shown once a day during this period. This level of advertising was chosen since the earlier chip-pan study had shown that a higher level of advertising did not produce any significant increase in the effect on attitudes or behaviour. A control area was introduced in order to provide a check against extraneous factors which might affect the number of space-heater fires during the period of study. The campaign concentrated on the dangers of misusing in particular mobile radiant electric space heaters in the home. The emphasis was on keeping heaters at a safe distance from combustible materials.

To monitor the effects of the campaign, the number and severity of all domestic fires caused by space heaters in general and by electric radiant space heaters in particular were recorded before and after the commencement of the campaign. For this purpose, data for the period 1968–77 extracted from the annual fire statistics were analysed by Gilbert (1979). In order to remove the effects due to temperature, Gilbert considered the number of fires in each year and estimated the relationship between the annual number of fires per million population and the mean annual air temperature. In order to see the time trend clearly, the incidence of space-heater fires during 1968–77 was corrected to a constant annual temperature of 9.9°C.

Data corrected for temperature revealed that the incidence of space-heater fires in dwellings had been declining in much the same way as for spaceheater fires generally. One of the reasons for this declining trend could be the increasing use of central heating. A comparison of the incidence of space-heater fires in the control and campaign areas did not show any significant change which could be attributed to the campaign. The normal seasonal variation in both areas would have masked any such difference which might have existed. In order to detect this difference, Gilbert carried out a further analysis which also indicated no discernible reduction in the number of space-heater fires which could be attributed to the campaign. In a further analysis, the precampaign relationships were used to predict the number of fires during the post-campaign period. A comparison of the actual and the predicted number of fires did not reveal any significant change due to the campaign. Also, the analysis could detect no changes attributable to the campaign in:

1 the type of space-heater fires: type of appliance involved (electric, gas, etc.), cause of fire (such as appliance fault, drying clothes) and material ignited (clothing, bedding, etc.);
2 the severity of space-heater fires in terms of the method adopted by the brigade to extinguish the fire.

Regulations and related inspections of gasoline distribution systems have contributed to limiting the number of fires in that area. Fire departments are actively involved in inspecting hazardous products and premises. There is widespread agreement that such programmes are necessary and effective although the particular level of effectiveness may be difficult to measure by analysing available data. Schaenman *et al.* (1976) suggested an approach to measuring the effectiveness of inspection programmes that would relate fire occurrence to inspection effort. It would measure the number of fires that were relatively preventable by inspections per 1,000 occupancies. Hall *et al.* (1978) applied the approach using data from seventeen cities and one county. They found that ‘cities that annually inspect all or nearly all inspectable properties appear to have substantially lower fire rates than do other cities’.

At the national level, publicity, education and inspection programmes are only carried out periodically and hence the cost of each programme can be estimated separately and easily with reasonable accuracy. For example, a fire department undertakes fire prevention campaigns as a secondary part of its main activity concerned with fire fighting. Hence, these campaigns are usually extra duties when fire fighters are not likely to be busy responding to fire incidents. For the reasons mentioned above, it may be sufficient to consider only the actual cost of running a fire prevention campaign without including any costs associated with the buildings and fire fighting equipment invested in a fire station. An accountant may, however, have a different view of the allocation of costs for various activities.

It may be comparatively easy to estimate the cost of a fire prevention programme but it is a formidable task to assess the benefit due to such a programme in monetary terms. The benefit generally lasts only for a short period unless this activity is carried out frequently. A fire prevention programme is usually not designed to permit proper statistical evaluation. The available evidence suggests that efforts directed at a particular type of fire (e.g. grease or chip-pan fires) are most likely to be successful. However, benefit-cost investigations on this aspect of the fire problem are sparse.

Rutstein and Butler (1977) met with some success in evaluating the cost effectiveness of the chip-pan fire publicity campaign discussed earlier. The equivalent cost of a national campaign at the same level of intensity as that in the Lancashire region (the lower television advertising level) was estimated to be about £650,000 at 1976 prices. The average damage in a chip-pan fire was of the order of £250 at 1976 prices. This figure represented the cost of making good any structural damage and replacing damaged contents, after allowing for the depreciation of equipment and contents.

With about 14,000 domestic chip-pan fires per year in the UK, it was estimated that, as a result of a publicity campaign, the number of such fires to which fire brigades were called would be reduced by 22 per cent over a year. The reduction in property damage would, therefore, be £770,000 (=0.22×14,000 ×250). This figure was likely to be an underestimate of the total reduction in property loss for the first year of the campaign since a large number of chippan fires were not reported to fire brigades. The possible, although much smaller, benefits beyond the first year were not evaluated. The benefit of £770,000 in the reduction of property damage would certainly have exceeded the cost of £650,000.

The publicity campaign mentioned above did not appear to produce any significant change in the proportion of chip-pan fires that resulted in injury. The ratio of the number of casualties to the number of chip-pan fires was 0.066. The corresponding reduction in the number of casualties over a year was estimated as 203 (=0.22×14,000×0.066). The reduction in the number of fatalities would be three or four, assuming that the ratio of fatal to non-fatal casualties remained unchanged. No attempt was made to assign monetary values to fatal and non-fatal injuries.

A reduction of 3,080 (=0.22×14,000) per year in the number of chip-pan fires attended by brigades would result in a saving in fuel costs and in wear and tear on equipment and appliances. This reduction only represented 1 per cent of the total number of fires attended by the brigades and hence there would be no other direct savings in brigade costs. However, a reduction in chip-pan fires attended will result in a slight improvement in the brigades' availability for other emergency calls, with consequent slight savings. The savings in brigade costs would be small and hence were not estimated. The chip-pan publicity may increase fire awareness more generally and have spill-over effects for other types of fires. It may also have longer-term effects on chip-pan and other types of domestic fires.

Other fire protection measures

There are other fire protection devices which are designed to provide safety for property and/or life. These include mainly fire doors, portable fire extinguishers and ventilation systems. Due to lack of sufficient data it is difficult to carry out a cost-benefit analysis of any of these devices. However, it would be worthwhile to discuss briefly in this section the effectiveness of these devices, which some studies have attempted to evaluate.

Fire doors

Doors of suitable construction can be said to be one of the most important elements in a building to save lives if a fire should occur. Fire safety codes for means of escape depend upon the fire/smoke-check door as an integral part of the escape plan. Without such doors safety from fire in any building, even a single-storey building, becomes difficult and often necessitates unorthodox and undesirable means of escape.

Even if fire doors are of adequate fire resistance and are strategically sited in a building, they are of no value if they are open when a fire occurs. Even doors for amenity purposes may, if closed, tend to delay the development and spread of fire. Some doors, e.g. the bedroom doors of parents in a dwelling, may have to be left open. This enables early discovery of a fire in the kitchen or sitting room in the absence of a smoke detector. It is arguable whether amenity doors should be shut or kept open but fire/smoke-check doors used for means of escape purposes should be kept closed if they are to be effective. Doors designed for security purposes are rarely used by large numbers of people. The exception to this is, of course, the entrance doors to flats and maisonettes.

To ascertain how serious the problem of open doors in buildings really is, the UK Fire Research Station carried out an analysis of the use of fire-check doors based on information collected by fire brigades during normal inspection visits. The results of the analysis are contained in Langdon-Thomas and Ramachandran (1970). The authors found that the frequencies of doors propped open at the time of fire brigade visits ranged from 5 per cent in assembly buildings to 39 per cent in institutional buildings. In storage premises the frequency was as high as 37 per cent. In the majority of these instances it was claimed that the doors were intended to be shut at night or in an emergency. In 1–7 per cent of cases the doors were found open but obstructed so that they could not be closed.

Langdon-Thomas and Ramachandran also found that the display of a notice asking people to keep a fire door closed, while not completely effective, generally reduced the number of doors propped open. In order to achieve the closing of the door some type of mechanical closing device may be adopted: single or double action floor springs, overhead door closures and spring hinges. The authors found that, in regard to closing action, the third type was the most satisfactory automatic closing device; 63 per cent of overhead door closures and 35 per cent of the floor spring type had defective closing action. The authors also suggested the use of a smoke detector coupled with a door retainer.

Fire doors in industrial buildings, if kept closed, can be expected to reduce property damage in a fire. In order to estimate this reduction (saving), Ramachandran (1968) analysed a small sample of data on large fires which were available for the years 1965 and 1966. Loss in each of these seventeen fires was £10,000 or more. In five, the doors were in the open position, including a very large fire in a paper tube factory, with a loss exceeding £1 million, in which a number of fire doors were left open. Excluding this fire, the average loss in the remaining four fires was £135,000. In twelve fires the doors were closed and performed satisfactorily so that the average loss was only £106,000 even if a very large fire with a loss of £450,000 was included. It was, therefore, estimated that keeping the fire doors closed in industrial buildings could save at least £30,000 per fire (at 1965 prices). In two other cases, closed doors contained the fire: a fire with a loss of £10,000 in a retail grocers and provision merchants and another with a loss of £75,000 in a cinema and bingo hall.

Fire extinguishers

In some fires the occupants of a building use a number of first-aid methods to attack the fires before the arrival of the brigade. Portable fire extinguishers constitute one such method apart from sundry means such as buckets of water or sand, use of a garden hose and smothering. Extinguishers available on the market are mainly of the following types: dry powder, water, carbon tetrachloride, foam and other vaporising liquids, and carbon dioxide.

Some fires are extinguished or controlled by first-aid means. An initial attack by occupants does reduce the severity of a fire but there have been some instances in which such an action has led to fatal or non-fatal casualties. In industrial and commercial buildings early detection followed by quick action to extinguish the fires by sprinklers, extinguishers or other means reduces the damage but this saving would be higher if first-aid fire fighting were not undertaken. This implies that, if a fire is discovered early by human or automatic detection devices, priority should be given to calling the fire brigade quickly rather than launching an attack by first-aid means.

While early detection followed by a call to the fire brigade appears to be a better option than first-aid fire fighting, some doubts about the effectiveness of fire extinguishers have also been expressed by some research studies in the UK. An analysis of fire brigade data by Ramachandran *et al.* (1972) disclosed that extinguishers were unlikely to be as effective as sundry means in attacking dwelling fires. In this study, effectiveness of first-aid methods was assessed in terms of the proportion of fires put out by these methods and the average time taken by brigades to control fires that were not put out. Occupants were able to put out 43 per cent of the fires tackled by sundry means but only 27.5 per cent of those in which extinguishers were used. The average control time for fire brigades was 6.5 minutes for sundry means and 8.9 minutes for extinguishers.

It is possible that extinguishers in dwellings were located at considerable distances from places of fire origin, e.g. in cars or garages. An analysis by Sime *et al.* (1981) gave some indication that people have an inadequate knowledge of the location of extinguishers. A householder may be more inclined to tackle a fire that is in an armchair than one in a chip-pan. According to Chandler (1978), people were less likely to use extinguishers on small fires, which might partly explain the lower success rate with extinguishers than with other methods in hospitals. This conclusion was confirmed by Canter (1985) who found that the contribution of extinguishers to fire fighting was subject to many constraints in actual fires. Canter also suggested that people (especially staff in hospitals, hotels, etc.) should be made aware of the location of extinguishers and trained in the use and capabilities of different types and sizes.

As in the case of sprinklers, a number of small fires extinguished by portable fire extinguishers were not reported to the fire brigades. In the UK, statistics supplied by the Fire Extinguishing Trade Association (*Fire Prevention,* March 1990) indicate that over 70 per cent of fires are not reported to the fire brigade because they are put out using fire extinguishers. In addition, 17 per cent of the fires reported to the brigade were found to have been put out by staff or residents using fire extinguishers prior to the brigade's arrival. All the factors and data mentioned above should be taken into account in a detailed statistical analysis to establish the effectiveness of extinguishers.

Ventilation systems

A fire which occurs in a restricted area, such as the kitchen of a dwelling with all the doors and windows closed, may burn out within the confined room area without anyone being aware of its existence. This happens because of a lack of oxygen. In a large uncompartmented building, however, the seepage of air through gaps in the structure is sufficient to prevent the fire being starved of oxygen. As the fire grows, smoke and hot gases will collect at roof level and will in a fairly short time (depending upon the material that is burning) extend from floor to ceiling if there is no means of expelling them as fast as they are produced. Hot smoky gases can also collect in the upper parts of a compartment that is partially or completely involved in a fire. Initially these gases form a stratified layer beneath the ceiling which, without venting, deepens and after a relatively short time mixes with the clear air beneath. The speed with which an unvented compartment or building can become smoke-logged has been demonstrated in many fires.

Venting is the removal of hot smoky gases from the upper parts of a compartment or building and the introduction of air from outside into the lower parts. This process may involve natural convection through openings that occur fortuitously or are provided purposely, or it may involve mechanical (powered) extracts or inlets or both. Hinkley (1988) discussed the basic engineering concepts underlying the design of complete venting systems, including the provision of openings (vents and inlets) or fans and allied features, such as the provision of screens (curtains) to limit the spread of smoke beneath the ceiling. It is important that a venting system be designed as a whole, taking into account other fire safety measures including provision of structural fire protection, escape routes and sprinklers.

Venting is provided with one or more of three objectives:

1 to facilitate the escape of people by restricting the spread of smoke and hot gases through escape routes;
2 to facilitate fire fighting by enabling fire fighters to enter the building and to see the seat of the fire, which would enable them to bring the fire under control quickly;
3 to reduce damage due to smoke and hot gases.

The extent to which these objectives are fulfilled is a measure of the effectiveness of a ventilation system. The effectiveness would vary from one system to another and from one type of building to another. Statistical data are lacking to assess this effectiveness quantitatively.

Chapter 6

Interactions and trade-offs

For over a century, regulatory control for fire safety has been achieved mainly through a framework of prescriptive rules, particularly for passive fire protection measures. These measures include limitations on building height and size, provision of fire-resistant compartments, restriction on compartment size, selection of building materials, and other methods to reduce the risk of fire spread and limit the size of the fire. At the same time, the building design should incorporate features of layout and facilities which would enable the occupants to escape rapidly and safely from the effects of a fire.

The level for life safety implicit in the fire regulations can possibly be achieved through combinations of passive and active fire protection measures which are appropriate to the hazard involved. Active measures such as sprinklers which are primarily designed for property protection can provide life safety as well. Combinations of safety measures produce interactions in their joint performance to provide prescribed levels of life and property protection. A balanced fire safety system would recognise these interactions and permit adjustments in requirements. This is commonly referred to as 'trade-off' or 'equivalence'. A question arises as to whether combinations of different levels of passive and active measures would be cost-effective. This problem involves complex statistical and economic analyses requiring large amounts of data which are not available at present. Attempts are, however, made in this chapter to provide a framework for such analyses. Interactions of safety measures with fire brigade operations and insurance are also investigated.

Sprinklers and passive fire protection measures

Sprinklers and building size

In fire safety codes, the main objective of provisions against external fire spread is to ensure that the possibility of a conflagration due to fire spread from one building to another is reduced. This aim is to achieve this by specifying a maximum 'basic' size to a building in terms of floor area and height, relative to fire brigade capability. The size of a building has been identified as one of the major factors influencing fire severity and extent of fire spread in the building of fire origin.

Sprinklers increase the chance of a fire being confined to the material or object first ignited. This performance would reduce the probability of flashover in the room (or compartment) of fire origin which, in turn, would reduce the probability of fire spreading beyond the room to other parts of the building of fire origin and causing a conflagration. It is, therefore, reasonable to relax the restriction on building size if sprinklers are installed and to permit an increase in the maximum size beyond that specified for a building of the same type without sprinklers.

It is logical to base the extent of increase in building size that can be permitted for a sprinklered building on the principle of 'equivalent damage'. According to this principle, the damage in a sprinklered building of larger size should not exceed the damage level specified for a building of 'basic' size without sprinklers. This level, which should be acceptable to the property owner and society at large, can be determined with due regard to consequences in terms of life and property damage.

To determine the equivalence of fire safety measures, Harmathy (1986) has suggested a probabilistic model based on annual loss expressed as the product of an expected number of ignitions per year and the average loss expected in a fire. The loss in a fire following ignition can be evaluated by considering the losses and probabilities for the following classes of fires:

1 fires that remain in the pre-flashover stage;
2 fires that grow into the fully developed stage.

The second category is further subdivided into:

(a) fires spreading by convection through a door or window left open or through some other opening;
(b) fires spreading by the destruction of one or more non-mobile building elements (wall, ceiling, etc.);
(c) fires that do not spread.

For each of these categories Harmathy has considered both property and human losses due to spread of fire and smoke.

It seems extremely unlikely that statistical data will be available in sufficient detail to evaluate the probabilities and losses for the categories of fires specified by Harmathy. Detailed data may be available for a 'reference building', which may be defined as a two-storey apartment building in a small town, with normal access by the fire department, built without combustible linings of any kind and employing no special fire safety measures. To evaluate the incremental probabilities for any other type of building with deviations from the conditions specified for the reference building, Harmathy has suggested the use of the Delphi technique based on the opinion and experience of fire safety experts.

An alternative method suggested by Ramachandran (1990) is as follows. Statistical studies have shown that the area likely to be damaged in the building of fire origin, D (A), is given by the 'power' relationship:

$$D(A)=CA^{ß} \tag{6.1}$$

where A is the total floor area (size) of a building and C and ß are constants for any risk category. Rutstein (1979) has estimated the values of C and ß for several types of buildings in the UK. According to him, with the total floor area A in square meters, C=2.25 and ß=0.45 for all manufacturing industries. These figures relate to buildings with a minimum level of fire protection (without sprinklers). With C=2.25, ß has a value of 0.27 for an industrial building with sprinklers (Ramachandran, 1988).

As proposed by Ramachandran (1990), on the basis of equivalent damage expectancy in a fire, from equation (6.1):

$$A_s = [A_u]^{\beta_u/\beta_s} \tag{6.2}$$

where A_s is the size of a sprinklered building equivalent in damage to the size A_u of a non-sprinklered building. The parameter $ß_u$ pertains to a non-sprinklered building and $ß_s$ to a sprinklered building. The value of the ratio $ß_u/ß_s$ is about 1.67 (=0.45/0.27) for all manufacturing industries in the UK. This ratio inserted into equation (6.2) would give an unacceptably large value for A_s for any value specified for A_u.

Hence, for evaluating ß, Ramachandran suggested that the 'power' relationship in equation (6.1) may be based on maximum area damage as indicated by a fire that has spread beyond the room of origin instead of the average damage in a fire. For the UK textile industry, for example, $ß_u$=0.68 and $ß_s$=0.60 with ($ß_u/ß_s$)=1.13 for such a spreading fire. The value of parameter C=4.43 m^2 in both cases. Using these figures, the linear relationship, on a (log×log) scale, between damage and building size is depicted in Figure 6.1. The figure is applicable to buildings larger than 105 m^2.

In the above example, if maximum damage of 2,300 m^2 is acceptable, the basic building size, A_u, can be 10,000 m^2. In this case, on the basis of an equivalent maximum damage, the size of a sprinklered building, A_s, can be 33,000 m^2. This figure is based on the assumption that the sprinkler system operates satisfactorily in a fire. If a reliability investigation suggests a probability of 0.1 for the non-operation of sprinklers, A_s for a sprinklered building should be reduced to 28,000 m^2 as given by:

$$(0.9)\, A_s^{\beta_s} + (0.1)\, A_s^{\beta_u} = A_u^{\beta_u} \tag{6.3}$$

Statistical analyses such as the one described above, provide support for relaxing restrictions on the size of buildings that are fitted throughout with automatic

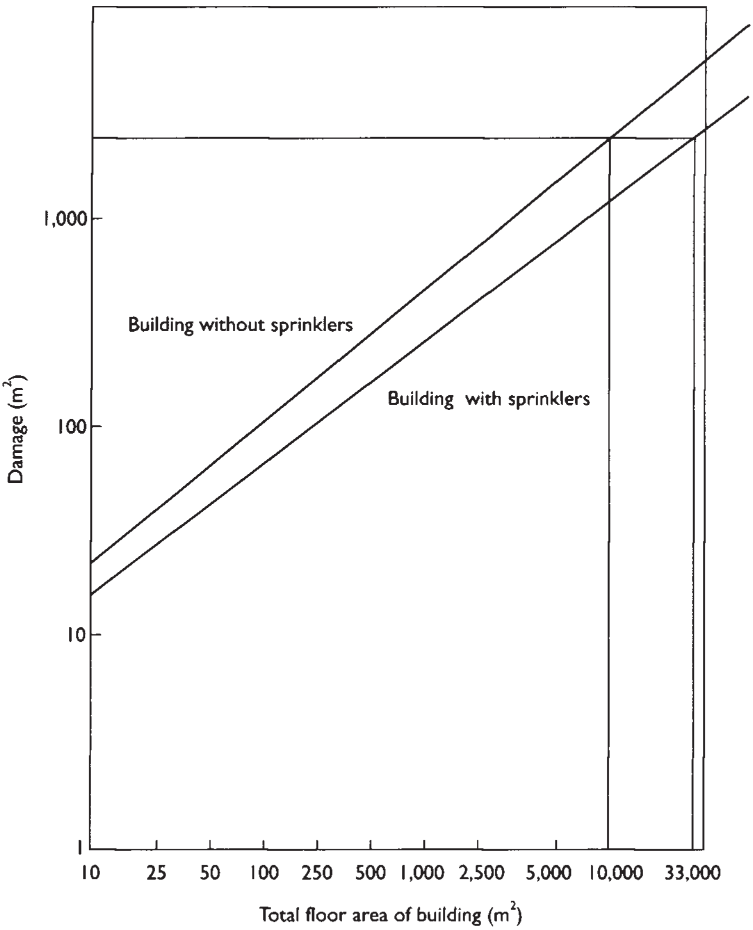


Figure 6.1 Damage and building size

sprinkler systems which meet relevant standards. Such a concession for sprinklered buildings, in some form or other, has already been incorporated in the fire regulations of some countries. An example is Department of the Environment (1992, table 12), issued for practical guidance on meeting the relevant requirements of the Building Regulations 1991. For any 'purpose group', depending on the height of the floor of the top storey above ground level (more than or not more than 20 m), the maximum floor area permitted for any one storey in the building or compartment can be doubled if the building is fully sprinklered. For example, for an industrial building more than 20 m in height, the maximum floor area permitted for any one storey or compartment is 2,000 m^2 if there are no sprinklers and 4,000 m^2 if there are. In effect, for a given height category, the total floor area of a building with sprinklers can be double that of one without sprinklers.

Doubling the size of a building equipped with sprinklers would involve additional costs of building construction and the installation (and maintenance) of the fire protection system. Against these costs, there are no additional benefits from the national economic point of view although the relaxation in building size is justified on the basis of 'equivalent damage' to life and property. However, there may be an economic justification for the relaxation from the point of view of a property owner.

Consider, for example, a department store to be built with a total floor area 8,000 m^2. With the maximum permissible floor area of 2,000 m^2, and no limit on building height, the building can have four floors and a height of 20 m at 5 m per floor if it is not provided with sprinklers. With sprinklers, the height of the building can be confined to 10 m and two floors, each with a maximum permissible area 4,000 m^2. A reduction in the number of floors but with the same total floor area is unlikely to reduce the construction cost of the building significantly. There may be some saving in this cost since a building with sprinklers can have fewer compartments and each compartment have a larger floor area. But, as discussed above (pp. 60–3), the installation of sprinklers can be economically justified in view of the tax allowances and savings on fire insurance premiums.

Sprinklers and compartment size

Damage within the compartment of fire origin can be expected to increase with an increase in the size of the compartment. In this case also, the 'power' relationship in equation (6.1) is approximately valid. Taking again the textile industry in the UK as an example, based on maximum damage within a compartment, $ß_u$=0.57 for a compartment without sprinklers and $ß_s$=0.42 for a comparment with sprinklers which operate in the event of a fire occurring (see Ramachandran, 1990). The parameter C has the value 4.43 m^2 in both cases.

Figure 6.2 on a (log×log) scale shows the relationship between the size of compartment and maximum damage within such an enclosure in the event of a fire. The figure is applicable to compartments larger than 32 m^2. According to this figure, if maximum damage of 153 m^2 is acceptable, a sprinklered compartment of 4,000 m^2 is equivalent in damage to a compartment of 500 m^2 without sprinklers. The size of the sprinklered compartment will reduce to 3,000 m^2 if equation (6.3) is used and a probability of 0.1 is assigned for the non-operation of sprinklers. Calculations based on equation (6.3) would show that a sprinklered compartment of 15,000 m^2 is equivalent to a non-sprinklered compartment of 2,000 m^2 if a maximum damage of 337 m^2 is acceptable.

However, to be on the safe side, the fire regulation only permits doubling the maximum compartment size if sprinklers are installed. For an industrial building, in the UK for example, as specified in Department of the Environment

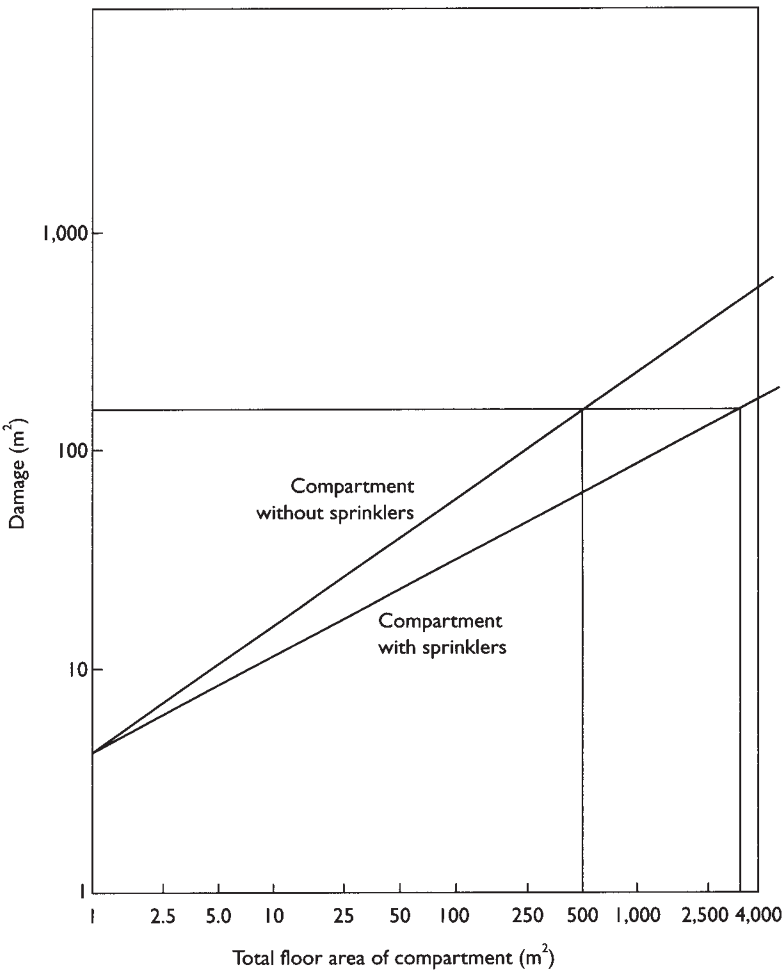


Figure 6.2 Damage and compartment size

(1992, table 12), the maximum size of a compartment filled with sprinklers can be increased to 14,000 m^2 from 7,000 m^2 if the height of the building is not more than 20 m, and to 4,000 m^2 from 2,000 m^2 if the height of the building is more than 20 m; for a department store which belongs to the purpose group 'shop', with no limitation on the building height, the maximum size of a sprinklered compartment can be increased to 4,000 m^2 from 2,000 m^2.

Consider, as an example, a department store of total floor area 12,000 m^2 to be built on two floors, each floor covering an area of 6,000 m^2. There are two design choices. First, each floor can have four compartments, each of 1,500 m^2 and without sprinklers. Alternatively, by installing sprinklers, the number of compartments on each floor can be reduced to two by increasing the size of each compartment to 3,000 m^2.

Following the example above (pp. 60–3), with water supply from the mains, it would cost £204,000 to install sprinklers to protect an area of 12,000 m^2. However, there will be a saving in the construction costs of compartment walls. For two vertical compartments, there is a need for only one compartment wall of, say, height 9 m and length 39 m whereas four vertical compartments without sprinklers would require three such compartment walls. Depending on the area of the compartment walls, the foundations and other components of construction costs, the cost of passive protection, according to some unpublished information, can be about £130,000 for four compartments and £45,000 for two compartments. Hence, by installing sprinklers and doubling the compartment size, there will be a saving of about £85,000 in the cost of passive protection. Subtracting this amount from the capital cost of sprinklers, the net cost for installing sprinklers will be about £119,000. With amortisation over forty years at 10 per cent rate of interest, the annual net cost is £12,200.

Following Rutstein (1979), for shops, the expected value of damage in a fire is given by equation (6.1) with $C=0.95$ and $ß=0.5$ for a compartment with a minimum level of fire protection. Hence, for a compartment of 1,500 m^2 without sprinklers, damage of 37 m^2 can be expected if a fire is confined to the compartment. According to UK fire statistics for 1984–6, the probability of a fire spreading beyond an unsprinklered room in a shop is 0.13. This probability includes fires which spread by the destruction of compartment boundaries as well as those which spread by convection (advance of flame and hot gases.) In the event of this undesirable event occurring, the likely damage may be assumed to be 4,000 m^2. Data are not available at present to estimate this damage for a compartment of any given size. The damage expected in a fire in the nonsprinklered building considered is, therefore:

$$552\ m^2=(37\times0.87)+(4{,}000\times0.13)$$

For a compartment with sprinklers of 3,000 m^2, with $C=0.95$ and $ß=0.25$ for shops, the damage expected in a fire is 7 m^2 if the fire is confined to the compartment. The probability of fire spreading beyond a sprinklered compartment in a shop is 0.02. In this case also a damage of 4,000 m^2 may be assumed, such that the damage expected from a fire in the building, if sprinklers are installed

$$87\ m^2=(7\times0.98)+(4{,}000\times0.02)$$

If a probability of 0.1 is assigned for the non-operation of sprinklers, the damage expected would be:

$$134.8\ m^2=(87\times0.9)+(565\times0.1)$$

The second term on the right-hand side of the above equation is based on a damage of 52 m^2 within a compartment of 3,000 m^2 assuming that, if the sprinklers do not operate, the compartment has effectively no sprinklers.

The annual probability of a fire starting in a compartment of 1,500 m^2 is 0.1, as given by the formula:

$$F(A)=KA^{\alpha} \tag{6.4}$$

where, according to Rutstein (1979), K=0.000066 and α=1.0 for shops. For a compartment of 3,000 m2, the annual probability of fire starting is 0.2. A fire can start in any of the compartments in a building. Hence, summing up for all eight compartments in the non-sprinklered case or four compartments in the sprinklered case, it may be seen that the annual probability of fire starting in the building is 0.8, which can otherwise be estimated from equation (6.4) with A=12,000 m^2. The annual saving due to sprinklers in area damage is, therefore:

$$(552-135)\times 0.8=334\ m^2$$

Hence, at a loss rate of £480 per m^2, the annual saving in financial terms is likely to be £160,000. Rutstein and Cooke (1979) estimated a loss rate of £160 per m^2 at 1979 prices.

The annual saving of £160,000 due to sprinklers is higher than even the initial net cost of £119,000; it is considerably higher than the amortised annual net cost of £12,200. Hence, from the national economic point of view, if sprinklers are installed there can be no arguments in a decision to increase the compartment size from 1,500 m^2 to 3,000 m^2 in a department store of size 12,000m^2.

If a fire-resistant compartment is 100 per cent reliable, a fire starting in the compartment will not spread beyond its structural boundaries. Under this assumption, the damage likely to be sustained would be 37 m^2 for an unsprinklered compartment of 1,500 m^2 and 11.5 m^2 for a sprinklered compartment of 3,000 m^2. The latter damage figure is based on a probability of 0.1 for nonoperation of the sprinklers. In the case considered above, the saving in direct damage due to sprinklers will drastically reduce to 25.5 m^2 in a fire, or £9,800 per annum. Since the annual saving is less than the annual net cost of £12,200, a decision to increase the compartment size and install sprinklers is not cost-effective from the national economic point of view. This result significantly overestimates the effectiveness of structural fire protection and underestimates the effectiveness of sprinklers. Statistics of actual fires clearly indicate a small chance of a fire spreading beyond the compartment of origin and causing considerable damage. This chance is significantly reduced by sprinklers which reduce the probability of flashover and increase the probability of a fire being confined to the material or object first ignited.

With a value density of £1,500 per m^2, the value at risk in the building with 12,000 m^2 floor area would be £18 million. The annual saving in insurance premiums would be about £36,000 at the rate of £0.20 saving per £100 of value, as discussed on pp. 60–3. This amount, together with tax allowances, would exceed significantly the annual amortised net cost of £12,200 for installing sprinklers. This figure, as discussed earlier, has been obtained by subtracting the saving of £85,000 on the cost of compartment walls from the capital cost of £204,000 for installing sprinklers. The property owner certainly has an economic justification for increasing the compartment size to 3,000 m^2 (from 1,500 m^2) and installing sprinklers.

Sprinklers and fire resistance

Destruction of the structural boundaries of a compartment is caused by a high level of fire severity during the post-flashover stage, if such a fully developed stage is reached by a fire. The fire resistance period of a structural element, as ascertained in a standard fire resistance test, e.g. British Standard BS476, should be equal to or exceed the high level of severity expected in a fire. To estimate this level for any occupancy type, analytical formulae have also been developed in fire science literature which express severity as a function of compartment dimensions, thermal inertia of compartment boundaries, ventilation factor and fire load (quantity of combustible material).

Since fire load is a random variable, its value corresponding to a fractile of 80 per cent of the probability distribution of the load density together with a minimum (safe) value for the ventilation factor is considered as an estimate of a potentially high level of severity. By prescribing an equivalent value for the fire resistance of a barrier element such as wall, ceiling or floor, the probability of 'barrier failure' is expected to be 0.20. (A compartment 'fails' when, due to severe heat, it violates a performance criterion such as stability, integrity or thermal insulation.) In an expanded probabilistic model, both fire severity and resistance are treated as random variables (see Ramachandran, 1990, 1995a).

Sprinklers, if they operate satisfactorily, have a high chance of extinguishing a fire or reducing its severity. They therefore increase the chance of a fire being confined to the material or object first ignited, thus reducing the probability of flashover and compartment failure. Consequently, sprinklers reduce the probability of a fire spreading beyond the compartment of origin. It can therefore be argued that the fire resistance of a sprinklered compartment can be reduced to a level such that the probability of a fire spreading beyond the compartment does not exceed an acceptable value specified for a compartment without sprinklers.

The reduction in fire resistance appropriate for a compartment with sprinklers of any occupancy type can be determined by incorporating in the analytical formula mentioned in the previous paragraph a fire load density corresponding to a fractile lower than 80 per cent of the probability distribution of load density.

A simple probabilistic model for this purpose has been proposed by Ramachandran (1993a, 1995a). According to these investigations, the fire resistance period of a compartment with sprinklers can be about 60 per cent of the resistance period specified for one without them. This percentage reduction has been recommended in the Eurocode (1992) and fire safety codes of some countries. The extent to which the fire resistance of a sprinklered compartment may be reduced can be determined more accurately by applying the expanded probabilistic model for compartment failure mentioned earlier.

Theoretically, the fire resistance of a compartment can be reduced to zero if a sprinkler system is 100 per cent reliable. Since statistical data have revealed some unreliability in the operation of sprinklers in a fire, fire regulations are somewhat reluctant to lower the fire resistance requirement for a sprinklered compartment, particularly if an increase in the compartment size is permitted. A bigger compartment has the potential to produce a higher level of maximum fire severity due to an increase in the total fire load. From the national economic point of view, if sprinklers are installed, fire regulations may permit either an increase in the compartment size or a reduction in fire resistance. If concessions are given for both compartment size and fire resistance, damage to life and property may exceed an acceptable level.

At the national economic level, the annual reduction in fire loss due to fire resistance or sprinklers or a combination of both these measures should exceed the annual costs involved. Detailed statistical data for carrying out this investigation are still not available. Ramachandran (1982a) attempted this problem for some groups of industrial buildings using information available in the reports on fires attended by the fire brigades in the UK. From the particulars given in these reports about the materials used in the construction of walls and floors, two classes of fire resistance were distinguished somewhat arbitrarily:

1 high fire resistance:
   (a) wall materials: stone, brick, concrete, breeze block and asbestos by themselves or in combination with glass or plastic;
   (b) floor materials: concrete, brick, tile and earth either by themselves or in combination with glass or plastic;
2 low fire resistance: all buildings not belonging to the ‘high’ category.

Details such as thickness of walls and floors, nature of concrete aggregates and application of plaster were not given in the reports.

Thus, single-storey buildings with highly fire resistant walls and multistorey buildings with highly fire resistant floors were considered highly fire resistant buildings. On the other hand, single-storey buildings with low fire resistant walls and multistorey buildings with low fire resistant floors were regarded as low fire resistant buildings. Two sizes of buildings were considered: 100,000 ft^2 (9,290 m^2) and 1,000,000 ft^2 (92,900 m^2).

For the cost of sprinklers, Ramachandran used the equation derived by

Rutstein and Cooke (1979) for ordinary hazard mentioned above (p. 56). The costs were updated at 1980 prices. Based on Home Office (1980), the cost of fire resistance was estimated as 0.5 per cent of building cost. In 1980, an industrial building cost about £33 per ft^2 of floor area.

Loss (L) from a fire in a building of total floor area A was estimated with the aid of the 'power' relationship:

$$L = K_L A^{\beta_L} \tag{6.5}$$

similar to equation (6.1). The constants K_L and $ß_L$ depend on the nature of industrial activity associated with the building, the level of fire protection and other such factors affecting the spread of fire. The parameters were estimated for each class of buildings in each industry using data on large fire losses in conjunction with extreme value techniques developed by Ramachandran (1974a, 1975a). A class was defined as a combination of three factors: storeys, sprinklers and fire resistance. Equation (6.4) was used to estimate the annual probability of fire starting, together with the results of Rutstein (1979) for different industries.

The cost figures were amortised over a period of forty years at 10 per cent rate of interest using a value of 0.1023 for the capital recovery factor K in Table 3.1 (p. 23). Accordingly, the annual cost used for sprinklers was £2,470 for a building with floor area of 100,000 ft^2 and £23,820 for the larger building with floor area of 1 million sq ft. For higher fire resistance the annual cost figures were £1,690 for the smaller building and £16,880 for the larger building. Using a building with lower fire resistance and no sprinklers as the 'base' or 'reference' building, the reduction in annual fire loss was considered the annual gain. This gross gain minus the annual cost of fire protection provided an estimate of the annual net gain; shown in Table 6.1.

A comparison of the figures in the third and fourth columns of Table 6.1 suggested that provision of sprinklers instead of high fire resistance has economic justification only for multistorey textile industry buildings and smaller multistorey buildings involved in clothing, footwear and timber manufacture. In all other cases, high fire resistance appears to have a greater economic value than sprinklers. The results in Table 6.1 cast doubts on the economic justification for both high fire resistance and sprinklers in some industrial buildings; they gave some support to a reduction in fire resistance requirements for multistorey industrial buildings equipped with sprinklers. Results for single-storey buildings are not consistent and hence not included in the final analysis.

Consider the problem from the point of view of a property owner in the UK who is planning to construct a single-storey department store of floor area 6,000 m^2. According to the requirement specified in Department of the Environment (1992, table 12), the building should have at least three compartments, each of floor area 2,000 m^2. As the height of the building is less than 5 m, the property owner has three options which satisfy the constraints

Table 6.1 Multistorey buildings: annual net gain at 1980 prices (£)

Industry	*Floor area ('000 ft²)*	*Only high fire resistance*	*Only sprinklers*	*High fire resistance and sprinklers*
(1)	*(2)*	*(3)*	*(4)*	*(5)*
Textiles	100	1,105	3,563	2,446
	1,000	45,738	47,127	39,726
Chemical and allied	100	214	−1,880	−1,897
	1,000	11,834	−10,532	−8,781
Clothing, footwear	100	−945	−733	−2,021
	1,000	10,059	23	−6,170
Timber, furniture	100	−221	1,301	281
	1,000	70,214	60,267	72,725
Paper, printing and publishing	100	2,698	228	1,531
	1,000	186,442	101,044	186,565

imposed by the requirement (in ibid., table A2, Appendix A) for minimum periods of fire resistance. First, sprinklers need not be installed but, in this case, the building should have 60 minutes' fire resistance. Second, the fire resistance of the building can be reduced to 30 minutes by installing sprinklers. As a third option, sprinklers may be installed but the fire resistance can be maintained at 60 minutes. For the second and third options involving sprinklers the number of compartments can be reduced to two, each with floor area 3,000 m^2, but this concession is not considered.

It is estimated that, at an average rate of £500 per m^2, the cost of the building is about £3 million. This cost is the same for all the options but the cost due to fire resistance would vary according to the formula in equation 5.2 (p. 44). The variable cost would be £180,000 (=0.001×60×£3 million) for 60 minutes' fire resistance and £90,000 (=0.001×30×£3 million) for 30 minutes' fire resistance. The annual equivalent of these costs is £18,400 and £9,200 respectively if amortised over forty years at 10 per cent rate of interest. At £17 per m^2, the capital cost of sprinklers, with water supply from the mains, is estimated to be £102,000; the annual amortised equivalent of this cost is £10,400.

On average the value of the building and contents is £1,500 per m^2. The total value of the building and contents is, hence, £9 million. An insurance broker quoted the rates per £100 of value for a fire insurance premium for a department store at £0.30 for 60 minutes' fire resistance without sprinklers, £0.35 for 30 minutes' fire resistance with sprinklers and £0.10 for 60 minutes' fire resistance with sprinklers. If a single-storey department store has only 30 minutes' fire resistance and no sprinklers, the insurance premium rate may be as high as £0.45 per £100 of value. But such a building is unlikely to be accepted for insurance; it would also violate the fire regulation requirement for shops. For the building considered, the annual insurance premiums are £27,000 for 60 minutes' fire resistance without sprinklers, £31,500 for 30 minutes' fire resistance with sprinklers and £9,000 for 60 minutes' fire resistance with sprinklers.

The annual costs for insurance and fire protection for the three options are shown in Table 6.2. These are the only cost components which vary and hence need to be considered in order to compare the economic value of the three options. A comparison of the total annual costs shows that the second option with 30 minutes' fire resistance and sprinklers, even though it meets the fire regulation, is less cost-effective than the first option with 60 minutes' fire resistance and no sprinklers. This result stems from the fact that the saving due to a reduction in the fire resistance may not be sufficient to compensate the extra cost involved in installing sprinklers. Moreover, insurers generally charge a slightly higher rate for a building with low fire resistance even if it is provided with sprinklers. The second option may be marginally more cost-effective than the first if the number of compartments is reduced to two since, with sprinklers, each compartment can cover a floor area of 3,000 m^2.

The third option, with 60 minutes' fire resistance and sprinklers, may appear to provide overprotection but it is the most economical from the point of view of the property owner. This conclusion is mainly due to the considerable amount of rebate on insurance premiums given for such a high level of fire protection.

Consider, as another example, a large five-storey department store with the floor of the top storey 25 m above ground level and total floor area of 30,000 m^2 with each floor covering 6,000 m^2 and separated into three compartments of 2,000 m^2. At £500 per m^2 of floor area the building cost is £15 million. With a value density of £1,500 per m^2, the total value of building and contents is estimated to be £45 million. For such a building, according to fire regulations, the fire resistance should be 90 minutes if sprinklers are not installed, and 60

Table 6.2 Fire protection options for a single-storey department store: total annual costs (£)

Components of cost	*Options*		
	60 mins fire resistance No sprinklers	*30 mins fire resistance Sprinklers*	*60 mins fire resistance Sprinklers*
Fire resistance	18,400	9,200	18,400
Sprinklers	—	10,400	10,400
Insurance premium	27,000	31,500	9,000
Total annual cost	45,400	51,100 (50,100)	37,800 (36,800)

Note: The figures within brackets denote net total annual costs after subtracting an estimated annual amount of £1,000 towards tax allowances over a 40-year period.

minutes if the building is provided with sprinklers. In this case also, the insurer may regard 60 minutes' fire resistance for a multistorey department store as inadequate even if sprinklers are installed and hence charge a premium rate of £0.35 per £100 of value. For 90 minutes' fire resistance without sprinklers the rate would be lower (£0.30), as mentioned in the earlier example. The rate will reduce drastically to £0.10 per £100 of value if 90 minutes' fire resistance is maintained and sprinklers are installed.

Following the calculations as in the first example, it can be seen that the total annual cost for this multistorey department store is of the order of £273,000 if the building has 90 minutes' fire resistance without sprinklers—£138,000 towards the provision of fire resistance and £135,000 towards fire insurance. If the building is provided with 60 minutes' fire resistance and sprinklers the total annual cost would be about £298,000. This cost is made up of £92,000 for fire resistance, £52,000 for sprinklers and £157,500 for insurance; an annual average amount of £3,500 over a forty-year period has been subtracted for tax allowances. It may, therefore, be concluded that for this multistorey department store, 90 minutes' fire resistance without sprinklers is a marginally more economic option than 60 minutes' fire resistance with sprinklers. The latter option may be marginally more economic if the number of compartments on each floor is reduced to two. In this example, the most economic option is 90 minutes' fire resistance with sprinklers. For this high level of fire protection, the total annual cost of £235,000 is composed of £138,000 towards the provision of fire resistance, £52,000 towards the installation of sprinklers and a considerably low insurance premium of £45,000.

The analyses discussed above reveal that, due particularly to a significant reduction in the insurance premium, a high level of fire protection with sprinklers and adequate fire resistance is the most economic option from the point of view of the property owner. But this option has been judged earlier as not cost-effective at the national economic level. This result, according to Table 6.1, has only been based on property damage. A high level of fire resistance and sprinklers can, perhaps, be economically justified at the national level by including also damage to life in the cost-benefit analysis.

Sprinklers and means of escape

The means of escape from a one- or two-storey house or from a flat or a maisonette are relatively simple to provide. Few provisions for these occupancies in the UK are specified in Department of the Environment (1992, sections 1 and 2). As discussed in detail in sections 3–5 of this document, buildings other than dwellings require more complex means of escape.

For buildings other than dwellings, the first component of the escape route is the horizontal elemental, such as corridors. The general principle is that any person on any floor confronted by an outbreak of fire should quickly be able to reach the storey exit and make a safe escape. Following this principle, maximum travel distance to the nearest exit is specified in the document mentioned above for different types of occupancies. For office buildings, shops and commercial buildings, for example, the limitation on travel distance is 18m where travel is possible in one direction only and 45 m when travel is possible in more than one direction.

Subject to the limitation on travel distance, the minimum number of escape routes and exits to be provided would depend on the number of occupants in the room, tier or storey considered. This minimum ranges from two for a maximum of 500 persons to eight for a maximum of 16,000 persons. For more than 16,000 persons, one extra escape route/exit per 5,000 persons or part thereof is required in addition to the eight escape routes/exits. The horizontal part of an escape route should have a certain minimum width, depending on number of persons who need to use it.

The maximum travel distance has been determined particularly with reference to the people in the room of fire origin for whom the combustion products pose the greatest risk. These people need to discover the existence of a fire in their room very soon after the start of the ignition in order to escape safely without sustaining fatal or non-fatal injuries. In the event of a fire, automatic fire detection systems such as heat and smoke detectors usually respond normally in two or three minutes, whereas it might take as long as six minutes for sufficient heat to be generated to activate a sprinkler head not of the fast-response type. People in the room of fire origin can be seriously affected by fire and smoke if they do not escape within three or four minutes.

However, it ought to be recognised that, by extinguishing a fire or controlling its spread, sprinklers provide extra escape time for the occupants of a building who are not in the room of fire origin. Several statistical studies have shown that sprinklers significantly reduce the probability of a fire spreading beyond the room of origin. They also reduce the rate of growth of smoke, which poses a greater threat than fire (that is, heat and flame) to occupants not in the immediate vicinity of the place of fire origin.

For these reasons sprinklers have the potential to reduce significantly the number of fatal and non-fatal casualties likely to be sustained if a fire breaks out in a large building with number of people at risk (see Ramachandran, 1993b; Melinek, 1993b). Hence, it can be argued that, for a sprinklered building, the maximum travel distance to the entrance of a staircase can be increased up to a limit such that the probability of occurrence of one or more fatalities does not exceed an acceptable level. Such a trade-off concession, particularly for buildings with fast-response sprinklers, has been incorporated in the Life Safety Code of the National Fire Protection Association, USA, according to which the travel distance can be increased by 33–50 per cent. Similar concessions exist in the fire safety regulations of Canada, New Zealand and Sweden but not of the UK (see Malhotra, 1987). A relaxation in the travel distance for sprinklered buildings is currently being considered by the Home Office.

An increase in the maximum travel distance to the entrance of a staircase might enable the construction of fewer staircases. This will produce a reduction in their construction costs. This benefit together with saving on insurance premiums may exceed the cost of installing sprinklers. Sufficient data are not available at present to carry out this economic analysis. At the national level, life risk would increase due to a reduction in the number of staircases, although it may not exceed the level expected by constructing number of staircases according to the current fire regulation. In the absence of sufficient data for valid economic justification it is difficult to permit an increase in maximum travel distance for a building equipped with sprinklers. Such a relaxation may, perhaps, be considered if smoke ventilation systems are also installed in addition to sprinklers.

An increase in travel distance implies an increase in the 'design evacuation time', t, discussed in Chapter 5 with reference to equation (5.10), applicable for a building designed for total (simultaneous) evacuation. The value of 2.5 minutes currently recommended for t in the UK fire regulation is regarded as an acceptable period within which all the occupants of a floor should be able to enter the nearest staircase after leaving their places of occupation. With this value for t, the width b required for the staircase is determined according to equation (5.9) or (5.10) for any given number of persons, M, on a floor who are expected to enter the staircase.

Consider, for example, a six-storey building with a population of 690 people and designed for total (simultaneous) evacuation. Calculations based on equation (5.10) or (5.9) would show that the total width of the stairs should be at least 1.7 m. Two 1.7m staircases would be necessary in order to meet the need to 'discount' one staircase assumed to be unavailable due to fire or smoke. According to UK fire regulations the minimum staircase width should be 1.1 m to serve more than 220 people. If the building is sprinklered, the design evacuation time, t, may be increased to, say, 4 minutes, such that equation (5.9) derived from equation (5.10) is modified to:

$$M=320\, b' +50\, (b' -0.3)\, (n-1) \tag{6.6}$$

In this case, with M=690 and n=6, the total width of the staircases can be reduced to b' equal to 1.34 m. Two 1.34 m staircases would be necessary to allow for the 'discounting' of one stair.

The parameter M can be regarded as capacity and (M/b) as capacity, c, per metre width of stairs. Reducing the staircase width is effectively equivalent to maintaining the width at the same level b but increasing the capacity per metre width to c'. For the example considered, calculations show that, if the building is sprinklered, the capacity per metre width can be increased to c'=515 (= 690/1.34) from c=406 (=690/1.7). Only US fire regulations permit an increase of 50 per cent in capacity per unit width of stairways for buildings equipped with fire suppression systems.

A reduction in the total width of staircases will produce a gain in rentable floor space. This benefit added to saving on insurance premiums and tax allowances would exceed the cost of installing sprinklers. An increase in life risk due to a reduction in staircase width would be compensated by an increase in life safety provided by sprinklers. Due to lack of data, it is difficult to establish the economic justification for reducing the staircase width in a building fitted with sprinklers either at the level of a property owner or at the national level.

Sprinklers and active fire protection measures

Sprinklers and automatic fire detectors

By discovering the existence of a fire very soon after ignition takes place, an automatic fire detector, either of heat or smoke, enables the commencement of early fire fighting, particularly by first-aid means such as buckets of water or sand and portable fire extinguishers. A fire is small during its early stage of development and, if attacked during that stage, it can be extinguished or controlled before it spreads and causes any significant damage to property (see Ramachandran and Chandler, 1984b). Early discovery of a fire by an automatic detector also reduces life risk by providing more time for occupants to escape to safe places within or outside the building of fire origin. If the detector is connected to the local fire brigade, they can soon arrive at the fire scene and put out the fire quickly.

To discover the existence of a fire, sprinklers installed in industrial and commercial buildings are generally less sensitive, in the sense that their operating times are longer than those of automatic detectors. Normally, it would take about six minutes before the heat generated by a fire is sufficient to activate a sprinkler head whereas a detector is designed to operate in two or three minutes after the start of the ignition. Consequently, if both these systems are installed in a building, early discovery of a fire by a detector is likely to be followed by first-aid fire fighting such that the sprinkler system is not pressed into action. According to UK fire statistics, a high percentage (about 50 per cent) of fires in properties with sprinklers are extinguished by first-aid fire fighting. These fires are apparently discovered soon after ignition either by occupants or by automatic detectors.

Insurance companies offer very low discounts on fire insurance premiums for detector systems whether connected to the local fire station or not. However, if both detectors and sprinklers are installed in an industrial or commercial building, due to tax allowances and the substantial discounts on insurance premiums for sprinklers, the costs of these two systems can be recovered in six to ten years depending on the value at risk in buildings and contents. The recovery period will be shorter if the property is also insured for consequential losses.

At the national economic level, the total annual cost incurred in installing sprinklers and detectors should be less than the probable reduction in annual damage to property and life. Sufficient statistics are not available to perform this economic analysis. Sprinklers and detectors are likely to be cost-effective from the national economic point of view if both are installed in such premises as warehouses which lack constant human surveillance, and in buildings with large number of occupants, e.g. large office and apartment buildings, hotels and department stores. Sprinklers are unlikely to be economic in small residential buildings fitted with detectors.

Sprinklers and smoke ventilation systems

The interaction between sprinklers and smoke ventilation systems has so far not been clearly evaluated by fire scientists and engineers. This interaction arises from the fact that water sprays from activated sprinklers remove buoyancy from combustion products and generate air currents which counter the outflow from the vents and, additionally, transport combustion products to the floor. Use of vents may reduce the total water demand by the sprinkler system, but this benefit due to vents has not yet been clearly established. There may also be other types of interaction between sprinklers and vents; it may take a few more years of research and experimentation before all the interactions between these two types of fire protection measure are well ascertained and evaluated. Sufficient statistical information needs to be collected to assess the effects of the interactions on damage to life and property and the performance of the fire service.

There is some discussion about whether a vent should operate before a sprinkler or not. There are indications from current research that the effect of venting on the opening of the first sprinklers and their capacity to control the fire is likely to be small. There are also indications that the earlier the vents are opened the greater the likelihood that they would be effective in preventing smoke-logging of a sprinklered building. The controversy over first operation of sprinklers or vents can, perhaps, be resolved by deciding for any type of building whether property protection or life safety is the main objective. In the initial stage of fire growth a vent should operate before a sprinkler if life safety is the dominant objective, e.g. in hotels, shopping centres, office buildings. In industrial buildings, the first sprinkler may operate before the opening of any vent.

Automatic fire detectors and other fire protection measures

The interaction between automatic fire detectors and sprinklers has already been discussed above. The interaction between detectors and other fire protection measures is the subject matter of this section.

Means of escape

As mentioned earlier, by discovering the existence of a fire very soon after the start of ignition, automatic detectors provide extra time for the occupants in the room of fire origin and in other parts of the building to escape. Consequently, detectors have a great potential in reducing life risk (see Ramachandran, 1990, 1993b). It can, therefore, be argued that the design evacuation time and travel distance to the entrance of a staircase can be increased for a building fitted with detectors (Ramachandran, 1990); but such a concession does not appear to have been incorporated in the fire regulations of any country.

It can again be argued that the total width of stairs can be reduced if a building is fitted with automatic fire detectors. This concession appears to exist in some form in the fire regulations of some countries: in the UK, for example, a building can be designed for ‘phased evacuation’ if it has been fitted with an appropriate fire warning system. Under this scheme, people to be evacuated first are all those of reduced mobility and those on the storeys most immediately affected by the fire, usually the floor of fire origin and the floor above. Subsequently, if there is a need to evacuate more people, it is carried out two floors at a time. The minimum aggregate width of stairs specified for phased evacuation as described above enables narrower stairs to be incorporated than would be the case if the building were designed for total (simultaneous) evacuation.

If a building is equipped with advanced detection systems such as addressable systems (see p. 76), generally known as informative fire warning systems (IFWS), there is a stronger case for increasing the design evacuation time (and travel distance to the entrance of a staircase) or reducing the total width of stairs (see Ramachandran, 1991b). The IFWS are computer-controlled and are capable of communicating to the building occupants timely and convincing information about the existence and exact location of a fire. In IFWS, appropriate messages can be displayed which would enable people to distinguish fire alarms from other alarms, including test alarms. By communicating to occupants detailed information about a fire, IFWS reduce delays in the commencement of evacuation and thus enable the occupants to reach safe places quickly within or outside the building of fire origin. IFWS, therefore, provide a higher level of life safety than ‘conventional’ fire detection systems (Ramachandran, 1993b).

First-aid fire fighting

Automatic fire detection systems, both ‘conventional’ and IFWS, do not put out fires; they only warn the occupants of the existence of a fire in a building. Early discovery of a fire by a detector system or by an occupant needs to be followed up by quick action to evacuate the building and extinguish the fire (Ramachandran and Chandler, 1984b). Before the arrival of the fire brigade at the scene, attempts may be made to put out the fire. This action may be undertaken automatically by sprinklers, if installed, or manually by occupants by using sundry first-aid fire fighting methods such as buckets of water or sand, smothering or portable fire extinguishers. Studies casting doubts on the effectiveness of portable fire extinguishers have already been discussed (pp. 85–6). Hence, it would be safer to call the fire brigade immediately after a fire is discovered.

Fire safety systems and fire brigades

Building design

Subdivision of a building, particularly a large one, into fire-resistant compartments has long been the core of fire safety measures although building fires spread mostly by convection (advance of flame and hot gases) rather than by the destruction of the structural boundaries of a compartment. If the boundaries are of sufficient fire resistance, it is argued, the building and its structure will not suffer collapse or become unstable under fully developed fire conditions and the fire will be contained within the compartment for an estimated period of time. This performance of structural fire protection would enable a fire brigade to arrive at the fire scene and commence fire fighting before the fire spreads beyond the compartment. The fire resistance of a compartment or building should, therefore, be determined with due regard to the attendance time of a brigade, which is a function of the travel distance from a fire station to the building.

The probability of a fire growing into the fully developed stage and spreading beyond a compartment depends also on the size of the compartment as well as the fire resistance of the structural boundaries of the compartment and other factors such as fire load (quantity of combustible material), area of ventilation and thermal inertia of the boundaries. Fire spread beyond the compartment to other parts of a building depends on the design and size of the building. There is a relationship between compartment size and building height. Compartments ideally should not extend to more than two or three floors in low-rise buildings and not more than one floor in high-rise buildings and basements. Each floor in a high-rise building should be a fire-resistant compartment. The difficulty for fire brigades of fighting fires in high-rise buildings and in basements requires that as much horizontal compartmentation as possible is provided.

As discussed above, the ability of a fire brigade to arrive early at the scene of a fire and extinguish it quickly depends on the size and fire resistance of compartments and on the size, particularly the height, of the building involved in the fire. The quality and quantity of fire fighting equipment used are other determinants of fire brigade capability. The factors mentioned above, together with relaxations for fire protection measures such as sprinklers, are considered to some extent in the development of fire safety codes for buildings in the UK. However, these requirements for fire safety should be assessed quantitatively and be revised, if necessary, by applying deterministic and probabilistic risk evaluation techniques.

Sprinklers

As was previously mentioned (p. 54), sprinklers extinguish several fires which are not even reported to the fire brigades. Some fires to which brigades are called are also put out by the system before the arrival of the brigades. The effectiveness of sprinklers in reducing damage to property and life has been discussed above (pp. 54–5).

Even if they fail to extinguish a fire, sprinklers slow down the rate of fire growth and restrict the extent of its spread until the arrival of the brigade. This performance and the early fire warning given by sprinklers enable a brigade to commence fire fighting when a fire is small, and bring it under control and extinguish it quickly. Statistical data are available in the UK for estimating the reduction in brigade control time due to sprinklers (see Ramachandran, 1974b). For the reasons mentioned above, sprinklers considerably reduce the time (and money) spent by fire brigades in responding to fire incidents.

The interaction between sprinkler performance and fire brigade operation as described above could have a significant effect on the number of fire stations required in a particular city or area. In the USA, for example, the City of Fresno was, after 1970, the scene of a remarkable experiment on the capability of sprinklers in reducing fire loss. Within the city all buildings in two separate districts, ranging from one to sixteen storeys high, were fitted with complete automatic sprinkler protection. This gave 93.5 per cent and 96 per cent sprinkler protection in those two areas. Despite an 8 per cent increase in the number of fires, the fire losses in those areas were reduced considerably with the result that a fire station could be closed down.

Automatic fire detection systems

As we discussed above (pp. 104–5), early discovery or detection of a fire would enable fire fighting by first-aid methods and/or fire brigade to commence when the fire is small. This would reduce the time required by the brigade to bring the fire under control. Statistical models such as the one shown in equation (5.11), can be applied to estimate the reduction in control time due to detectors. Statistical studies indicate that, on average, the control time will be reduced by half a minute for every minute of early arrival of the brigade at the fire scene. Assuming a detector operating time of 1 minute, the average control time can be reduced by 4.5 minutes if, in the absence of detectors, the average time taken for discovering fires in a city or region is 10 minutes.

As defined with reference to equation (5.11), the attendance time of a fire brigade is part of the time period from the start of ignition to the arrival of the brigade at the scene of fire. The major component of the attendance time is the travel time: the time between a fire fighting unit leaving its quarters and its arrival at the fire scene. Travel times from fire stations depend on their distances from fire scenes, apart from factors such as travel speed and traffic congestion.

The location of a specified number of fire stations would, therefore, affect the travel time; the average travel time for an area can be reduced by changing the locations of fire stations. This can also be achieved by increasing the number of fire stations in an area. The average attendance time for an area can therefore be reduced by optimising the number and location of fire stations subject to economic and other practical constraints. Walker *et al.* (1979) have discussed this problem in detail.

The attendance time and control time are major components of the service time: the total time taken by fire station personnel (and appliances) to attend a fire incident, extinguish the fire and then return to the station. The average value of the service time required for any area can be determined such that it meets an acceptable level of damage to property and life. Subject to this level specified for average service time, there is a trade-off between attendance time and control time. Since, as discussed earlier, automatic fire detection systems have the potential to reduce the average control time for an area, the average attendance time for this area can be increased up to a limit within the level specified for average service time. An increase in attendance time would lead to a reduction in the number of fire stations required for an area.

Determination of the number of fire stations required for an area protected (or not) by detectors is a complex statistical problem. One solution depends on the relationship between service time and fire damage (to property and life). Attempts have been made in fire science literature to establish the relationship between attendance time and fire damage (see, for example, Hogg, 1973; Maclean, 1979; Corman *et al.,* 1976; Halpern *et al.,* 1979).

Halpern (1979) has investigated the problem of substitutability of investment in detector-alarm systems versus fire department expenditure on manned fire stations and equipment with regard to protection of single- and two-family dwellings. He has presented a model which provides a cost-benefit comparison between the productivity of detector-alarm systems and manned fire stations in reducing fire losses. The analysis was based on data collected in Calgary, Canada. Assuming that ten detectors per home was sufficient and using a New York study as a general guideline, Halpern concluded that the detectoralarm system was a viable and competitive alternative to additional fire stations.

There are two problems which need to be considered in an analysis of trade-offs between automatic fire detection systems and number of fire stations. First, detector systems in some properties may be connected directly to fire stations. Such a system, if it operates satisfactorily, will considerably reduce the delay in calling a fire station after a fire is detected.

The second problem is concerned with the reliability of the system. There are two aspects of unreliability relating to detector systems. First, for some reason, the system may not operate when there is a real fire; the probability of non-operation is generally low, particularly for informative fire warning systems. Second, due to malfunction or some other cause, the system may operate when there is no fire, thus giving a false alarm. The frequency of false alarms can be high in some areas and a waste of time and money for a fire brigade.

Smoke ventilation systems

One of the objectives in installing smoke ventilation systems is to enable fire fighters to enter a building involved in a fire and to easily locate the seat of the fire. The extent to which this objective is achieved can be assessed by comparing fire brigades' average control time for fires in buildings with ventilation systems with that for fires in buildings without these systems. Data available at present are not sufficient to carry out this investigation.

However, tentative conclusions can be drawn by analysing data collected by leading manufacturers of smoke ventilation systems. Colt International, for example, compiled case histories of fires in industrial buildings. These were not just success stories of Colt ventilation systems; they included also a cross-section of case histories to show the effects of fires in different industries with different degrees of fire protection. Data provided by such case histories can be combined with those contained in reports on fires furnished by fire brigades. An analysis of the combined data can provide some indication of the effectiveness of smoke ventilation systems.

Ramachandran (unpublished) attempted the statistical analysis mentioned above some years ago using fire case histories published by Colt International in October 1975. These related to seventy-three fires which occurred during 1957–74. Fire brigade reports were identified for fifty-five of these fires which occurred in the UK. According to the information contained in these reports, the average control time was 126 minutes for nineteen fires in buildings without ventilation systems or sprinklers. The average control time was 57 minutes in twenty-six fires in buildings with only ventilation systems and 64 minutes in seven fires in buildings with both vents and sprinklers. These figures, although based on small samples of data, indicate that fire brigades are able to bring fires under control in buildings with ventilation systems quicker than fires in buildings not equipped with these systems. For three fires in buildings with only sprinklers and no vents, the average control time was 86 minutes.

Fire protection and insurance

The role of insurance

Fire insurance is a vital part of fire risk management activities to be undertaken before the occurrence of a fire in a building in order to mitigate the damage likely to be sustained if and when a fire actually occurs. Other activities in this respect are concerned with risk identification, risk evaluation and risk reduction or loss control. The last of the three tasks is executed by adopting appropriate fire prevention and protection measures which might reduce the risk to life and property to a level acceptable to the property owner and society at large. If not, the responsibility for dealing with the residual risk may have to be transferred to an insurance company through fire insurance. For this service, the property owner has to pay the insurance company a reasonable sum every year as a premium and claim financial compensation from the company if and when a fire occurs.

The primary role of a fire insurance company is, therefore, to accept the responsibility for managing the 'residual risk' and provide the property owner with sufficient finance to enable him or her to restart the activity disrupted by a fire. Its secondary role is to promote the adoption of fire prevention and protection measures in order to reduce the national wastage due to fires. For adopting these measures, insurance companies offer incentives in the form of reduced insurance premiums. Hence, there may be some conflict between the two roles since a high level of fire safety might lessen the dependence of the property owner on fire insurance.

Self-insurance

By transferring the residual risk to an insurance company a property owner is bearing part of the risk posed by fires. This part for which the property owner is responsible is covered by self-insurance. The level of self-insurance specified in an insurance contract is known as a deductible, which is further discussed below (pp. 121–7).

Insurance firms impose reasonable amounts of deductibles, particularly for commercial and industrial properties, as part of their role in the promotion of loss control measures. To encourage the acceptance of deductibles, insurance companies offer reductions in insurance premiums higher than those normally given for adopting fire protection measures.

The deductible amount appropriate for a property depends mainly on the level of fire protection provided. Fire protection measures such as sprinklers, if maintained satisfactorily, are capable of reducing the damage considerably if a fire breaks out. Hence, by adopting such measures, a property owner can take the risk of accepting a large deductible. Insurance premiums generally decrease with increasing deductibles.

Optimum package of fire protection and insurance

An industrial or commercial firm is generally aware of the rebates on fire insurance premiums due to the installation of fire protection measures and the acceptance of self-insurance deductibles. However, in the determination of an economic deductible, the firm is unlikely to consider sufficiently the value of fire protection measures in reducing the direct damage to its property and consequential losses such as loss of production, market and profits, discussed in Chapter 9. With adequate fire protection, the firm can take some risk and accept a large deductible which will minimise the total expenditure that comprises self-insured fire damage, the cost of fire protection and insurance premiums.

To determine an economically optimum package of fire protection and insurance, an industrial firm can consider individual and combinations of fire protection measures together with varying deductible levels. This analysis can be performed within a framework provided by the decision tree technique discussed in Chapter 7. Statistical methods based on the concept of probability distribution can be applied to estimate the probable reduction in damage due to fire protection measures and the likely self-insured losses for various deductible levels.

The analysis described in Chapter 7 will be followed by property owners who are 'risk-neutral'. But most of them would be keen to avoid risks and adopt a risk-averse attitude. Some of them may be able to bear small losses but are averse to the risk caused by large losses which might seriously disrupt or bankrupt their business or industrial activities. Such risk preferences can be quantified by applying utility theory (Chapter 8). This technique can also provide an estimate of the maximum amount an industrial or commercial firm can spend on fire protection, self-insurance and insurance premiums. This amount depends on factors such as the firm's assets, financial strength and performance and consequential losses as well as the risk-taking attitude. Within the maximum tolerable expenditure, an economic deductible level consistent with the fire protection measures adopted can be identified (Chapter 8).

Property owners may identify incorrect or unacceptable decisions for fire protection and insurance strategies if the deductible schedules of insurance companies do not accurately reflect the economic value of fire protection measures. Calculation of rebates on insurance premiums should also take into consideration the maximum amount a group of policy holders can spend or are willing to spend on fire insurance. Solutions to these problems are discussed in Chapter 11.

Some antagonism may be encountered when promoting the concept of trade-offs between fire protection and self-insurance/insurance. An insurance company may regard large deductibles as uneconomic since they would reduce its income from premiums. The reduction in premium income may not sufficiently compensate the amount of work the firm will save in not settling and paying small claims. A property owner, on the other hand, may prefer full insurance or a small deductible since, in spite of all the fire prevention and protection measures adopted, the residual risk due to the occurrence of a large fire with serious consequences may be unacceptable although small.

Chapter 7

Decision analysis

Introduction

Fire risk assessment is mainly concerned with the evaluation of the probabilities of occurrence of undesirable events which can cause significant damage to life and property. Such events include flames reaching the ceiling of the room where a fire starts and the fire spreading beyond the room. For this purpose complex stochastic models (Ramachandran, 1995b) have been developed to predict the growth of a fire within and beyond a room as a function of time. However, a simple technique known as fault tree analysis (pp. 114–16) is generally adopted in practical problems to evaluate the probability of occurrence of an undesirable (top) event in the presence or absence of a fire protection device. A reduction in this probability is a measure of the effectiveness of the device. Fault trees and their inverse, success trees, are known as logic trees.

A decision tree (pp. 116–19) is another logic tree model which provides a graphic as well as an analytical tool to compare systematically the effectiveness of different fire protection measures and their combinations. Fault tree analyses of such alternative fire protection strategies together with information on probable damage if the top event occurs can provide input data for a decision tree. Other statistical techniques such as the probability distribution of fire damage may also be used for this purpose. A decision tree analysis would enable the determination of a fire protection strategy which will minimise the total of all costs relevant to any economic level considered.

As discussed in the previous chapters, the total cost at the national economic level is composed of the costs of installing and maintaining fire protection systems and probable fire damage to life and property. For a property owner, the total cost includes costs associated with fire protection, the probable fire loss the owner has to bear for accepting a self-insurance deductible and the insurance premium to cover losses exceeding the deductible amount (see pp. 121–7). The main benefit to the property owner is the reduced insurance premiums which depends on the type of fire protection measure adopted and the deductible amount selected.

Initial or prior assessment of probabilities used in a decision analysis can be revised in the light of expert opinion and additional data if and when they become available. Bayesian analysis (pp. 127–30) is the technique generally adopted for carrying out this revision.

Decision analysis

Fault trees

A fault tree provides a simple method of evaluating the probability of occurrence of an undesirable (top) event leading to a serious fire. The tree is constructed by placing in correct sequential order various factors affecting the top event. This is generally done by working backwards from the top event and specifying the events, faults or conditions that can cause the top event; then working backwards from each of these, which in effect become secondary top events, to a final set of basic events, faults or conditions. A diagrammatic representation of the process resembles the branches of a tree. Probabilities are assigned to the branches for quantifying uncertainties.

Figure 7.1 is a simple example of a fault tree, the undesirable top event being a fire spreading beyond a room unprotected by sprinklers. This event would occur if the entire room were involved in the fire and the fire-resistant structural boundaries of the room failed to prevent the fire spread. Full room involve-ment would occur if the fire were not extinguished by first-aid means, such as portable fire extinguishers and hence spreads beyond the object first ignited. A fire may start due to one of several causes and ignite an object in a room.

The events in a fault tree are connected by logic gates which show what combination of the constituent events could cause the particular top event. These are mainly AND gates in which all the constituent events have to occur simultaneously and OR gates in which only one of the constituent events needs to occur to cause the occurrence of the specific top event. Figure 7.1 illustrates

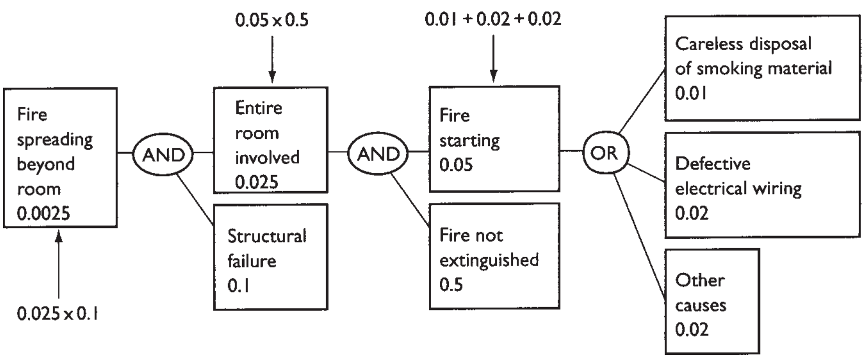


Figure 7.1 Fault tree for a fire spreading beyond a room without sprinklers

the logic underlying the AND and OR gates. The multiplication theorem is applied to the probabilities of the constituents of an AND gate and the addition theorem to the probabilities of the constituents of an OR gate.

According to the probabilities of events specified in Figure 7.1, the probability of a fire starting and spreading beyond the room of origin is 0.0025 if the room is not protected by sprinklers. Sprinklers, if installed, might extinguish a fire before it spreads beyond the object first ignited and involves the entire room. The probability of sprinklers achieving this objective has been estimated to be 0.9 with a failure probability of 0.1. Sprinklers would thus reduce the probability of the top event occurring from 0.0025 to 0.0005 ($=0.05\times0.1\times0.1$).

Consider another example concerned with the undesirable event of flames generated by a fire in a room reaching the ceiling. For this top event to occur all of the following three factors should be present:

1 an ignition source (A)—source A_1 or A_2.
2 heat transfer condition (B)—condition B_1 or $B_{2;}$
3 a material (C)—material C1 or C_2 or C_3.

The fault tree for this example is shown in Figure 7.2, which is an inverted tree with branches stretching downwards.

The events (factors) A, B and C in Figure 7.2 are connected by an AND gate whereas the subevents or factors for each of these events are connected by an OR gate. For purposes of illustration, hypothetical probabilities are specified in Figure 7.2 for the basic events. Using these probabilities the multiplication theorem for the AND gate and the addition theorem for the OR gate have been applied to provide an estimate of the probability (0.0214) of occurrence of the top event, flames reaching the ceiling.

The probabilities for the occurrence of top events estimated in Figures 7.1 and 7.2 are approximate values based on simple probabilistic principles. More accurate values of these probabilities can be obtained by applying complex calculation techniques (Boolean algebra) relating to cut sets or path sets (see Pagés and Gondran, 1986). A cut set is a set of basic events whose occurrence would cause the top event to occur. A path set is a set of basic events whose nonoccurrence ensures the non-occurrence of the top event. For the second example (Figure 7.2) discussed above there are twelve cut sets such as the set involving the factors A_1, B_1 and C_1 which is denoted by (A_1, B_1, C_1). The three path sets for this example are (A_1, A_2), (B_1, B_2) and (C_1, C_2, C_3). A discussion about the evaluation methods based on cut sets and path sets is beyond the scope of this book.

The background to fault trees is based on reliability theory (Green and Bourne, 1972). The reliability of a system is a composite function of the reliability of its components or parts. For example, an automatic fire detection system installed in a large building consists of component parts such as detector

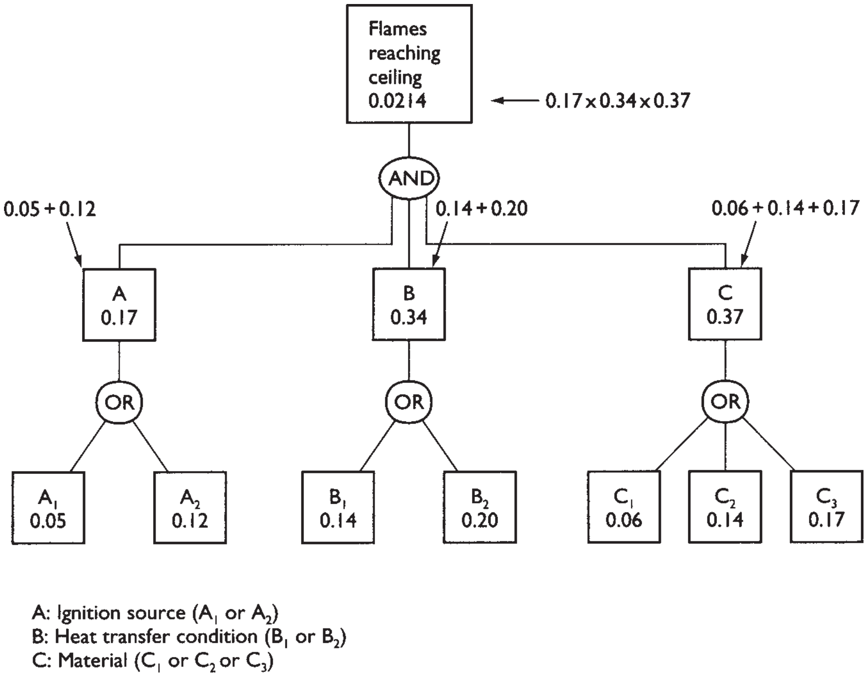


Figure 7.2 Fault tree for flames reaching the ceiling of a room

heads, zone panels, central control panel and connection to fire brigade. Information on the reliability of these component parts and their connections would provide an estimate of the reliability of the whole system in detecting a fire when it occurs and calling the fire brigade. Fault trees have been developed in the chemical industry to identify processes that might lead to detonation and in the nuclear industry to predict the likelihood of certain types of nuclear accidents.

As discussed above, the object of a fault tree analysis is to identify the chain of factors, causes or events leading to the occurrence of an undesirable top event. It can then be investigated whether it is possible to eliminate or reduce the probability of occurrence of any of the events in the chain by adopting appropriate control measures or actions. Such measures or actions would, in turn, reduce the probability of occurrence of the top event.

Decision trees

If a fire starts in a building with probability F, it might grow to cause the occurrence of an undesirable top event with probability F_u. A fault tree analysis, as described in the previous section, would provide an estimate of F_u. If the top event occurs, there may be consequences which can be quantified by probable damage, D_u, to life and property. The probable damage in a fire is, therefore, given by the product of $F.F_u.D_u$. In this model based on a fault tree analysis, it is assumed that the damage likely to be sustained if the top event does not occur is negligible. Other models, e.g. probability distribution, would provide an estimate of probable fire damage $\bar{x}$ for the entire range of the random variable x denoting damage. For such a model the probable damage is given by $F.\bar{x}$.

The object of fire safety is to identify a course of safety action or protection strategy which will minimise the probable damage $F.F_u.D_u$ or $F\bar{x}$. But the provision of fire protection for a building will involve a cost C for installing and maintaining the protection system. The modified objective at a national economic level is, therefore, to identify a protection strategy which will minimise the total cost $C+F\bar{x}$. The insurance premium is another cost to be considered by a property owner.

The selection of a fire protection strategy which minimises the total cost is facilitated by representing the various alternative strategies or options available on the branches of a decision tree which provides a graphic as well as an analytical tool. Figure 7.3 is an example of a decision tree representing eight options available to the owner of an industrial property to reduce the adverse effects of fire incidents. These result from four fire protection options, each with two choices for insurance. The term 'no deductible' applies to full fire insurance coverage for the property and the term 'self-insurance' to 'no insurance'. The tree can be expanded by incorporating another insurance option discussed on pp. 121–7: partial insurance plus partial self-insurance with a deductible. The tree can be further expanded by considering several deductible levels and fire protection choices.

As shown in Figure 7.3, the eight fire protection and insurance options are represented by the branches of the decision tree emanating from decision forks. Each option would involve some risk of fire damage, varying from a small or no loss to a big loss resulting from almost total destruction of the property. These two limits for the loss are shown on the branches of the decision tree emanating from probability forks.

For any option, the variability in the loss between the two limits can be analysed by identifying an appropriate probability distribution, e.g. Pareto, log normal, and estimating its parameters with the aid of statistical data on fire losses. Based on this distribution the average or expected loss in a fire can be estimated to quantify the risk of loss which the property owner has to bear under a given option. This expected loss, denoted by $\bar{x}$, would vary from option to option; it can be converted to an annual loss by multiplying it by F, which may be redefined to refer specifically to the annual probability of fire starting or the expected number (frequency) of fires in a year. The annual loss expected is hence given by the product of $F\bar{x}$. The value of F will not vary from option to option.

Apart from the expected annual fire loss $F\bar{x}$, each option would also involve an annual cost C towards fire protection and annual fire insurance premium I.

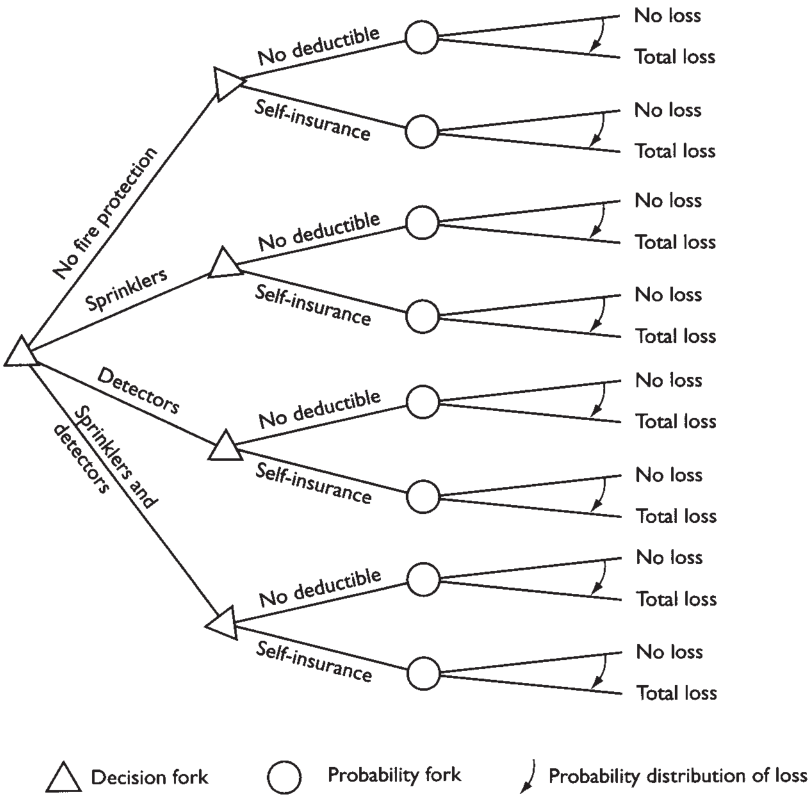


Figure 7.3 Decision tree for investment in fire protection and/or insurance

For C, a net amount may be estimated to take account of benefits such as tax allowances and costs towards maintenance of the protection system and other expenditure, if any. The sum of these three annual costs is the total annual cost; denoted by T. The object of a decision analysis is to identify the option likely to involve the least total cost.

It should be pointed out that $F\bar{x}$ is the part of fire loss which a property owner has to bear for taking the risk of carrying some level of self-insurance. The value of $\bar{x}$ will be very small if full insurance cover with no self-insurance deductible is provided for a property. With full insurance, a fire insurance company will reimburse the property owner almost the entire loss when a fire breaks out. If the property is fully self-insured with no insurance cover, $\bar{x}$ will be equal to the average loss expected in the range below the value of the property and its contents.

In the USA, the National Fire Protection Association and the General Services Agency have developed decision trees which have resulted in the concept of the goal oriented systems approach to fire safety (National Bureau of

Standards, 1977). An analysis of the decision tree type was carried out by Helzer *et al.* (1979) to evaluate alternative strategies for reducing residential upholstered-furniture fire losses. These authors considered three alternatives: no action; mandatory smoke detector installation; and an upholstered-furniture standard. The alternatives were evaluated on the basis of minimising the total cost plus loss to society over time. Subject to the assumptions used, the analysis showed that the detector alternative and the proposed standard were essentially equivalent and preferred to the no-action alternative.

For airport buildings, Shpilberg and Neufville (1974a) carried out a decision analysis to optimise the choice of fire protection and insurance. This investigation involved the application of utility theory and is discussed in detail in Chapter 8 (pp. 146–51). The decision tree used by the authors is reproduced in Figure 8.3. The authors considered two fire protection strategies: sprinklers and no sprinklers and different amounts of self-insurance deductibles.

Decision analysis

Consider, as an example, the four branches in Figure 7.3, involving sprinklers and insurance but no partial insurance or self-insurance. The property owner is faced with four alternative courses of action as enumerated in Table 7.1. If sprinklers are not installed and insurance cover is not obtained, the property owner has to bear the entire cost of fire damage, the expected value of which is $\bar{x}_0$. The total annual cost in this case is $F\bar{x}_0$ where F is the annual probability or number of fires. With no sprinklers, if full insurance cover is taken, the total annual cost is the annual insurance premium I_0 since most of the fire damage will be compensated by the insurance company. The premium has to be paid whether a fire occurs or not.

Consider now the installation of sprinklers which would involve an annual cost of C_s. This cost, as mentioned earlier, is the net amortised cost of installing sprinklers after subtracting from the gross amount of benefits such as tax allowances and grants reduced to an annual basis. If appreciable, an annual sum may be added to C_s towards maintenance of the sprinkler system and charges

Table 7.1 Sprinklers and insurance: four choices

Choices	*Annual costs*			
	Sprinklers	*Full insurance*	*Fire damage*	*Total annual cost*
No sprinklers, no insurance	—	—	$F\bar{x}_0$	$F\bar{x}_0$
Sprinklers, no insurance	C_s	—	$F\bar{x}_s$	$C_s + F\bar{x}_s$
No sprinklers, insurance	—	I_0	—	I_0
Sprinklers, insurance	C_s	I_s	—	$C_s + I_s$

levied for water used for the system. With sprinklers and no insurance the total annual cost is $C_s+F\bar{x}_s$ with $\bar{x}_s$ denoting the expected fire damage which is likely to be considerably less than $\bar{x}_0$. If full insurance cover is obtained, the total annual cost would be C_s+I_s with an annual insurance premium Is considerably less than I_0.

It may be seen that, without insurance, installation of sprinklers would be justified if:

$$C_s+F\bar{x}_s<F\bar{x}_0$$

which is the same as the condition

$$F(\bar{x}_0-\bar{x}_s)>C_s$$

In other words, the probable reduction in annual fire damage due to sprinklers should exceed the net annual cost of sprinklers. This condition would be generally satisfied by a large building for which the probability (F) of fire starting is not very small. With insurance, installation of sprinklers would be justified if:

$$C_s+I_s<I_0$$

or

$$I_0-I_s>C_s$$

This condition would be satisfied by most of the industrial or commercial buildings for which insurance companies offer substantial reductions in premiums for direct and consequential loss cover.

Consider now the comparisons requiring decisions on full insurance cover. Insurance would be justified if:

$$I_0<F\bar{x}_0 \tag{7.1}$$

in the absence of sprinklers, or if:

$$C_s+I_s<C_{s+}F\bar{x}_s$$

or

$$I_s<F\bar{x}_s \tag{7.2}$$

in the presence of sprinklers. Neither of these conditions can be satisfied since, to transact its business successfully, an insurance company has to add two types of loading to the 'risk premiums' $F\bar{x}_0$ and $F\bar{x}_s$. The first loading is known as 'safety loading' and the second is to cover the insurer's operating costs, which include profits, taxes and other administrative expenses (see Chapter 11). Due to this basic principle underlying insurance activity, the insurance option would appear to be uneconomic.

However, it is necessary to obtain insurance cover for the following reason. The period in years estimated by 1/F is known as the 'return period' for the occurrence of a fire. If a fire occurred at the end of this period the owner of a property could set apart annually, in advance, a sum of $F\bar{x}_s$ or $F\bar{x}_0$ depending on whether a sprinkler system had been installed or not. There is no need to have insurance protection if the exact time of occurrence of a fire can be predicted but, due to the influence of random (uncontrollable) factors, a fire can break out at any time during the 'return period'. The direct material loss in a fire can be higher than $\bar{x}_s$ or $\bar{x}_0$ and can also cause indirect (consequential) losses. Insurance converts such a loss of unknown magnitude occurring at a random time into a known cost, the insurance premium payable annually. The premium must necessarily be larger than the expected (average) loss for the reasons mentioned earlier. The four options analysed in this section have been included in the example discussed in the next section.

Deductibles

Definition

To promote loss control activities, insurance companies offer incentives in the form of reduced premiums to property owners who agree to share with them the financial burden caused by fire losses. This partial risk transfer to an insurer and partial risk-retention (self-insurance) by a property owner is known as a 'deductible'. As explained by Strauss (1975), there are basically two types of deductibles: amount deductibles and time deductibles. The latter type, defined in units of time, is only possible with an insurance where a loss occurs over a certain period of time and is not an instantaneous event. Thus a time deductible is quite suitable in fire consequential loss or loss of profits insurance (Chapter 9). This chapter is only concerned with amount deductibles which are related to direct material damage in a fire and are essentially of two kinds: pure deductibles and franchise. According to the second kind, not discussed in this chapter, the insurer is required to indemnify in full any losses exceeding an agreed limit without deducting the insured's share, while the insured is responsible for any losses lower than the agreed limit.

This chapter discusses the first kind of amount deductibles, 'pure' deductibles, where the insurer provides no indemnification for losses below the amount agreed on but, when indemnifying losses exceeding that amount, is responsible for the claim minus the deductible amount. Symbolically, the insurer has no liability for any loss up to the deductible limit D. For any loss L greater than D the insurer's liability is limited to (L-D); in this case the insured has to bear part of the loss equivalent to the amount D.

The insured, therefore, faces the problem of enlarging the decision tree (Figure 7.3) with the introduction of different levels of deductibles and selecting an optimum level. He or she must somehow balance the greater insurance protection that comes from a small deductible with the corresponding increase in the premium. At one extreme, the insured can have minimum fire protection coupled with the smallest deductible and hence self-insure the property only for very small losses, or, at the other extreme, have a high level of fire protection with a large deductible and thus self-insure for all but very large losses. The additional cost of increased fire protection needs to be compensated by the additional saving on premiums provided by a decrease in the insurance coverage with a large deductible. The problem, therefore, is to determine an optimum scheme of fire protection and insurance, taking into account all the costs and benefits involved.

Property owner's liability

If fire loss has a log normal distribution, following Ramachandran (1982b), the expected value of loss *x* in a fire in a property with total financial value *v* at risk is given by:

$$\bar{x}_v = [G\,(k - \sigma) \,/\, G\,(k)] \exp\left(\mu + \frac{\sigma^2}{2}\right) \tag{7.3}$$

where μ and σ are the mean and standard deviation of log *x* (to base *e*), G*(t)* is the (cumulative) distribution function of the standard normal variable with mean zero and standard deviation unity and

$$k = (\log_e v - \mu) \,/\, \sigma$$

The probability of loss exceeding *x* is [1-(G(u)/G(k))] where u=($\log_e$ x-μ)/σ. The entire amount of expected loss given by equation (7.3) has to be borne by the property owner if insurance cover, part or full, is not obtained.

If a fire occurs in a property insured for a deductible amount D, the owner can expect to be responsible for a sum of:

$$\bar{x}_D = \frac{G(w - \sigma)}{G(k)} \exp\left(\mu + \frac{\sigma^2}{2}\right) + D\left[1 - \frac{G(w)}{G(k)}\right] \tag{7.4}$$

where w=($\log_e$ D-μ)σ.

On average, for policies with a deductible D the insurance firm is likely to be liable for a sum of:

$$\bar{R}_{\mathrm{D}} = \frac{G(k-\sigma) - G(w-\sigma)}{G(k)} \exp\left(\mu + \frac{\sigma^2}{2}\right) - D\left[1 - \frac{G(w)}{G(k)}\right] \quad (7.5)$$

per claim. It may be verified that:

$$\bar{x}_{\mathrm{D}} + \bar{R}_{\mathrm{D}} = \frac{G(k-\sigma)}{G(k)} \exp\left(\mu + \frac{\sigma^2}{2}\right)$$

which is the expected (average) value of loss x given by $\bar{x}_V$ in equation (7.3). The insured and the insurer share the average loss according to $\bar{x}_D$ and $\bar{R}_D$

Example

Consider now the example discussed by Ramachandran (1984) relating to a small multistorey textile industry building of total floor area 2,500 m^2. With a value density of £200 per m^2 (1966 prices), the total value of the property was assumed to be £500,000 (1966 prices). The probability (F) of a fire starting during a year in a textile industry building of total floor area 2,500 m^2 was estimated to be 0.12. This was based on a ‘power’ relationship between the probability of fire starting and building size (or value) discussed in Chapter 6 (equation 6.4) and Rutstein’s (1979) estimates for the constants in this relationship.

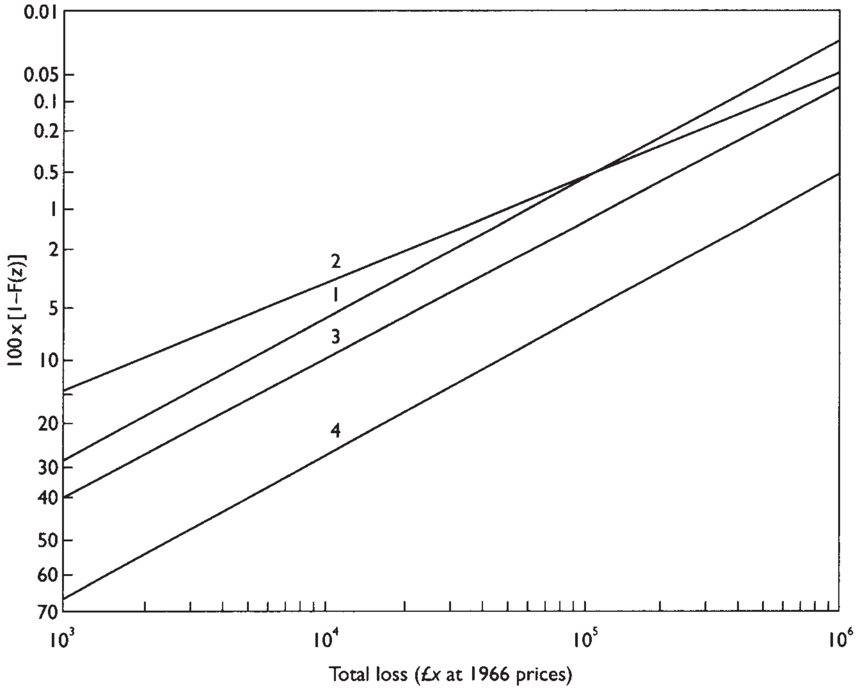
If a textile industry building is multistoreyed, according to Rogers (1977), the mean, μ, and standard deviation, σ, of the logarithm (base e) of loss (in 1966 prices) in units of thousands of pounds are as follows:

With sprinklers:	μ = -3.267,	σ=3.085
Without sprinklers:	μ = 0.923,	σ=2.284

Rogers assumed a log normal distribution as depicted in Figure 7.4. Using the results given above and equations (7.3) to (7.5), the values of $\bar{x}_{\mathrm{D}}$, $\bar{R}_{\mathrm{D}}$ and the expected total annual loss to the property owner have been calculated and are given in Table 7.2.

According to Ramachandran (1984), the cost of installing sprinklers in a building of total floor area 2,500 m^2 was £2,400 at 1966 prices. This was equivalent to an annual cost of £240 (1966 prices) at an interest rate of 10 per cent and forty years for the life of a building. The annual maintenance cost was negligible in comparison with the initial cost. The figure of £240 has been used in Table 7.2 although a small amount should be subtracted towards benefits such as tax allowances.

According to hypothetical calculations carried out by Ramachandran (1984), the annual premium rate for full insurance coverage would be 0.0025 for a property equipped with sprinklers and 0.0065 for a property without sprinklers.



Line	Subpopulation	Parameters[a]
1	Sprinklers/single-storey	$\mu = -0.616$ $\sigma = 1.024$
2	Sprinklers/multistorey	$\mu = -1.419$ $\sigma = 1.340$
3	No sprinklers/single-storey	$\mu = -0.334$ $\sigma = 1.062$
4	No sprinklers/multistorey	$\mu = 0.401$ $\sigma = 0.992$

Figure 7.4 The survivor probability distribution of fire loss for each class in the textile industry

Source: Rogers (1977)

Notes

[a] The parameters μ and s are the mean and standard deviation of $\log_{10}x$.

F(*z*) (cumulative distribution for *z*)= probability of loss less than or equal to *z*.

V(*x*) (cumulative distribution for *x*)= probability of loss less than or equal to *x*.

Survivor probability=l-F(*z*)=l-V(*x*)= probability of loss exceeding *x* or *z*.

Hence, for the example considered, the annual premium at 1966 prices would be £1,250 if sprinklers were installed and £3,250 if there were none. Suppose an insurance firm calculates rebates for deductibles on the basis of the risk premium $\bar{R}_D$, for a sprinklered building the annual premium for a £50,000 deductible would be:

Table 7.2 Multistorey textile industry building: expected total annual cost (1966 prices) (V=£500,000)

	Deductible level (D) (£)	*Average self-insurance cost per fire ($\bar{x}_D$) (£)*	*Annual self-insurance cost ($F\bar{x}_D$)[a] (£)*	*Average risk premium per fire ($\bar{R}_D$) (£)*	*Annual insurance premium (I_D) (£)*	*Expected total annual cost[b] (T_D)[c] (£)*
With sprinklers	Full insurance	—	—	2,200	1,250	1,490
	50,000	1,400	168	800	455	863
	100,000	1,700	204	500	284	728
	Full self-insurance	2,200	264	—	—	504
Without sprinklers	Full insurance	—	—	17,700	3,250	3,250
	50,000	10,000	1,200	7,700	1,414	2,614
	100,000	13,100	1,572	4,600	845	2,417
	Full self-insurance	17,700	2,124	—	—	2,124

Notes

a $F = 0.12$

b Includes £240 (C_S) for sprinklers

c $T_D = F\bar{x}_D + I_D + C_S$

$$\frac{800}{2,200} \times 1,250 = £455$$

Similarly, the annual premium for this building would be £284 for a £100,000 deductible. Similar calculations would show that, for the non-sprinklered case, the annual premium is £1,414 for a £50,000 deductible and £845 for a £100,000 deductible. (All the premiums mentioned above are at 1966 prices.) No quotation from any insurance company was obtained to check the accuracy of the premium figures since the object of the study was to explain the concepts involved in a decision analysis.

The figures above have been used in Table 7.2 to estimate the total annual cost expected to be incurred by the property owner. The total cost T_D is given by:

$$T_D = F\bar{x}_D + ID + CS \qquad (7.6)$$

where F (=0.12) is the annual probability of fire starting, I_D the annual insurance premium for a deductible D, and C_s (=£240) the annual cost of sprinkler protection, if sprinklers have been installed.

The figures in Table 7.2 for $\bar{x}_D$ and $\bar{R}_D$ are applicable to a fire which grows beyond the 'infant' stage. The probability of the fire not reaching this stage and remaining small has not been considered. In the case of sprinklers, the results relate to a fire in which the system operates. If necessary, these figures can be adjusted by assigning an appropriate probability for the system not operating in a fire.

The figures in Table 7.2 are at 1966 prices and can be expressed at current prices by applying an appropriate factor based on, say, indices of retail prices. Such a correction for inflation will not affect the observations which support the theoretical arguments discussed earlier. Sprinklers considerably reduce the cost of fire damage ($\bar{x}_D$) and the total annual cost which includes the cost of protection. The annual savings will be proportionately higher for buildings larger than 2,500 m^2 in total floor area, as estimated by Ramachandran (1984) for a building of 10,000 m^2. Whether a building has sprinklers or not, the total cost would decrease with increasing levels of self-insurance. This trend could inevitably lead to the incorrect decision that full self-insurance or no insurance is a cheaper option than full insurance. It is essential to protect a property with some insurance, full or partial, to mitigate in particular the crippling consequences of a large fire. With sprinkler protection, a property owner can take the risk of accepting the financial burden associated with a large deductible.

Sensitive factors

The results of a decision analysis, particularly those relating to insurance options, are sensitive to the value assigned to the probability F of fire starting.

For this parameter a global value of 0.12 has been adopted when estimating the figures in Table 7.2. Calculations based on equations (7.1) and (7.2) would show that the full insurance option would be economical if F exceeds 0.18 (= 3,250/17,700) for a building without sprinklers or exceeds 0.57 (=1,250/2,200) for a building with sprinklers. The probability of fire starting, of course, does not depend on the presence or absence of sprinklers. It is necessary to estimate with reasonable accuracy the value of F for a particular building from past data on fires in this building or from other sources. If past data on fire damage are available even for a few fires, advanced statistical techniques can be applied to construct the probability distribution of fire damage *(x)* specially for this building.

The results of a decision analysis are also sensitive to rebates on fire insurance premiums for different levels of deductibles. The loading on an insurance risk premium towards operating costs, mentioned earlier, is generally independent of the size of a deductible. Saving on operating costs is not proportional to the saving on a claim amount arising from a deductible. But, by accepting deductibles, there will be some saving on these costs since the insurer will not have to settle and pay for small losses. Rebates for deductibles depend very much on the method adopted by an insurance company to calculate the risk premium and the loadings. As observed by Shpilberg and Neufville (1974a), inaccurate deductible schedules can produce unexpected results leading to incorrect decisions. Calculation of rebates for deductibles should take sufficient account of the reduction in loss due to a fire protection measure (see pp. 192–5).

Risk preferences

As discussed in this and the previous section, the method usually adopted in a decision analysis or benefit-cost analysis (Chapter 5) is based on expected values of losses and costs. This approach implies that a property owner has a ‘neutral’ attitude towards fire risk. But most property owners are ‘risk-averse’ and would take the necessary precautionary measures to avoid the occurrence of a large fire, however small the probability of this event might be. They would seriously consider the intrinsic values of fire losses and the costs of fire protection and insurance. This intrinsic value is known as the ‘disutility’ of a loss or the cost or ‘utility’ of a gain. The risk preferences of a property owner can be encoded with the aid of utility functions, which is the subject matter of Chapter 8.

Bayesian analysis

Introduction

As we pointed out in the previous section, the results of a decision analysis are sensitive to the probabilities attached to parameters such as the probability of a fire starting and fire loss. Sufficient information to estimate these quantities is unlikely to be available for carrying out the analysis for a particular building. In such cases, a prior or initial assessment is generally made of the likelihood of an event occurring. Then, an expert is consulted or a sample of observations collected in order to confirm or revise the initial assessment. In some cases, statistical data for at least a group of similar risks (buildings) may be available to estimate the prior probabilities; this can be revised in the light of expert opinion and/or some data which may be available for the building considered. This is the particular problem discussed in this section, although Bayesian technique has been applied to several other types of problems.

Bayes' theorem

According to Bayes' theorem (La Valle, 1970) the 'posterior' probability, $P(H_i/A)$, of occurrence of event H_i given observation A is proportional to the 'prior' probability, $P(H_i)$, times the likelihood of A, given H_i, $P(A/H_i)$:

$$P(H_i/A) \propto P(A/H_i)\, P(H_i) \tag{7.7}$$

Equality is obtained by normalising with respect to the set of (exhaustive, mutually exclusive) events: $H_1, H_2, \ldots H_p$, or, in short, by dividing the right-hand side of equation (7.7) by

$$\sum_j P(A/H_j)\, P(H_j)$$

We can, therefore, write:

$$P(H_i/A) = \frac{P(A/H_i)\, P(H_i)}{\sum_j P(A/H_j)\, P(H_j)} \tag{7.8}$$

Example

Consider now the example discussed in the previous section. Based on national statistics, an estimate of 0.12 has been used for the probability (F) of a fire of significant size (not very small) starting during a year in a textile industrial building of total floor area 2,500 m^2. Suppose this 'global' figure has been reevaluated to be 0.25 for a particular building by considering human (e.g. careless disposal of cigarettes) and non-human (e.g. faulty electrical appliances) sources of ignition actually present in the building. In the absence of any data for this building, 0.25 may be considered as the prior probability $P(H_1)$ for the occurrence of a fire during a year with $P(H_2)=0.75$ for non-occurrence. It may be desirable to revise this initial assessment by analysing a sample of recent fires in the building considered. If this exercise, denoted by the letter A, produces an estimate of, say, 0.8 for the annual probability of fire starting, $P(A/H_1) = 0.8$ and $P(A/H_2) = 0.2$.

According to the sampling exercise mentioned above, the risk of fire starting in the building is considerably higher than the risk in an 'average' textile industry building of similar size in the UK. But, statistically, with a larger variance, the estimated figure of 0.8 provided by a small sample is likely to be less reliable than the estimate 0.25 based on a much larger sample. Hence, in assessing the economic value of a fire protection measure, it would be appropriate to consider the national estimate as well but to modify or revise it in the light of information provided by a sample of recent fires in that building.

Based on the figures mentioned above and using equation (7.8), the 'posterior' (revised) annual probability of fire occurrence in the particular building considered may be calculated:

$$P(H_1/A) = \frac{0.8 \times 0.25}{(0.8) \times (0.25) + (0.2) \times (0.75)} = 0.57 \tag{7.9}$$

The 'posterior' value of $P(H_2/A)$ is 0.43. Based on national data, expert opinion and sample data, the prior probability 0.25 for fire occurrence has thus been revised upwards to 0.57. If this higher value for F is inserted in equation (7.6) it will increase the total annual cost considerably such that the full insurance option will be more economical than self-insurance, full or partial, particularly for a building without sprinklers.

Suppose the sampling exercise has produced an estimate of 0.5 for the probability of fire starting, $P(A/H_1)$, in the building considered. In this case, calculations as in equation (7.9) would show that the 'posterior' probabilities $P(H_1/A)$ and $P(H_2/A)$ are the same as the corresponding 'prior' probabilities $P(H_1)$ and $P(H_2)$; there is no need to revise the initial assessment. The sampling exercise has merely confirmed that the initial assessment is reasonably correct.

As discussed above, probability estimates provided by a national or large sample must necessarily be utilised in a decision analysis if data are not available or cannot be collected for a particular building. However, if data can be collected for a particular building or group of buildings they can be used in a Bayesian analysis (equation (7.8)) to provide revised estimates of initial assessments based on national data. It would be apparent from equations (7.8) and (7.9) that the 'posterior', revised or final, values of the probabilities would be the same whether national or sample values are used for 'prior' or initial probabilities.

Bayesian technique thus provides a mechanism for coupling information from two sources: national data and sample data. Information provided by other sources can also be coupled with the aid of Bayesian technique. Such sources in the fire safety field include experimental data, results of simulation exercises based on mathematical models, and assessments made by fire safety engineers. Subject to financial constraints, some or all of the information sources mentioned above can be considered to estimate a range of 'posterior' probabilities for use in a decision analysis.

Other applications

Bayesian analysis may also be applied to the probability of loss *(x)* exceeding a specified level or probability of fire spreading beyond the room of origin. According to UK national fire statistics (Ramachandran, 1995b), for example, the probability of a fire spreading beyond a room in a textile industry building is 0.07 if the room has no sprinklers and 0.02 if it has sprinklers. For any particular building, these figures can be used as prior probabilities and revised on the basis of expert opinion or estimates provided by deterministic models.

Another application of Bayesian analysis in the fire protection field is concerned with the probability distribution of area damage or financial loss in a fire. The figures for the parameters u and σ of the log normal distribution for fire losses *(x)* discussed in the last section, for example, can be considered as prior values for multistorey textile industry buildings. These values can be revised with the aid of estimates provided by a sample of fires which occurred in buildings of this type during a recent period.

Consider now a sample of *n* fires for which the mean $\bar{Z}$ of logarithms of losses has the expected value μ and standard deviation $\sigma/\sqrt{n}$. With these parameter values, $\bar{Z}$ would vary from sample to sample, each of size *n,* according to a normal distribution. This distribution of $\bar{Z}$ is referred to as the 'prior' distribution because it has been specified with values of its parameters prior to the collection of data for the sample. The conditional distribution of $\bar{Z}$ given the sample data is called the 'posterior' distribution of $\bar{Z}$ whose mean is known as Bayes' estimator of $\bar{Z}$. Estimation of the posterior distribution from a knowledge of the prior distribution is a complex statistical problem which is beyond the scope of this book.

Chapter 8

Utility theory

This chapter is a slightly modified version of Chapter 9, section 5, contributed by the author to the *SFPE Handbook of Fire Protection Engineering,* 2nd edn, Quincy, MA; National Fire Protection Association, 1995. The author wishes to thank the Society of Fire Protection Engineers for its permission to reproduce this chapter.

Introduction

In Chapter 4, we discussed the technique of cost-benefit analysis to determine the acceptability of an investment project and to compare the economic value of different projects. The application of this method to fire protection problems was also illustrated. For benefits such as reduction in fire damage which involve chance effects, expected values are calculated by weighting them according to their probabilities.

In cost-benefit analysis, as it is usually carried out, expected values of costs and benefits are evaluated in monetary terms. This expected monetary value approach assumes that the decision-maker is risk-neutral, but most decision-makers would be keen to avoid risks and adopt a risk-averse attitude. Some people may prefer to take risks. Any person is usually a risk-preferer for ventures involving small losses and a risk-avoider for those involving large values. Such risk preferences can be quantified by appropriate utility functions which measure the intrinsic values of positive monetary outcomes, i.e. gains. Disutility, the negative counterpart of utility, is the appropriate term in an analysis involving negative outcomes such as fire loss, the cost of fire protection and insurance. The decision analysis needs to be carried out in terms of expected disutilities associated with fire loss and costs. The object of this chapter is to explain the basic concepts concerned with utility/disutility theory and to illustrate their application to fire protection and insurance problems.

The utility concept

The concept of utility needs to be explained first. Utility is defined as the intrinsic value of money which, as shown by Von Neumann and Morgenstern

(1947), can be quantified in terms of the rational economic behaviour of people in satisfying their needs. In the context of decision analysis, utility is a number measuring the attractiveness of a consequence: the higher the utility, the more desirable the consequence, the measurement being made on a probability scale.

It will be simpler to explain the need for the utility theory approach by considering examples based on participation in a game of chance. Suppose a person is offered the following bet, involving no cost, on the toss of a coin: he or she wins £200 if the coin comes up heads and loses £100 if the coin comes up tails. If the coin is fair the probability of heads or tails coming up is ½. The expected payoff is:

$$½(£200)+½(-£100)=£50$$

if the person playing the game takes the bet and zero if he or she does not take the bet.

For a similar game involving a cost of £10 the net payoff is £40, as given by:

$$½(£190)+½(-£110)=£40$$

According to the expected value criterion, the bet should be taken by the person even if it involves a cost since it looks intuitively advantageous, unless the individual is opposed in principle to gambling.

In the coin-tossing game with no cost, let the amounts involved be £20,000 and £10,000 instead of £200 and £100. The expected payoff is £5,000 if the bet is taken and zero if the bet is not taken. According to the expected value criterion, the bet should be taken, especially in view of the large expected payoff. Will the person playing the game do so? Probably not, unless he or she is wealthy enough so that a loss of £10,000 would not seriously affect his or her financial position. The possible gain of £20,000 is tempting but there is still a 50 per cent chance of a loss of £10,000.

As another example, consider a choice between two bets. In the first bet, the person playing the game wins £3 million if a coin comes up heads and wins £2 million if the coin comes up tails. In the second bet that person wins £10 million if the coin comes up heads but wins nothing if the coin comes up tails. The expected payoffs of the two bets are £2.5 million and £5 million. The second bet has a much larger expected payoff than the first and hence should be chosen on the basis of the expected value criterion. However, most people would probably choose the first bet since they could certainly win at least £2 million, which is a large sum of money. By taking the second bet there is a 50 per cent chance of winning nothing.

As discussed above (pp. 119–21), providing insurance cover for a property may appear to be uneconomic if the expected monetary value approach is followed. But an insurance premium is a known (certain) cost whereas the loss expected in a fire is an unknown cost subject to statistical uncertainty. The property owner would prefer the certain loss of a small sum (the insurance premium) to a small chance of a loss much larger than the loss expected in the event of a fire. By taking full insurance cover, almost the entire value of a property can be recovered in the event of a catastrophic fire. By not taking full insurance cover, there is a small chance of losing the entire amount invested in the property. The preference for a small fixed loss over a risk of large loss originates primarily from an aversion to the psychological state of uncertainty. For the reasons mentioned above, the expected monetary value approach is not a satisfactory method for decisions involving fire protection and insurance.

These examples illustrate the fact that, for a specific person, the 'value' of gaining £*x* (or the 'consequence' of losing £*x*) is not necessarily *x* times the 'value' or 'consequence' of gaining or losing a single pound. The value of money may also differ from person to person depending on other economic factors such as assets. The gain or loss of a small sum may not affect the financial strength of a rich person but it could cause serious problems to a poor person. If it could somehow be possible to measure the true relative values to the decision-maker of the various possible payoffs in a problem of decision-making under uncertainty, expectations could be taken in terms of these 'true' values instead of the monetary values. The theory of utility or disutility prescribes such a decision-making rule: the maximisation of expected utility or the minimisation of expected disutility. According to the original rule, the object is to maximise the expected monetary gain or minimise the expected monetary loss or cost.

Utility theory makes it possible to measure the 'true' or 'intrinsic' value to a decision-maker of a gain or loss; this includes all aspects of payoffs or consequence, monetary or otherwise. This theory provides a means of encoding risk preferences in such a way that the risky venture with the highest expected utility or the lowest expected disutility is preferred. Symbolically, if the monetary value of the ith outcome is X_i, the utility corresponding to a gain X_i is $U(X_i)$; the disutility corresponding to a loss X_i may be denoted by $D(X_i)$. If a probability $p_{ui}(X_i)$ is associated with gain X_i, the expected value of $U(X_i)$ is $p_{ui}(X_i)$. $U(X_i)$. Likewise, if a probability p_{di} (X_i) is associated with loss X_i the expected value of $D(X_i)$ is $p_{di}(X_i)$. $D(X_i)$.

Utility functions

The mathematical structure of the function U(X) is central to the application of utility theory. Figure 8.1 shows graphically three typical utility functions that are usually encountered in this analysis (see Moore, 1972). The function represented by the straight line A is appropriate for a decision-maker operating on an expected monetary value (EMV) basis. This line satisfies the equation U(X) =X and represents risk neutrality. The concave curve B corresponds to a risk-averse (or risk-avoiding) decision-maker and the convex curve C to a

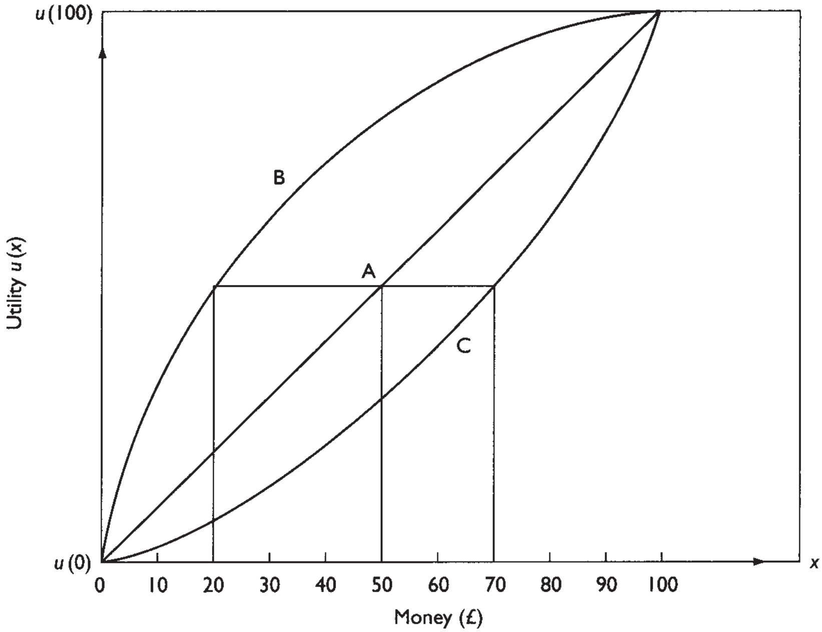


Figure 8.1 Typical utility functions

risk-prone (or risk-taking) decision-maker. For a decision-maker who is more risk-prone than the EMV man or who prefers a risk, the utility of a fair game exceeds the utility of not gambling and hence a fair game will always be played. On the other hand, a decision-maker who is more risk averse than the EMV man does not like or cannot afford risks and is a risk avoider. Some individuals could have a sigmoid form of utility function as illustrated by Figure 8.2. Such a person is a risk preferer for small values of X but a risk avoider for larger values.

Consider now a game with 0.5 chance of winning £100 and 0.5 chance of winning nothing which has the expected value £50. The expected value line A in Figure 8.1 connects the points [O, U(O)] and [100, U(100)]. To find the utility of the game for the risk avoider (curve B), find the utility value corresponding to the point on the straight line above the expected value £50 of the game. By reading to the left, cutting curve B, this is equal to U(£20) so that the decision-maker's cash equivalent (CE) for the game is £20. He would be willing to pay up to £20 to be able to participate in the game. This is still below the EMV of £50 since the utility function B is that of a risk avoider. The difference between the EMV and CE is the risk premium, which is £30 in this example. The decision-maker would be willing to pay £30 to avoid the risk involved in participating in the game.

In the case of a risk taker, denoted by curve C, the utility of the game is equal

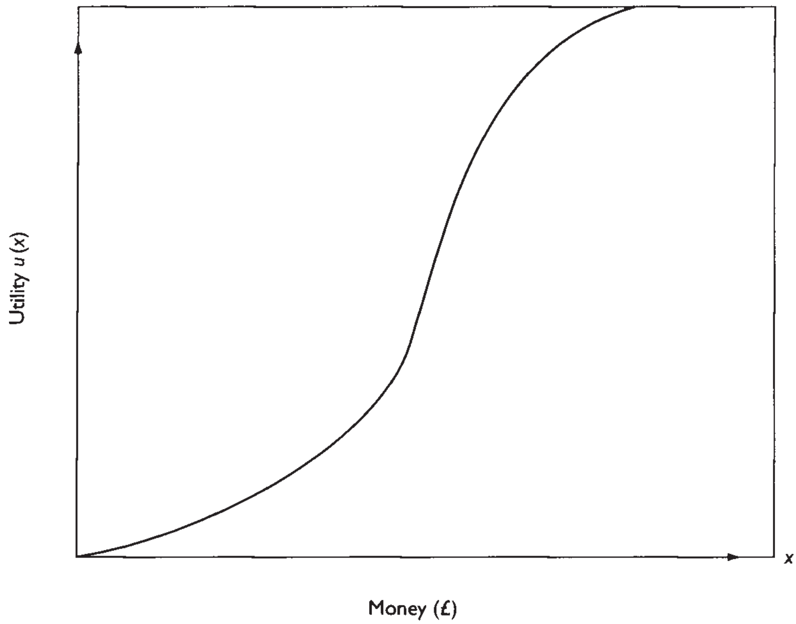


Figure 8.2 Sigmoid utility function

to U(£70) so £70 is the cash equivalent of the game. Although the expected value is only £50, the risk taker is willing to pay up to £70 to be able to participate in the game. Hence the risk premium is -£20; it is negative because the decision-maker, instead of being willing to pay a premium to avoid the risk in the game, is willing to pay a premium (above and beyond the expected value) in order to be able to participate in the game.

The risk premium (RP) discussed above is the amount which a decision-maker on the basis of his or her utility function is willing to pay to avoid or participate in a risky activity. For increasing utility functions such as those shown in Figure 8.1, the risk premium for any risk venture is defined as:

$$RP=EMV-CE \tag{8.1}$$

where EMV is the expected monetary value and CE the cash equivalent. The RP is positive for a risk-averse decision-maker (curve B) and negative for a risk taker (curve C). For a risk-neutral person, RP is zero.

In the context of fire protection and insurance, Figure 8.1 may be interpreted as follows. With the money in units of a thousand pounds, the value of the property considered is £100,000. Any point on the x axis represents the value of the property remaining after a part of it is destroyed by fire. The origin on this axis represents total destruction and the point 100 no loss. If the loss in a fire has a uniform probability distribution, the expected loss would be £50,000 with a remaining value of £50,000. For an EMV decision-maker, the disutility of this loss has a cash equivalent of £50,000. As shown in Figure 8.1, for a risk-averse decision-maker (curve B), a loss of £50,000 would represent a remaining value of £20,000 or a disutility with a cash equivalent of £80,000. For a risk taker (curve C), a loss of £50,000 would cause a disutility with a CE of only £30,000.

Certainty monetary equivalent

The parameter CE is also referred to as the certainty monetary equivalent (CME) in the literature on utility theory (see Keeney and Raiffa, 1976). The CME is defined mathematically as given by:

$$\mathrm{U(CME)} = \mathrm{E}\,[\mathrm{U(X)}] = \bar{\mathrm{U}} \tag{8.2}$$

where the right-hand side is the expected value of the utility over the range of values taken by X. If x_1, $x_2 \ldots x_n$ are the values (consequences) with probability p_1, $p_2, \ldots p_n$

$$\bar{\mathrm{U}} = \mathrm{E}\,[\mathrm{U(X)}] = \sum_{i=1}^{n} p_i\, \mathrm{U}(x_i) \tag{8.3}$$

If X is a continuous variable with probability density function h(X), the expected utility is given by:

$$\bar{\mathrm{U}} = \int_x \mathrm{U(X)}\, h\, (\mathrm{X}) \tag{8.4}$$

The CME of a risky venture V is an amount $\hat{x}$ such that the decision-maker is indifferent between V and the amount $\hat{x}$ for certain. The expected value (or consequence) is given by:

$$\bar{x} = \mathrm{E}\,(x_i) = \sum_{i=1}^{n} p_i\, x_i \tag{8.5}$$

or by

$$\bar{x} = \int_x xh\,(x) \tag{8.6}$$

in the continuous case.

Consider, as an example, the utility function:

$$U(X) = -e^{-cX} \tag{8.7}$$

Suppose the decision-maker is faced with a venture with two possible outcomes: x_1 with probability ½ and x_2 with probability ½. The expected value of the venture

$$\bar{x} = (x_1 + x_2)/2$$

The certainty equivalent is the solution to:

$$U(\hat{x}) = -e^{-c\hat{x}} = -\frac{e^{-cx_1} + e^{-cx_2}}{2}$$

It may be verified that for c=1, x_1=10 and x_2=20, the certainty equivalent is:

$$\hat{x}=10.69$$

such that

$$-e^{-10.69} = -\frac{e^{-10} + e^{-20}}{2}$$

For c=0.2, x_1=10, x_2=20:

$$\hat{x}=12.85$$

The expected value is:

$$(10+20)/2=15$$

in both cases.

Consider now the case when x varies continuously from 0 to 20 with the exponential probability density function:

$$f(x) = ke^{-x} \tag{8.8}$$

Since

$$\int_0^{20} f(x) = 1$$

the value of k is unity for all practical purposes so that $f(x)=e^{-x}$. The expected value is:

$$\bar{x} = \int_0^{20} x\, e^{-x} = 1$$

Suppose we take the utility function as:

$$U(x) = -e^{-2x}$$

The certainty equivalent is given by $\hat{x}$ such that:

$$-e^{-2\hat{x}} = -\int_0^{20} e^{-2x}\, e^{-x}$$

$$= -\int_0^{20} e^{-3x} = -\tfrac{1}{3}$$

$$\hat{x} = 0.55$$

Consider, as another example, a risk-averse decision-maker with a disutility function increasing with loss *x:*

$$D(x)=\exp(\theta x) \tag{8.9}$$

who is faced with a fire risk with two possible losses: x_1=£40,000 and x_2= £20,000, both likely to occur with a probability 0.5. The expected loss (EMV) is:

(½×£40,000)+(½×£20,000)=£30,000

With the losses in units of £10,000, the CME $\hat{x}$ of the disutility is the solution of:

$$D(\hat{x}) = \exp(\theta\hat{x})$$

$$= [½ \times \exp(4\theta)] + [½ \times \exp(2\theta)]$$

Calculations would show that $\hat{x}$ has the value of £34,300 for θ=1, £35,700 for θ=1.5 and £36,600 for θ=2. Thus, the CME of disutility, which is greater than the EMV, increases with increasing degrees of risk aversion reflected by increasing values of θ. For disutility functions, RP (equation (8.1)) is negative for a risk-averse decision-maker who is prepared to spend an amount (CME) greater than EMV for fire protection and insurance.

Fire protection and insurance

Against the background ideas described above we can now investigate the possibility of applying utility theory to fire protection and insurance problems. It is apparent that we have to choose a risk-averse disutility function since the problem is one of risk avoidance. A property owner should spend more money than the expected loss towards fire protection and insurance. But how much more should he or she spend or be willing to spend? This amount depends on the attitude of the property owner towards fire risk and the extent of risk aversion based on factors such as assets and consequential losses.

Consider a property owner with an asset W. If a loss of x is incurred in a fire this asset would reduce to:

$$X=W-x \tag{8.10}$$

An appropriate utility function in terms of positive X would be:

$$U(X) =-\exp(-\theta X),\theta>0 \tag{8.11}$$

which is an increasing risk-averse utility function (see Keeney and Raiffa, 1976). Although the extent of risk aversion quantified by θ is constant for all X, this exponential utility function is generally recommended in view of its computational simplicity. Equation (8.11) may be rewritten as:

$$U(x)=-W' \exp(\theta x)$$

where $W'= \exp(-\theta W)$. As discussed earlier, the certainty equivalent $\hat{x}$ in terms of fire loss x is given by:

$$-W' \exp(\theta \hat{x}) = -W' \int_x \exp(\theta x)\, v(x) \tag{8.12}$$

where $v(x)$ is the probability density function of fire loss x. From equation (8.12) it is apparent that the certainty equivalent is independent of the parameter W′, a constant related to the asset W. For this reason, for the calculation of CE it will be sufficient to use the risk-averse utility function:

$$U(x)=-\exp(\theta x),\ \theta>0 \tag{8.13}$$

in terms of the fire loss x. The value of asset W is, of course, taken into consideration in determining the extent of risk aversion θ.

As x increases from zero, U(x) decreases from a value of -1. In other words, as x increases the net asset X (equation (8.10)) and hence utility decreases. But as x increases the 'disutility' increases. In that sense disutility is the negative of utility and the disutility function may be written as:

$$D(x)=\exp(\theta x)$$

as in equation (8.9).

It may be seen that equations (8.9) and (8.13) will both lead to the same value of the certainty equivalent. Shpilberg and Neufville (1974b) used the form in equation (8.13) in their earlier investigation but later (1974a) they modified this function to:

$$U(x)=\exp(-\theta x) \tag{8.14}$$

According to statistical studies carried out by Ramachandran (1972, 1974a, 1975b) and Shpilberg (1974) and other authors mentioned in these papers, loss in a fire has a skewed (non-normal) probability distribution. In general the transformed variable z (=log x), i.e. the logarithm of loss, has a probability distribution of the 'exponential type'. Among distributions belonging to this type, normal for z, which is same as log normal for x, has been recommended widely for modelling fire insurance claims. Exponential for z or Pareto for x has been considered by some actuaries (see Chapter 11).

Shpilberg and Neufville (1974a, b) used utility functions in equations (8.13) and (8.14) in conjunction with probabilities of fire loss falling in different ranges of magnitudes. But these utility functions are computationally difficult for performing integration if continuous forms of probability distributions of loss are used, particularly log normal. Hence, as suggested by Ramachandran (1984), z (=log x) may be used in equation (8.13) instead of x, so the utility function is:

$$U(z)=-\exp(\theta z)$$

which is equivalent to the disutility function:

$$D(x)=x^{\theta} \tag{8.15}$$

The disutility function in equation (8.15) is an increasing function with $\theta=1$ representing risk neutrality. The value of θ should be greater than unity to express a risk-averse attitude.

Consider a property worth total financial value V belonging to a risk category with fire loss x having a log normal distribution. If μ and s are the mean and standard deviation of z (= log x), base e, following the method described by Ramachandran (1982b), the certainty equivalent for the range (o, V) is given by:

$$\hat{x}_v^{\theta} = \frac{1}{G(k)} \bullet \frac{1}{\sqrt{2\pi}\sigma} \int_{-\infty}^{\log V} \exp\left[-1/2\left(\frac{z-\mu}{\sigma}\right)^2\right] \exp(\theta z)$$

$$= \frac{G(k-\sigma\theta)}{G(k)} \exp\left[\mu\theta + \frac{\sigma^2\theta^2}{2}\right] \tag{8.16}$$

where:

$$k = (\log_e V - \mu)/\sigma$$

$$G(k) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{k} \exp\left(-\frac{t^2}{2}\right)$$

$$G(k - \sigma\theta) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{k-\sigma\theta} \exp\left(-\frac{t^2}{2}\right)$$

and G(t) is the standard normal distribution. The expected value of the loss is given by θ=1 in equation (8.16); see also equation (7.3) (p. 122).

For an increasing disutility function such as equation (8.15), the certainty equivalent (CE) is greater than the expected value (EMV) for a risk-averse decision-maker with θ>1. As mentioned earlier, the risk premium RP given in equation (8.1) maybe redefined as:

$$RP_d = CE - EMV \tag{8.17}$$

RP_d is not the insurance premium; it is the loading to be added to EMV to provide an estimate of CE. As discussed earlier in connection with curve B in Figure 8.1, the certainty equivalent CE is the maximum insurance premium which a property owner will be prepared to pay in order to meet the uncertain consequences of a fire (see also Keeney and Raiffa, 1976). Fire risk cannot be avoided. The property owner has to participate in the risky game involving a loss due to a fire, but the consequences (disutility) can be mitigated by insurance cover which converts an uncertain loss into a known cost, the insurance premium payable at a certain date. If we compare two property owners, the one with a higher value of θ (more risk averse) will be prepared to spend more money on insurance cover than the other property owner. The degree of risk aversion increases with θ.

The value of the expected loss, EMV, will decrease with increasing levels of fire protection. By adopting efficient fire protection measures, a property owner can manage to spend on insurance an amount less than the maximum CE consistent with the extent of his or her risk aversion. Without fire protection that person may have to spend on insurance more than the corresponding CE, depending on the risk aversion of the insurance company reflected in the insurance premium. Of course, fire protection involves investment and maintenance costs but devices such as sprinklers qualify for tax allowances in addition to reduced insurance premiums.

Apart from the two options, full insurance or no insurance (full self-insurance), a property owner can also consider partial insurance with partial self-insurance. This option, known as 'deductible' (on pp. 121–2), requires the participation of the insured in a loss up to a certain limit agreed with the insurer in advance. With a 'pure' deductible the insured has to bear the entire amount of any loss up to the deductible level D. For a loss L greater than D, the insured's liability is limited to D since he or she will receive the difference (L-D) from the insurer. With a deductible the insured is given the advantage of reduced premiums, which is an incentive to take a good deal of interest in adopting loss prevention and reduction measures since he or she will have to bear a part or the whole of the loss whenever a fire occurs.

Assuming a log normal distribution for loss x with μ and σ as the mean and standard deviation for z (=log x) and using the disutility function in equation (8.15), the certainty equivalent $\hat{x}_{DV}$ for a deductible level D and property worth V is given by:

$$\hat{x}^{\theta}_{DV} = \frac{1}{G(k)} \int_{-\infty}^{\log D} e^{z\theta} f(z) + \frac{1}{G(k)} \int_{\log D}^{\log V} D^{\theta} f(z)$$

where:

$$f(z) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-1/2\left(\frac{Z-\mu}{\sigma}\right)^2\right]$$

and the parameters k and G(k) have already been defined. Performing the integration it may be seen that:

$$\hat{x}^{\theta}_{DV} = \frac{G(w-\sigma\theta)}{G(k)} \exp\left(\mu\theta + \frac{\sigma^2\theta^2}{2}\right) + D^{\theta}\left[1-\frac{G(w)}{G(k)}\right] \tag{8.18}$$

where:

$$w = (\log_e D - \mu)/\sigma$$

$$G(w) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{w} \exp\left(-\frac{t^2}{2}\right)$$

$$G(w-\sigma\theta) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{w-\sigma\theta} \exp\left(-\frac{t^2}{2}\right)$$

For full self-insurance (no insurance), D=V and w=k such that equation (8.18) reduces to equation (8.16).

The expected value $\bar{x}_{DV}$ of the amount the property owner has to bear is given by θ=1 in equation (8.18); see also equation (7.4) (p. 122). The certainty equivalent $\hat{x}_{DV}$ is the monetary equivalent of the disutility the property owner has to incur in making provision for self-insurance. If such a provision is not made, the owner could use that amount productively in an investment project. However, with a deductible, the insurance premium is reduced. Hence the disutility associated with self-insurance would be compensated to some extent by a decrease in the disutility associated with the cost of insurance. The extent of this compensation depends on the actual costs of insurance with and without the deductible.

An approximate value of the maximum insurance premium which a property owner will be willing to pay with a deductible D is $\bar{R}_{DV}$ given by the following formula:

$$\hat{R}^{\theta}_{DV} = \frac{1}{G(k)} \int_{\log D}^{\log V} e^{z\theta} \, f(z) - D^{\theta} \, [1 - \frac{G(w)}{G(k)}]$$

$$= \frac{G(k - \sigma\theta) - G(w - \sigma\theta)}{G(k)} \exp\left(\mu\theta + \frac{\sigma^2\theta^2}{2}\right)$$

$$- D^{\theta}\left[1 - \frac{G(w)}{G(k)}\right] \tag{8.19}$$

The expected value $\bar{R}_{DV}$ of the amount the insurance firm has to bear is given by θ=1 in equation (8.19); see also equation (7.5) (p. 123). To calculate the insurance premium appropriate to deductible D, the insurer will add to $\bar{R}_{DV}$ a safety loading and another loading towards the operating costs. It may be observed that the total value given by equations (8.18) and (8.19) is equal to the value given by equation (8.16). We have:

$$\hat{x}^{\theta}_{DV} + \hat{R}^{\theta}_{DV} = \hat{x}^{\theta} \tag{8.20}$$

The property owner incurs a total disutility $\hat{x}^{\theta}$, part of which is towards the provision of self-insurance ($\hat{x}^{\theta}_{DV}$) and the remaining part towards insurance ($\hat{R}^{\theta}_{DV}$). This result, although true conceptually, is based on the approximate value given by equation (8.19). The exact value of $\hat{R}^{\theta}_{DV}$ is given by:

$$\frac{1}{G(k)} \int_{\log D}^{\log V} (x - D)^{\theta} \, f(z) = \frac{1}{G(k)} \int_{\log D}^{\log V} (e^{z} - D)^{\theta} \, f(z)$$

which is difficult to compute.

Consider the example discussed on pp. 123–6. For this example, based on equations (8.16), (8.18) and (8.19), the expected values and certainty equivalents are given in Table 8.1 for θ=1.2 and 1.5 and two deductible levels, £50,000 and £100,000.

Table 8.1 Multistorey textile industry building: expected losses and certainty equivalents (1966 prices) (V=£500,000)

Insurance option	*Sprinklers*			*No sprinklers*		
	Expected loss (£)	*Certainty equivalent* $\theta = 1.2$ *(£)*	$\theta = 1.5$ *(£)*	*Expected loss (£)*	*Certainty equivalent* $\theta = 1.2$ *(£)*	$\theta = 1.5$ *(£)*
Full insurance (no deductible)	2,200	3,800	7,400	17,700	23,500	33,200
£50,000 deductible						
Self-insurance disutility	1,400	2,200	3,500	10,000	11,800	14,400
Insurance disutility	800	2,100	5,700	7,700	14,500	26,500
£100,000 deductible						
Self-insurance disutility	1,700	2,700	4,700	13,100	16,000	20,700
Insurance disutility	500	1,500	4,600	4,600	10,200	21,100

From the results in Table 8.1 it is apparent that, whatever may be the insurance option, sprinklers reduce the expected loss to a considerable extent. Consequently, by installing sprinklers a property owner can expect a substantial saving on the insurance premium for any deductible level. This will reduce the disutility associated with the insurance premium, the actual reduction depending on the premium charged by the insurance company selected by the property owner.

Sprinklers also significantly reduce the disutility suffered by the property owner in making provisions for self-insurance in financial planning. As might be anticipated, the expected loss and self-insurance disutility increase with increasing deductive levels. The increase in this disutility is somewhat high for a building without sprinklers but only marginal for a building that has them, particularly for low values of θ (greater than unity). Self-insurance or insurance disutility for any insurance option increases with θ, the degree of risk aversion. It may be verified that equation (8.20) is satisfied by the figures in Table 8.1. For example, for the building with sprinklers with θ=1.5 and £50,000 deductible:

$$(3.5)^{1.5} + (5.7)^{1.5} = (7.4)^{1.5}$$

In the analysis so far, financial loss has been considered a (random) variable with a log normal probability distribution whose parameters μ and σ have been estimated. This method requires data on financial losses which may not be available in some cases. As for fires attended by fire brigades in the UK, data may be available on the extent of fire spread according to the following classification:

1 confined to object first ignited;
2 spread beyond object but confined to room of fire origin;
3 spread beyond room of fire origin.

The data will provide an estimate of the probability of fire falling into each of the three classes mentioned above. For any particular building such spread probabilities can also be estimated by adopting a detailed engineering method developed by Fitzgerald (1985).

Let the probabilities for the three spread categories be denoted by p_a, p_b and p_c such that:

$$p_a+p_b+p_c=1$$

Also let x_a, x_b and x_c be the average area expected to be destroyed by fire for the three categories. The expected value of area destroyed is given by:

$$\bar{x}=p_ax_a+p_bx_b+p_cx_c$$

For a utility function of the form in equation (8.15) the certainty equivalent is $\hat{x}$ given by:

$$\hat{x}^{\theta} = p_a x_a^{\theta} + p_b x_b^{\theta} + p_c x_c^{\theta}$$

Both $\bar{x}$ and $\hat{x}$ can be converted to approximate monetary values by using financial loss per unit area.

Consider the following data for a particular building:

$p_a=0.5$, $x_a=5$ m^2
$p_b=0.4$, $x_b=20$ m^2
$p_c=0.1$, $x_c=3{,}000$ m^2

The expected value of area destroyed is 310.5 m^2. With θ=1.5 in equation (8.15) the certainty equivalent is 647.4 m^2, such that:

$$(647.4)^{1.5} = (0.5)\,(5)^{1.5} + (0.4)\,(20)^{1.5} + (0.1)\,(3{,}000)^{1.5}$$

It may be verified that, for θ=2, the certainty equivalent is 948.8 sq metres.

Utility function and decision analysis

In a conventional decision analysis (see pp. 116–21) the monetary values of costs and losses are used with the object of identifying a fire protection plus insurance package that will have the least total cost. However, as discussed earlier, it would be desirable to carry out the analysis in terms of the disutility associated with the total cost and select a package that will have the minimum total disutility. Following equation (7.6) (p. 126), the expected value of the total disutility is given approximately by:

$$\hat{T}_D^{\theta} = I_{DV}^{\theta} + C^{\theta} + F\hat{x}_{DV}^{\theta} \qquad (8.21)$$

where $\hat{T}_D$ is the certainty equivalent of total cost, F is the annual probability of fire occurring and $\hat{x}_{DV}$ is given by equation (8.18). (For θ=1, equation (8.21) reduces to equation (7.6).) The parameter I_{DV} is the annual insurance premium for a property with value V and deductible level D, and C is the annual cost of fire protection. In principle, I_{DV} should decrease with increasing D so that an increase in the disutility associated with $\hat{x}_{DV}$ would be compensated by a decrease in the disutility associated with I_{DV}. The actual reduction in the insurance premium I_{DV} depends on the insurance company and its attitude towards risk. The property owner's attitude to risk and capacity to bear the required insurance premium is reflected by $\hat{R}_{DV}$ (equation (8.19)).

Since the value of θ would vary from one property owner to another, an insurance company should take into account this variation and the value of $\hat{R}_{DV}$

in the calculation of I_{DV}. But the general practice is to add loadings on $\bar{R}_{DV}$ which are usually not directly proportional to $\bar{R}_{DV}$. Hence, I_{DV} may be regarded as independent of $\bar{R}_{DV}$ and $\bar{x}_{DV}$. The cost of fire protection (C) is, of course, independent of I_{DV} and $\bar{x}_{DV}$. For these reasons, equation (8.21) appears to be a reasonable model for calculating the certainty equivalent of the disutility associated with the total cost. According to this equation, the total disutility due to *independent* factors is the sum of disutilities associated with the factors.

Consider the example discussed on pp. 123–6 and with reference to Table 8.1. In this example, F=0.12 and, if the building has sprinklers, C=£240 at 1966 prices. For full insurance cover, the annual premium at 1966 prices would be £1,250 with sprinklers and £3,250 without sprinklers.

Suppose the insurance company calculates rebates for deductibles in terms of insurance disutility for θ=1.5 in Table 8.1 instead of the expected loss, as in Chapter 7. Then, if the building has sprinklers, the annual premium for a £50,000 deductible would be:

$$\frac{5{,}700}{7{,}400} \times 1{,}250 = 960$$

Similarly, the annual premium for this building would be £780 for a £100,000 deductible. Also, in the non-sprinkler case the annual premium would be £2,590 for a £50,000 deductible and £2,070 for a £100,000 deductible.

Making use of the estimates above, the results in Table 8.2 have been obtained for the certainty equivalent based on the total disutility of the total annual cost. The values for θ=1.2 and θ=1.5 are based on equation (8.21) and those for θ=1 on equation (7.6). The values for $\hat{x}_{DV}$ (self-insurance disutility) and $\bar{x}_{DV}$ (expected value) have been taken from Table 8.1. For full insurance $\hat{x}_{DV}$ and $\bar{x}_{DV}$ have zero values since the property owner is compensated for the entire loss and does not suffer from any self-insurance disutility. Also C=0 for a building without sprinklers. Values in Table 8.1 describe the situation in the event of a fire occurring and do not take into account the annual probability F (=0.12) of fire occurrence. Hence these values are higher than those in Table 8.2.

Table 8.2 Multistorey textile industry building: certainty equivalent of the total annual cost (1966 prices) (V=£500,000)

Insurance option	*Sprinklers*			*No sprinklers*		
	θ = 1 (£)	*θ = 1.2 (£)*	*θ = 1.5 (£)*	*θ = 1 (£)*	*θ = 1.2 (£)*	*θ = 1.5 (£)*
Full insurance	1,490	1,392	1,319	3,250	3,250	3,250
£50,000 deductible	1,368	1,357	1,504	3,790	4,110	4,863
£100,000 deductible	1,224	1,259	1,603	3,642	4,288	5,886

The results in Table 8.2 clearly confirm the economic value of sprinklers. Also, for a building with sprinklers, the total disutility for $\theta=1.2$ decreases with increasing levels of deductible under the assumed figures used in the calculations. If figures for actual insurance premiums are obtained and used in this analysis the results may be somewhat different. However, it appears that by installing sprinklers in a building the property owner can take a risk and accept a large deductible provided he or she is moderately risk averse ($\theta=1.2$). If the owner is very risk averse ($\theta=1.5$), full insurance will be the best option. Full insurance will also be the safest option if the building is not equipped with sprinklers.

Shpilberg and Neufville (1974a) applied the decision analysis procedure to the problem of choosing levels of fire protection that might be the best for airport facilities, whose principal exposure to risk comes from fuel spills and from stored cargo. In practice, the facilities are usually protected by sprinkler systems. Customarily, the insurance policy for a facility does not cover any aircraft; they are covered separately. Because of the limited statistical data that exist in this area the study was confined to two levels of fire protection:

1 no fixed fire protection equipment, some fire-resistant construction and fire walls, some portable extinguishers;
2 average level of fixed fire protection equipment, fire-resistant construction, adequate water supplies.

The authors considered the most popular deductibles in the aircraft industry—$5,000, $10,000, $20,000, $50,000, $100,000 and $500,000—together with the non-deductible and self-insurance choices. To simplify the calculations, instead of the probability distribution of fire damage, nine ranges of damage and their associated probabilities were used in the analysis. Actual losses observed were all at facilities with sprinklers. The probabilities of losses for similar facilities without sprinklers were developed by using industry data which indicated that average losses in unsprinklered facilities without sprinklers were three to five times higher than the average losses in sprinklered facilities.

The decision tree adopted by Shpilberg and Neufville for large airport facilities is reproduced in Figure 8.3. In the light of previous experience, the authors assumed that the property owners were constantly risk averse with the utility function:

$$U(L)=\exp(-4.6L)$$

The results of their evaluation of each of the sixteen possible levels of fire protection and insurance for large facilities are reproduced in Figure 8.4. The expected monetary costs are on the left-hand side and the certainty monetary equivalents based on the utility function on the right-hand side. Because risk-averse people place a very high value on large and total losses, the CMEs are all increasingly higher than the expected monetary losses for higher deduc

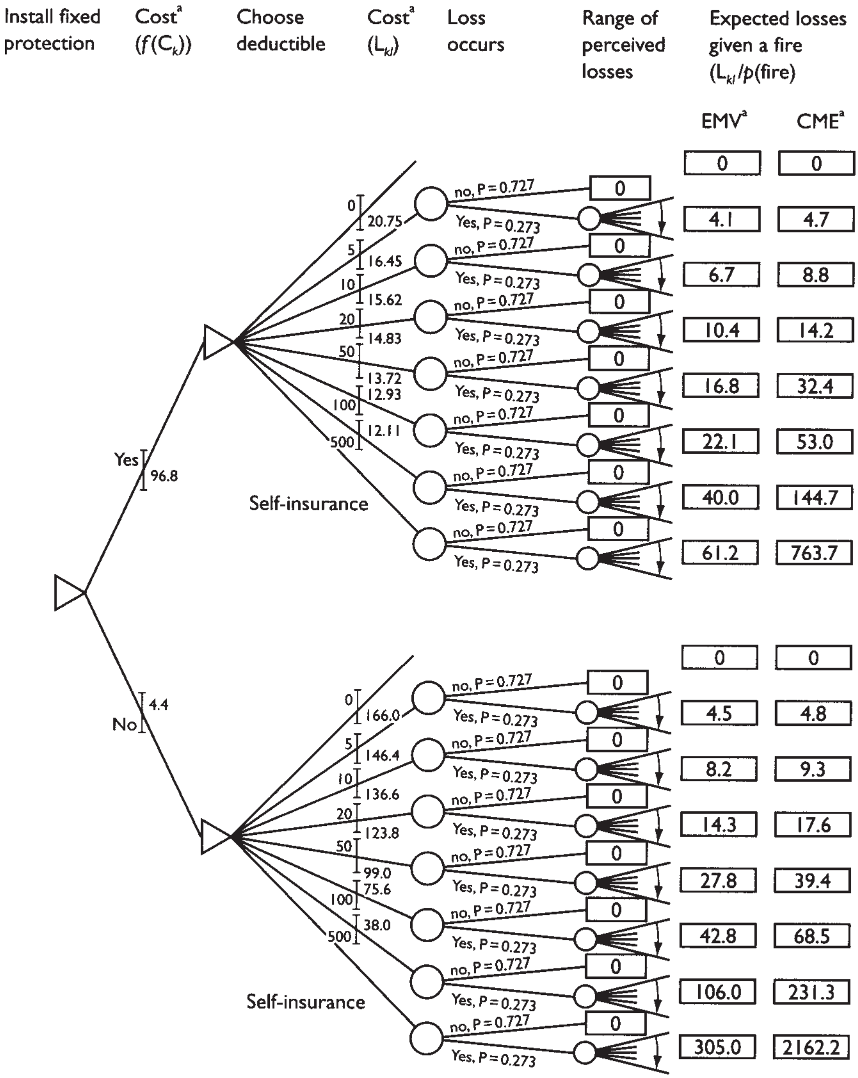


Figure 8.3 Decision tree for \$35 million airport facility based on expected monetary value and certainty monetary equivalent of losses
Source: Shpilberg and Neufville (1974b)
Note: [a]In $\$ \times 10^3$

tibles. The analysis indicated that the best option for the owner of a new facility would be to build it without sprinklers and then take out an insurance policy with a \$100,000 deductible. The best deductible for airport facilities with sprinklers was found to be \$20,000 for a small facility but only \$5,000 for a large facility.

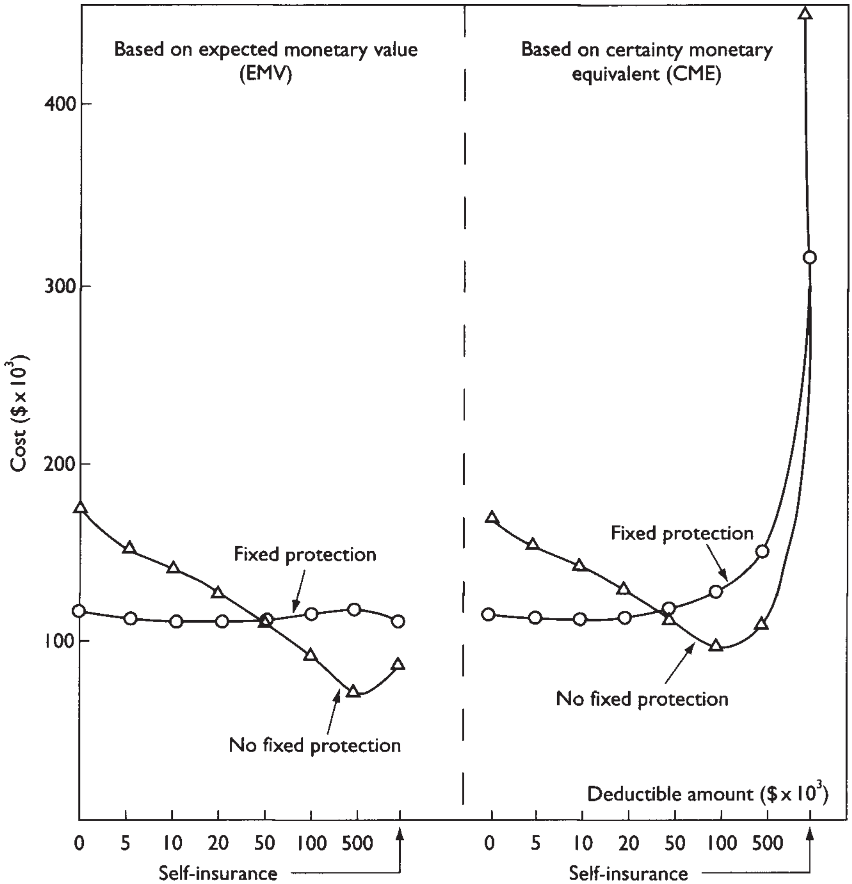


Figure 8.4 Annual cost as a function of deductible coverage and fixed protection for a $35 million airport facility
Source: Shpilberg and Neufville (1974b)

It must be remembered that the investigation carried out by Shpilberg and Neufville and the analysis described with reference to Tables 8.1 and 8.2 have considered only direct material damage to property. No consideration has been given to factors such as the loss of future revenues caused by business interruption, which are only partially insurable, or by changes in the safety image of an industry or the loss of lives. A huge loss in profits might seriously disrupt or even bankrupt a business activity. It is difficult to put a monetary value on human life although this is necessary, as discussed in Chapter 10. Multiple-death fires usually have serious social, economic and political consequences. Fires causing large consequential losses due to lost production, exports and employment and extra imports could cause a good deal of stress to the national economy.

The results of the examples discussed in this chapter should not be taken as recommendations of levels of self-insurance or fire protection; every industrial or commercial property has its own economic trade-offs and alternatives. The choice of whether to invest in fire protection devices depends on the cost of fire protection and its relation to the cost of insurance, on the shape of the probability distribution of losses under different fire protection measures and on the particular degree of risk aversion of the decision-maker. Inaccurate or outdated deductible schedules adopted by insurance companies can produce unexpected results in terms of minimum insurance costs. These schedules are expected to reflect accurately the probability distribution of losses which could change over a period due to factors such as inflation and larger average exposed areas.

The main purpose of the decision analysis described in this section is to illustrate how complex decisions involving fire protection and insurance can be systematically analysed by rationalising the decision process and considering the implications of risk-averse behaviour. Although this method is specifically intended for property owners it can be used by insurance companies to analyse the implications of their premium rates (Chapter 11). The decision tree approach can also be used to study the investment policies for municipal fire protection or to design policies with respect to fire protection for high-rise buildings. Such problems would require the application of multi-attribute utility theory to take into consideration not only the economic risk but also loss of life and other intangible factors which cannot easily be quantified.

Construction of utility functions

Within the last few years, attempts have been made to measure how strongly people feel about accidents and their consequences and how much they are willing to spend to protect themselves against such risks. These measures have been developed by carrying out surveys in which carefully structured questionnaires are distributed to individuals for answering. Such data are statistically analysed to provide quantitative estimates of perception of and attitude to risk. The data are also used to construct utility functions which are then incorporated in decision analyses. Such surveys tend to be expensive and time-consuming if sufficient statistical accuracy is desired.

The shape of the utility or disutility function could be of the mathematical form shown in equations (8.13) or (8.14) or (8.15) since a property owner or a firm is generally risk averse. In terms of disutility D(x) [=-U(x)]. Equation (8.15), for example, implies that:

$$D\,(10x) = (10)^{\theta} x^{\theta}$$

which is $>10x^{\theta}$ or>10 D(x) for $\theta>1$. In other words, the disutility due to a single large loss of magnitude ten times that of a small loss is greater than the total disutility caused by ten small losses. The consequences of a single large fire are worse than the consequences of ten small fires of equivalent total loss. In the case of loss of life, it is important to consider not only the number of deaths but also whether they occur singly or as a result of catastrophes involving many deaths (see pp. 177–80).

Modifying equation (8.15), we could write:

$$D(x) = \left(\frac{x - m}{M - m}\right)^{\theta} \tag{8.22}$$

where m is the minimum, a loss less than which will cause no disruption to the business activity. A loss in excess of the maximum M might put the property owner out of business permanently or temporarily for a long duration. By choosing intermediate values of x which cause minor disruption, major disruption, etc., an approximate value for θ can be determined. Estimates of probable consequential losses due to fires would also provide data to construct an appropriate utility function. The value of θ also depends on the attitude to risk and financial strength of a particular property owner. As the fire damage x increases from m to M, $D(x)$ increases from zero to 1.

Although risk averse, the disutility function in equation (8.15) exhibits a decreasing degree of risk aversion. The risk aversion in a range with small losses is greater than the risk aversion in a range with larger losses. This is due to the fact that the risk aversion function:

$$q(x) = D''(x) / D'(x)$$

$$= \frac{\theta - 1}{x}$$

decreases with increasing x. (The functions $D'(x)$ and $D''(x)$ are the first and second derivatives of $D(x)$). In order to reflect realistically the true value of avoiding or providing for a large or catastrophic loss, the decision-maker may choose a risk-averse disutility function with an increasing risk aversion function. The following is one such disutility function:

$$D(x) = -\log(b - x) \tag{8.23}$$

whose risk aversion function:

$$q(x) = 1/(b - x)$$

increases with x in the range $x < b$. The value of b could correspond to the assets of the property owner or the value of building and contents. It is mathematically complex to use equation (8.23) in conjunction with a log normal probability distribution for fire loss x.

Chapter 9

Consequential/indirect loss

This chapter is a slightly modified version of Chapter 7, section 5, contributed by the author to the *SFPE Handbook of Fire Protection Engineering,* 2nd edn, Quincy, MA: published by the National Fire Protection Association, 1995. The author wishes to thank the Society of Fire Protection Engineers for its permission to reproduce this chapter.

Introduction: definition

During the course of its development, a fire can cause damage to a building and its contents and to occupants (fatal or non-fatal casualties). These costs are known as direct losses whereas those associated with the fire but incurred after it is extinguished are indirect or consequential losses. According to this definition the distress and financial loss that the death or injury of individuals would cause their families is an indirect loss. This component of indirect loss is, however, not discussed in this chapter which is concerned only with consequential losses such as loss of production, loss of trade, e.g. profits, of employment and of exports and costs towards extra imports. These losses occur mainly in the industrial and commercial sectors.

Consequential losses due to fires are an under-researched topic on which only very few investigations have been carried out. These studies and some major fires are briefly reviewed with reference to the evaluation of consequential losses and the factors affecting them. Other topics discussed include the role of fire protection and utility theory.

Levels of economic activity

In assessing consequential losses an important problem to be resolved is concerned with the differences between two major levels of economic activity: the private sector/community level and the national/societal level. The first includes the fire-hit firm and firms supplying to or purchasing materials, components or services from that firm. Costs associated with moving, temporary accommodation and lost profits are valid costs at the private sector level but not at the national level.

At the national level, the loss of a specific unit of productive capacity may be spread among the remaining capacity in the nation such that competitors seize the opportunity to enter the market and maintain the national rate and volume of manufacture. Consequently, there is likely to be only a small incremental loss to the national economy as a result of a fire in the premises of, say, a manufacturing firm. This is also because of the redistribution or 'netting out' effect of some of the losses at the societal level.

Insurance statistics

The effects of a fire upon the earning capacity of a firm can be measured in terms of loss of profits during the period of interruption following the damage until the resumption of the activity in which the firm was engaged before the fire. Loss of profits is usually expressed as a percentage of loss of turnover. Cover against this loss can be obtained by purchasing a consequential loss insurance policy, the premium for which is a function of the period of indemnity. Loss of profits sustained by a supplier or customer of the fire-hit firm can be covered by a normal consequential loss policy based on reduction in turnover.

The form of insurance policy in more general use in the United States is known as a business interruption insurance (BII) and this operates on lines similar to the United Kingdom contract of consequential loss insurance (CLI) with a turnover specification, though there are some differences. For the private sector level, insurance companies transacting BII or CLI are useful sources of data for estimating consequential losses due to fires in industrial and commercial premises. Organisations such as the Insurance Institute of America compile consequential loss data furnished by major insurance companies.

It is, however, doubtful whether insurance statistics can provide realistic estimates of consequential losses to the national economy which are influenced by several economic factors. These factors include level of employment or unemployment, level of capacity utilisation, volume of exports and imports, exchange rates and performance of national and international competitors. Due to the interactions of these factors, evaluation of consequential losses to the national economy is a complex problem requiring the application of econometric models such as the input-output type.

Special factors: private sector level

Certain types of industrial or commercial activities may have special factors affecting consequential losses. These factors were identified in a series of studies carried out by the Insurance Technical Bureau (ITB) in the United Kingdom, now defunct. The observations on consequential losses contained in these reports may or may not be applicable to conditions prevailing now in the United Kingdom or other countries. However, the following summaries extracted from three of the reports provide an indication of the various special factors that should be considered in the evaluation of consequential losses due to fires and other hazards.

A few production lines of a plant manufacturing pharmaceutical products (ITB, 1977) may generate an abnormally high proportion of gross profits. Restrictions imposed by the licensing authority may limit possibilities of manufacture in other plants or even other lines in the same plant. Natural raw materials may be irreplaceable out of season. Replacement of specialised plant and equipment, e.g. tailor-made driers or centrifuges, may involve long delays. Loss of laboratory facilities may seriously interrupt testing and quality control programmes.

The aerospace industry (ITB, 1976) is another example where some activities are of special importance, particularly in the development of a new aircraft-prototype assembly, untried or unproven research and development projects and fatigue testing of aircraft structures. Loss of any of the above could result in a significant interruption to the programme. In addition, the effect of delays on development or on the supply of components or assemblies from specialist equipment manufacturers can be serious. The interactions of the many activities and firms involved in the manufacture of aerospace products makes for involved consequential loss considerations.

Resin, paint and ink manufacture (ITB, 1978) would not normally be expected to give rise to unduly high consequential loss. Facilities are generally dispersed in small units throughout the country and there may be sufficient manufacturing capacity to absorb temporary loss at individual sites. Also few, if any, products are so special that they cannot be made elsewhere in the industry. Consequential loss, therefore, hinges primarily on the time taken to reinstate plant and the ability of management to arrange for the supply of goods from other sources, pending a return to full production. Loss of raw materials or finished goods would normally result in relatively short interruption periods. However, longer periods may be required for the replacement of tanks and pumps destroyed by fires and other hazards such as explosion.

Due to high investment costs, specialised equipment such as that which is electronically or computer controlled are generally used at full capacity in some industrial processes. Continuous operation of these processes may reduce the chance of a fire spreading but provides no scope for making up for lost production following a fire. Specialised equipment, if damaged by fire, cannot be replaced easily and quickly since either the equipment itself or spare parts for it may have to be imported. Industries using such equipment are liable to sustain high consequential losses.

Research studies: national level

While decades of research have provided a good deal of knowledge about the physical effects of fires, including direct damage, and methods to control them, there is still very little understanding of the indirect or consequential losses due to fires particularly at the national level. The scarcity of research studies on consequential losses is partly due to the fact that such losses are considered to some extent as the intangible costs of fires. Hence, these losses are not taken into account sufficiently in determining fire protection and insurance requirements for industrial and commercial buildings. Only some prudent business undertakings and their suppliers or customers adopt loss of profits or business interruption insurance as an essential complement of insurance against material (direct) damage. Consequential losses to the national economy are, however, rarely considered.

In the United Kingdom, during 1970–80 the Home Office carried out two research studies on consequential losses to the national economy. The first, by the Economist Intelligence Unit Ltd (1971), adopted an input-output type model in which all losses were considered as output losses. They would either be losses in the type of output actually hit by fire or losses in some other output because production factors—fixed assets, entrepreneurial effort or labour—had been less effectively employed as a result of the fire. The places where the effects of a fire were assumed to occur were: the fire-hit firm, a supplying firm, purchasing firm, a parallel firm and the rest of the economy. A fire-hit firm was defined as a compartment of production covering just the type of output which had been hit by a fire and no other output. A parallel firm was defined as the compartment of a firm which produced in parallel to the fire-hit compartment (which might be in the same firm or in another firm). Any effects in a parallel firm or somewhere else in the rest of the economy were assumed to be included in the calculation of the effects in a fire-hit firm, in a supplying firm or in a purchasing firm.

In the Home Office study, consequential losses were measured by the net present values of streams of annual outputs lost by the fire-hit firm, supplying firms and purchasing firms. With regard to the fire-hit firm it was necessary to determine a length of time over which fixed assets destroyed by fire were assumed not to be replaced by extra investment in the economy. This time choice had to depend on a view of the future course of the economy, which depended on unknown events and influences. Hence, alternative calculations were produced which were based on the remaining lives of the assets and on a number of shorter periods. The net present values were corrected for offsetting influences within the fire-hit firm, the supplying firms and the purchasing firms. These influences were due to two factors. First, some production factors affected by fire might be used elsewhere in the economy. Second, production factors already employed elsewhere might be used more intensively. The extent to which such off-setting influences operated would depend largely on the level of employment and the pressure of demand in the economy. Separate calculations were made for three alternative cases: slack, middle and tight conditions in the economy. Results were given for each of fifteen industries, including a factor by which a fixed assets valuation should be multiplied to give the sum of all the corrected output losses.

In order to verify the assumptions employed and results obtained in the study, the Home Office commissioned field research in 1977 aimed at an indepth investigation of a small sample of fires. This study, involving direct contact with fire-hit firms, concentrated upon direct, consequential and hence the total loss to the UK economy from industrial, distributive and service sector fires. During the first stage, ten firms covering a range of industries and fire size were interviewed in order to confirm the practicality of the method adopted. Fires on multioccupancy sites were excluded since it was found to be difficult to identify the firms hit by such fires.

Using the method identified in the first (pilot) stage, only seventy-five fires were investigated in the second stage for reasons of economy, but they were chosen to reflect certain key parameters involved in the sampling process. This was the minimum size that permitted coverage of one fire from each industry in each year. Since many of these fires produced no or small consequential loss to the national economy, ten more fires were selected to ascertain the key factors leading to large consequential losses. In all, twenty fires were identified in the second stage where the fire-hit firms had reported significant effects on one or more of the following: suppliers, customers, competitors, employment, investment and foreign trade. Firms involved in only sixteen of these fires agreed to participate in a further investigation in Stage 3. The fourth stage of the study was concerned with a postal survey to provide supplementary data and the analysis of all data, including those collected in earlier stages.

In the second study described above, estimates of direct loss were based on insurance figures. Consequential losses were considered to arise from loss of exports, extra imports, the diversion of resources from other productive activities and reduction in the efficiency of resource use following the fire. The study assumed full capacity utilisation of resources and that market values of the resources reflected their true worth. Insurance estimates of losses were used as measures of the assets destroyed in fires and, by application of national capital output ratios, these asset losses were translated into losses of output from fire. Allowances were made for the secondary impact upon suppliers and customers of fire-hit firms and for the impact on the level of capacity utilisation. A correction factor was applied to account for the ability of the economy to make good the losses of the fire-hit firm from other firms. The analysis produced estimates of the ratios of consequential to direct losses to the economy, for 'off-peak' and 'peak' years and for each industry and service sector. The main conclusion was that most fires, except those in chemical and allied industries, produced no consequential losses to the national economy. Only in one sector (chemicals) was evidence found of a statistical link between consequential losses and direct losses. The study failed to establish this link for other sectors and a number of other possible effects on consequential losses.

Research study: private sector level

The Home Office reports mentioned above were not published, due perhaps to the unacceptability of the results and conclusions by major industrial undertakings and insurance organisations. The only published research study appears to be the paper by Hicks and Liebermann (1979) which deals with costs and losses from the community/private perspective as they impact the fire victim. The property class categories addressed in this study included only commercial occupancies of four types: mercantile, non-manufacturing, manufacturing and warehouses.

Indirect losses could be viewed as a type of 'production process', the product being indirect fire losses. Hence, Hicks and Liebermann (1979) considered first the following expression based on a convenient formulation of the Cobb-Douglas production function (Henderson and Quandt 1971):

$$\mathrm{IL} = ke^{r\mathrm{T}}\,\mathrm{E}^{a}\mathrm{X}^{1-a} \tag{9.1}$$

where:

IL = indirect loss
k = constant
r, a = regression coefficients
E = expenditure for fire protection (-)
X = number of fires (+)
T = time (surrogate for technological advance) (-)

The signs in parenthesis relate to the expected values of the coefficients for the independent variables. The term $ke^{r\mathrm{T}}$ is a scalor factor in which *r* measures increases in fire department efficiency due to technological advances in suppression equipment, training and/or facilities as well as altered building codes, smoke alarms and the like. Equation (9.1) can be turned into a multiple regression model by taking logarithms of terms on both sides.

In principle, the parameters *r* and *a* can be estimated, but in practice it proved to be an insurmountable task to attempt to collect statistics in the detail required for the regression analysis. Hence, due to serious data constraints and limited resources to generate original statistics, the following general form was adopted, which proved successful:

$$\mathrm{IL}=c(\mathrm{DL})^{b} \tag{9.2}$$

where DL is the direct loss and *c* and *b* are constants. Equation (9.2) was based on the assumption that very small fires typically generate small indirect losses while large fires produce larger indirect losses. Equation (9.2) can be transformed into a simple regression by taking logarithms of terms on both sides.

It may be observed that the time component, T, in equation (9.1) has not been included in equation (9.2). This is because the test of this component did not yield satisfactory results. The values of the regression coefficients log *c* and *b* were estimated for six levels: local, national and the four types of occupancies mentioned earlier. The estimation for the first two levels was based on data for all the four types of occupancies. Data for the national level were provided by the Insurance Services Office (ISO), New York. For the local level, two insurance companies furnished information processed at the local insurance company level prior to transmission to the ISO; these statistics were augmented by those provided by six case studies. The ISO data and company statistics were combined for an occupancy level other than warehouses, for which only ISO data were available. All the data used in the six regression models were in millions of dollars normalised to 1976 dollar values.

Statistical tests of significance showed that the regression model fitted the data well in all cases except warehouses. Additional data might, perhaps, have improved the statistical significance of the warehouse model. The results obtained by Hicks and Liebermann (1979) are given in Table 9.1. Since nationally aggregated data were utilised it was recommended that the 'occupancy-specific' models be used only at the national level and that any desired analysis of local impacts be accomplished using the 'local' model.

Hicks and Liebermann have established a 'power' relationship between indirect and direct fire loss. The value of this exponent, parameter *b,* has been estimated to be greater than unity for local and national levels and less than unity for the occupancy levels. For any increase in direct loss, the ratio of indirect to direct loss would increase if $b>1$ and decrease if $b<1$. The ratio would be a constant if $b=1$. From the information given in the paper it was not possible to test whether the value of *b* was significantly different from unity for any of the six levels. The results of Hicks and Liebermann, however, cast doubts on the use of a constant value for the ratio between indirect and direct fire loss.

Table 9.1 Relationship between direct and indirect fire loss: model parametersa

Level	*Parameters*	
	c	*b*
Local	0.203	1.146
National	0.015	1.245
Mercantile	0.109	0.889
Non-manufacturing	0.069	0.874
Manufacturing	0.135	0.890
Warehouses	0.047	0.804

Notes
[a] Hicks and Liebermann (1979 and equation 2)
Losses in $millions at 1976 dollar values.

Statistical (actuarial) techniques are well developed for calculating the insurance premium for loss of profits due to fire (see, for example, Benckert, 1957). The 'risk premium' is a function of the period of indemnity and is generally expressed as the product of the loss frequency and the mean amount of loss. The loss frequency is assumed to be independent of the period of indemnity. The frequency function of the period of interruption following a fire has a log normal distribution (ibid.; Flach *et al.,* 1971). An insurance company generally adds two types of loading to the risk premium to calculate the premium payable by a policy-holder. A safety loading is added towards chance fluctuations of loss beyond the expected loss. Another loading is imposed to cover the insurer's operating costs, which include profits, taxes and other administrative expenses. A number of books have been published on different types of insurance and claims concerned with consequential losses (see, for example, Riley, 1967).

National estimates

According to *America Burning* (1973), productivity losses in the United States were somewhat greater than direct losses ($3.3 billion against $2.7 billion per annum). In a series of papers, Wilmot (1979, 1990, 1996) has produced national estimates on consequential losses for different countries for various years. According to his latest figures (1996), reproduced in Table 9.2, indirect fire losses in European countries, except Switzerland, were less than 25 per cent of the direct losses; the figure for Switzerland was 41 per cent. Wilmot's estimate for the USA was very low (9 per cent) compared with 122 per cent given

Table 9.2 Ratio of indirect to direct fire loss

Country	*Indirect loss*[a] *(% GDP)*	*Direct loss*[a] *(% GDP)*	*Ratio of indirect to direct loss*
United States	0.013	0.15	0.087
Japan	0.016 (1985–6)	0.08	0.200
Norway	0.005	0.24	0.021
Sweden	0.009	0.25	0.036
Netherlands	0.030 (1987–8)	0.19 (1987–8)	0.158
Austria	0.029 (1979–80)	0.21 (1979–80)	0.138
Germany, West	0.037 (1987–9)	0.20 (1989–90)	0.185
Denmark	0.034	0.26	0.130
Finland	0.021 (1988–9)	0.17 (1988–9)	0.124
United Kingdom	0.019	0.19	0.100
France	0.037 (1980–1)	0.23 (1981–2)	0.161
Switzerland	0.095 (1989)	0.23 (1989)	0.413

Notes
[a] Wilmot(1996)
Average values relating to 1991–3.

in *America Burning*. This large difference was due mainly to definitions adopted for consequential losses. Moreover, the figure in this report is very much out of date. Wilmot's figures are the only available national totals for consequential losses due to fires in different countries. They have been produced on widely varying bases and hence should be regarded with some reservations.

As Rasbash (1977) pointed out, low estimates such as those obtained by Wilmot may be due to the assessment of indirect losses to the nation rather than to the sum of such losses for those who suffer fires. At the national level, as mentioned earlier, one person's or firm's loss due to economic stress following a fire can be another person's or firm's gain, and therefore cancels it out. A question, however, arises as to whether the national picture is the one that really matters. An individual's loss and inconvenience are felt no less deeply even if other persons can benefit as a result. Moreover, for the individual who loses, the loss is acute, whereas for those who gain, the gain is usually marginal and probably unnoticed. If all such consequential losses and hurt were insured as the bulk of direct losses are, it would cost the community (nation and individual) a total consequential loss likely to be nearer to the direct loss (Rasbash, 1977).

The hypothesis postulated by Rasbash will have some validity if the values of the parameters c and b in equation (9.2) are both close to unity. The value of b in Table 9.1 may not be significantly different from unity at the national level (and other levels) if larger samples of data were used in the regression analysis. The value of c is, however, significantly closer to zero than to unity.

Major fires: case studies

A number of major fires causing severe consequential losses have occurred in several countries during the last two or three decades. In the United Kingdom, a warehouse at the Royal Army Ordnance Depot in Donnington was completely destroyed by fire and collapse in June 1983. The direct loss was estimated at £165 million but this figure was thought not to include stores which were destroyed and could not be replaced. In addition there could have been consequential losses due to the destruction of irreplaceable spare parts and these were not estimated. Apart from the financial loss there was also the strategic value of the goods, affecting the security of the United Kingdom.

In May 1972, one of the worst mining accidents in history occurred at the Sunshine Silver Mine located in Kellogg, Idaho. Ninety-one lives were lost when a fire broke out at the 3,400-foot level of the deepest silver mine in North America. Toxic smoke spread rapidly throughout the working areas of the mine, rendering useless a number of self-contained breathing devices available to those trapped there. Another major fire incident occurred on Staten Island in New York in February 1973 while forty workers were repairing the mylar lining of an LNG storage tank facility. A small fire began during the repair process and resulted in an explosive fire which trapped and killed all the workers inside the tank facility.

A number of catastrophic hotel fires with huge consequential losses have occurred during the last decade. In November 1980, a fire broke out in the kitchen area of a restaurant located on the lobby floor of the 26-storey casino and hotel, the MGM Grand Hotel in Las Vegas, Nevada. The fire rapidly involved the first-floor public areas of the hotel and smoke quickly coursed through elevator shafts and enclosed stairwells. Numerous victims were trapped in the high-rise tower, resulting in 84 fatal and over 600 non-fatal casualties. Property damage exceeded $150 million.

In February 1981, a fire broke out in the elevator corridor on the eighth floor of the 30-storey Las Vegas Hilton Hotel. The fire soon breached the window, causing flames to impinge on the floor directly above and, in a period of less than three minutes, the fire leaped in similar fashion to each of the elevator lobbies above the eighth floor. It resulted in the deaths of eight victims and personal injuries to approximately 350 people. On a comparative basis the personal injuries sustained by the survivors of the Hilton fire were more severe than in the MGM fire.

On the afternoon of New Year's Eve, 1986, a fire started in a ballroom on the ground floor of the 15-storey San Juan Dupont Plaza Hotel. Within eight minutes the fire trapped the majority of its victims in a casino located one storey above the area of origin. The fire killed 97 people and resulted in over 2,000 insurance claims.

Other major fires occurred in Kentucky Beverley Hills Supper Club (1977) and the Isle of Man Summerland Recreation Complex (1973). In the UK two major fires occurred in department stores: Henderson's, Liverpool (1960) and Woolworth's, Manchester (1979). Big hotels and department stores, such as those mentioned above, and their suppliers of goods and services would have sustained heavy consequential losses.

On 23 June 1990, a fire developed in the partly completed 14-storey building (phase 8), a multistorey office block in the Broadgate development, London (Fire Safety Engineering Consultants Ltd, 1991), which is built over the main British Rail line providing services predominantly to and from the east of London. The fire began in a large contractor's hut on the first floor and smoke spread unchecked throughout the building. The automatic fire detection and alarm system or sprinkler system were not yet operational. The total duration of the fire was in excess of 4½ hours, two hours of which represented the most severe phase of the fire with temperatures in excess of 1,000°C. The direct fire loss was more than £25 million, of which less than £2 million represented damage to floors (composite steel deck/concrete) and structural frame of steel construction. The balance of the loss was due mainly to smoke damage to the building fabric. An in-depth structural fire engineering investigation proved that the design of the connections of the floor slabs to the beams and of the beams to the columns were able to accommodate large deformations and forces without failure. The fact that the building was constructed of steel framework and composite floors meant that replacement of damaged members could be undertaken in a very short time—the structural repairs took only thirty days to complete.

In August 1991, a fire occurred in a building undergoing construction in a multistorey office complex at the Underwriting Centre, Minster Court, London (see Rosato, 1992). The cause of the fire was a discarded match which ignited a considerable amount of dry rubbish. Although the polystyrene blocks supporting the scaffolding were apparently fire resistant, they were protected with a cardboard-type material which could have ignited in a fire. Fortunately, the fire began early in the morning when only a handful of contractors had arrived for work. The fire was discovered at about 0730 hours on the north-east side of the upper-ground floor of the building. A sprinkler system had been installed but the heads had not been fitted at the time of the fire. The fire was attended by 150 fire fighters and brought under control at 1045 hours. The atrium was completely destroyed and all floors from the upper-ground upwards suffered considerably from fire, heat and smoke. The building services plant on the top floor was badly damaged by the intense heat created at this level during the fire. The direct damage to the building and its contents amounted to £105 million and the consequential losses to £60 million.

Case studies and litigation reports on major fires provide useful data on direct and consequential losses and the factors affecting them. These data and those available from other sources could be combined and a ‘meta-analysis’ performed to obtain reliable estimates on the relationship between direct and consequential losses for major industrial and commercial sectors.

The role of fire protection

Although insurance can provide indemnity against direct and consequential losses, in some cases, the loss of production over a period of several months can lead to a permanent loss of markets to the competitors and in extreme cases may even result in the closure of the firm and job losses. A high percentage of firms hit by large fires face bankruptcy within a short period after the fire (fire protection organisations such as the Fire Protection Association (FPA) in the UK and the National Fire Protection Association (NFPA) in the USA may have some figures for this percentage). It is in this area, serious disruption or bankruptcy, that the justification for fire prevention and protection measures becomes most important, particularly for parts of an industrial or commercial property with potentially high risks of consequential losses. It is necessary to identify such parts or areas of a property and provide appropriate safety measures.

The reports of the Insurance Technical Bureau (ITB) mentioned on pp. 154–5 also contain recommendations for necessary fire protection measures to be adopted, particularly to reduce consequential losses. In the pharmaceutical industry (ITB, 1977) for example, high levels of fire detection and protection are justified for production areas of patented products responsible for the bulk of profits. Adequate fire precautions are necessary for sites to which bulk chemicals and other raw materials are supplied from outside and in which they are stored. A high standard of engineering maintenance and housekeeping is important to prevent explosions due to leakage in bulk powder handling plant. Drums containing highly flammable liquids should be stored in a properly designed drum park with a kerb or bund, protection from the sun, suitable drainage and suitable arrangements for access to and handling of the drums. If the drum part is unavoidably close to buildings it should be provided with fixed fire-fighting facilities—water drench or foam as appropriate. Drums should never be discharged whilst inside a storage area but removed to a special area. The report of the ITB also contains recommendations for the location of solvent recovery plants and for the protection of tank farms containing solvents, several types of driers, centrifuges and laboratories including laboratory documents.

In buildings used for aircraft assembly or built for aircraft assembly but used for other purposes, factors such as the presence of heat sinks and ventilation arrangements might lengthen the time of response of conventional sprinkler arrangements. Shorter response times are achieved by deluge systems actuated by faster detectors such as rate-of-rise detectors (see ITB, 1976). It is desirable for such systems to be widely used for the protection of buildings with large volumes of flammable solvents and buildings over 10 m in height used for storage, general machinery or assembly purposes. Supplementary underwing protection is desirable for an aircraft with a large wing area, in particular delta-wing aircraft such as Concorde; such an aircraft would shield substantial areas from fire extinguishment by overhead sprinklers. In tall buildings with sprinklers and containing high values and in areas where fuels are present, detectors would enable fires to be contained more quickly, possibly before sprinklers are activated. The ITB report has discussed several factors to support the increased use of detectors in the aerospace industry, including factors which may reduce the effectiveness of the works fire brigade.

The third ITB report (1978) recommends several fire safety measures for paint and ink manufacturing industries. Measures to reduce the possibility of fire or explosion in resin plants include the use of indirect heating systems (oil and steam) or induction heating in place of conventional gas heating and the fitting of pressure relief valves with vent pipes to safe areas or, preferably, into vessels at least 1.5 times the capacity of the kettle being vented. Runaway reactions are usually prevented by 'crash cooling' procedures whereby water is circulated through cooling coils fitted inside or around the kettle. Other measures for resin plants include the installation of flame-proofed or intrinsically safe electrical equipment and sprinkler systems. In paint manufacture, solvent-containing products should be made in an area separate from aqueous-based (e.g. emulsion) lines, and oil-based paints should be segregated from highly flammable materials such as cellulose. Similarly, in the ink industry, black inks, paste inks and liquid inks should be segregated. (Segregating the manufacture of different paint types is a common practice.) Laboratories in paint and ink factories should be segregated from manufacturing zones; where this is not possible the laboratory should be pressurised. The ITB report contains several other safety recommendations for the paint and ink industry including sprinkler protection in storage areas, particularly where non-aqueous products are stored.

Woolhead (1989) has discussed the indirect losses to a business activity arising from electrical cable fires. For cable protection, special ready-mixed inert materials can be applied by brush, spray or trowel to single or grouped cables and supporting trays. These coatings are also moisture-and-humidity resistant. Some manufacturers can also provide material to stop fire where cables pass through apertures and fire barriers for cable trenches or cable tunnels. Other recommended safety measures include fire detection systems, water spray systems particularly where multilayers of cable trays are involved and gas flooding systems (halon or carbon dioxide). Apart from fire protection, a contingency plan (Chance, 1984) should be prepared for main exposure areas to include customers, suppliers of goods and services, transport and distribution.

Utility function

The negative values for log c (Table 9.1), the intercept term in the regression line based on equation (9.2), indicate that there will be no indirect losses from fires, the direct losses of which are less than a (minimum) threshold level. A direct loss in excess of a maximum might put a business out of action permanently or temporarily for a long duration. By considering only fires with direct losses between these minimum and maximum limits, equation (9.2) can be modified to the form in equation (8.22), (p. 152) with—$U(x)$ denoting disutility, the negative counterpart of utility, measured in terms of consequential losses. This modified form can provide some idea of the shape of the utility function for any area of an industrial or commercial activity. But the parameter θ of the utility function also depends on other factors such as the attitude to risk and financial strength of a property owner.

Chapter 10

Monetary value of human life

This chapter is a slightly modified version of Chapter 8, section 5, contributed by the author to the *SFPE Handbook of Fire Protection Engineering,* 2nd edn, Quincy, MA: National Fire Protection Association, 1995. The author wishes to thank the Society of Fire Protection Engineers, USA for its permission to reproduce this chapter.

Introduction

An economic analysis of safety expenditure involves a consideration of the costs of various safety measures and the benefits which can be expected from adopting these measures. For economic justification of this expenditure the benefits should exceed the costs. In principle, the costs of fire safety devices are not too difficult to determine but some of the benefits due to them are difficult to quantify. Benefits such as tax allowances and savings on insurance premiums are realised by the property owners with 'certainty'. But a reduction in fire damage due to a fire safety measure is an 'uncertain' benefit whose 'expected value' depends on the probabilities associated with the occurrence and spread of fire. Damage to a building and its contents can be fairly assessed but it is difficult to evaluate consequential losses due to loss of profits, production, exports and employment. Damage to life in terms of injuries and deaths is another important factor to be considered in fire safety problems. Insurance claims provide some data for the valuation of injury and an alternative method is to aggregate various components—treatment costs, the value of time lost, social costs, and the value of pain and suffering which is the most difficult to evaluate. The ultimate cost assessment which has to be made is the value of human life, which is the subject of this chapter.

The object here is to briefly review different methods of assessing the value of human life and their applications to some safety problems which provide numerical values. The use of the value of human life in fire protection economics is explained with the aid of a few examples. It is shown that policy-makers should carry out a sensitivity analysis using a range of values for human life to economically justify the recommendation of any fire safety measure. The analysis presented in this chapter is concerned with decision-making at the national level and the cost of a statistical fatality. A different approach would be used by a homeowner considering fire or life insurance.

Methods of valuing human life

Key aspects of the value of life and safety have been discussed by several authors who contributed to the proceedings of a conference held by the Geneva Association in 1981. This book (Jones-Lee, 1982) contains surveys of theoretical and empirical work and pertinent methodological and philosophical issues. Recent developments on this subject have been reviewed by Jones-Lee (1985). As discussed below, there are essentially five approaches to valuing human life.

The first method is concerned with gross output based on goods and services which a person can produce if he or she is not deprived by death of the opportunity to do so. Sometimes gross productivity is reduced by an amount representing consumption (net output). Discounted values are generally taken to allow for the lag with which the production or consumption occurs. The output approach usually gives a small value for life especially if discounted consumption is deducted from discounted production. This must be so since the community as a whole consumes most of what it produces. It is argued that when a person dies, although the community loses future output it also saves future consumption. The person's own consumption or the utility he or she would derive if alive is not counted as a loss.

The livelihood approach to the value of life which is not fundamentally different from the output approach, assigns valuations in direct proportion to income. The present value of future earnings of an individual is estimated and reduced by an amount equal to discounted consumption (Dawson, 1971). This would give the net economic value of an individual to his or her family. This method also gives a small value for life. As with the output approach, deduc-tion of consumption is to some extent unethical and not economically justifiable. The livelihood method normally favours males over females, working persons over those retired and higher-paid over lower-paid persons in a way that may not reflect individual or social preferences.

The third approach assumes that if an individual has a life insurance policy for £*x* then that person implicitly values his or her life at £*x*. Collection of the necessary data from insurance companies is not a difficult task and this is the major advantage in adopting the insurance method. There are, however, two drawbacks. First, decisions whether or not to take out insurance and the value of that insurance do not necessarily reflect a person's best judgement of the value of his or her life. It depends largely on the premium the assured can afford from income, taking into account family expenditure. Second, taking out an insurance policy does not affect the mortality risk to an individual; this action is not intended to compensate fully for death or to reduce the risk of accidental death.

Hence in insuring life it is not exactly a value trade-off that is considered between mortality risks and costs.

The fourth method for assessing the value of life involves court awards to the heirs of a deceased person as restitution from a party felt to be responsible for the fatality. Here again, collection of the necessary data will not be a problem. Assessments of the value of life could also be expected to be reasonably accurate since lawyers and judges have massive professional expertise in the *ex post* analysis of accidents. The object of such an analysis is to discover whether the risk could reasonably have been foreseen and whether it was justified or unreasonable.

There are, however, a few problems in using court awards to value human life. The court should ideally be concerned with the assessment of suitable sums as compensation for an objective loss, for example, loss of earnings of the deceased, as well as for a subjective loss, such as damages to wife and children for their bereavement and grief. In some European countries damages can include a subjective component but British courts are generally against compensation for subjective losses to persons who are not themselves physically injured. It is believed that bereavement and grief are not losses which deserve substantial compensation. It is difficult to quantify pain, grief and suffering. It is also difficult to value the quality of a life that has been lost. People who themselves suffer personal injury, of course, qualify for substantial damages for subjective losses. For obvious reasons resource costs such as medical and hospital expenses are significantly higher in serious injury cases than in fatal cases. Hence awards for subjective losses tend to be much larger and more important in serious non-fatal cases than in fatal ones. British courts have also limited to very low levels the damages which are awarded for reductions in life expectancy.

Lastly, in court awards we are considering the risks to individuals related to the plaintiff and the costs to the defendant. However, value judgements are likely to vary according to whether the individuals making these judgements are associated with the plaintiff, the defendant or the court.

The fifth approach is the one widely adopted for valuing life. It is based on the money people are willing to spend to increase their safety or to reduce a particular mortality risk (Linnerooth, 1975; Mishan, 1971). It is difficult to differentiate between the benefit from increasing people's feeling of safety and that from reducing the number of deaths. Anxiety is a disbenefit even if the risk is much smaller than believed. Likewise, people dying from risks of which they are unaware still suffer a loss. This approach to the value of life rests on the principle that living is a generally enjoyable activity for which people would be willing to sacrifice other activities such as consumption.

The implied value of life revealed by a willingness-to-pay criterion would depend on a number of factors. The acceptable expenditure per life saved for involuntary risks is likely to be higher than the acceptable expenditure for voluntary risks as people are often unwilling to accept involuntarily what they will accept voluntarily. The sum people are prepared to pay to reduce a given risk will also depend on the total level of risk and the amount already being spent on safety. This sum will also depend on the earnings of the individuals.

The theoretical superiority of the willingness-to-pay method consists in its connection with the principle of 'consumer sovereignty' that goods should be valued according to the value individuals put on them. This consumer preference approach treats safety as a commodity like any other, so that when a government carries out projects to alter people's safety it should estimate the costs and benefits as people do. This method would give a level of safety expenditure which people could be expected to accept or bear thereby avoiding the disadvantages of compulsory regulations which are often complex and ineffective and can destroy people's sense of responsibility (Melinek, 1974).

However, the willingness-to-pay criterion puts more weight on consumer sovereignty than it can really support. Safety is not at all like any other commodity that is consumed because of its connection with uncertainty (risk). Surveys have also shown variability and inconsistencies in the responses to questionnaires (Acton, 1975; Fischer and Vaupel, 1976; Keeler, 1970); quite simply, individuals have difficulty in answering questions involving very small changes in mortality risks. Due to insufficient knowledge about the risk most people find it difficult to quantify its magnitude accurately. Also the benefits are often intangible, for example, enjoyment, peace of mind. It is difficult to put a monetary value on these factors. As the literature on compensating wage differential indicates, individual willingness to pay can be estimated by methods other than direct questioning of individuals.

A great majority of accidents that occur are the result of events or a chain of events of a simple character: a slight miscalculation in overtaking a vehicle or excessive speed while driving a car or careless disposal of smoking materials in the home. Hence it is doubtful whether individuals are good judges of risks and costs. Since many accidents do occur, the question that must be posed is whether these accidents are generally the result of conscious and deliberate acts of risk-taking or whether they are indeed accidents unanticipated and unforeseen. It is possible that some accidents arise not from consciously taken risks but from risks which have not (or not adequately) been perceived at all. People not involved in an accident cannot estimate how they would behave in what is to them a hypothetical situation.

Applications

The methods commonly used are based on estimates of the expected loss and benefits due to a risky activity. The expected loss (L) due to the risk of death is the product of the value (V) placed on life and the probability *(p)* of death which is a numerical measure of the risk. A value for life is obtained by equating minimum acceptable benefit with expected loss. The implied value of life V is therefore given by:

$$V = \frac{L}{p} \tag{10.1}$$

The parameters L and *p* depend on the type of risk considered.

Consider, for example, the use of a subway by pedestrians (Melinek, 1974). It was estimated that the risk (probability) of being killed while crossing a road was approximately 1.225×10^{-8} and that people were willing to use a subway if the additional time was less than 16 seconds. Transport studies indicated that the value people put on their time was of the order of £0.24 per hour. Under these assumptions the implied value of life for this particular risk was estimated as:

$$V = £0.24 \times (16/3{,}600)/(1.225 \times 10^{-8}) = £87{,}000$$

at 1973 prices or about £260,000 at 1981 prices. For two other examples the estimated values of life based on mortality risks were as follows:

	1973 prices	*1981 prices*
Smoking	£28,000	£84,000
Employment (industrial accidents)	£200,000	£600,000

Based on these studies Melinek (1974) suggested a figure of £50,000 (at 1973 prices) for the implied value of life for fire protection problems. This is equivalent to an estimate of about £150,000 at 1981 prices. There is evidence that people are willing to take higher risks in voluntary activities. This factor may account for the low implied value of life from smoking. It is also likely that people assume that if they die from smoking it will be in old age.

The above estimates of the value of life make no allowance for the risk of injury or ill health. The number of injuries (death) depends on the hazard. For example, aircraft crashes result in few non-fatal injuries. On the other hand, a large proportion of injuries are caused by events (for example, abrasions, lifting) which cause few deaths. The number of injuries/deaths also depends on age. Fire fatalities tend to be very young or very old. Melinek (1974) has obtained the following figures for estimated values of life allowing for the subjective (but not financial) cost of injuries and ill health. He assumed that figures for injury are about 15 per cent of the estimated values of life:

	1973 prices	*1981 prices*
Use of subways	£74,000	£222,000
Smoking	£24,000	£72,000
Employment	£161,000	£483,000

If the subjective cost of injuries is not subtracted, then the value of life obtained includes the risk of injury.

Blomquist (1982) examined the methodology and results of various empirical studies which estimated values of life based on individual willingness to pay. The evidence on the value of life and safety comes from two different types of sources although both yield information on individual willingness to pay. One type is the implicit values derived from observable individual behaviour with respect to goods and services whose markets are well developed. Much of this type of evidence comes from the labour market through the estimation of risk compensating wage differentials. Implicit values are estimated from consumption activity also including housing and travel choices. Another type of evidence comes from creating hypothetical markets for health and safety and asking individuals directly how much they would pay for improvements contingent on the existence of such markets. Blomquist (1982) has discussed in detail the advantages and disadvantages of these methods used by several authors. Table 10.1 reproduced from his paper summarises these estimates. As revealed by the figures in this table, differing circumstances could lead to different values of life. The implied values would vary according to whether they arose through political decisions or in situations where responsibility was thought to lie in the private or personal sector.

It should be noted that only point estimates are given in Table 10.1 and that each study should be consulted for a discussion of the upper and lower bounds of the values of life. It should also be remembered that the value of life varies with risk, income, age, family status and other circumstances. When grouped by the range of estimated values of life the contingent values show the greatest range, followed by the values based on risk compensating wage differentials and values from consumption activity. When grouped by risk reduction a clearer pattern emerges: the estimated values of life tend to increase as the risk reduction declines. This is understandable to some extent since, in equation (10.1) for implied value of life, the risk factor, that is, the probability p of death, appears in the denominator. The average values of life for different risk levels are as follows:

Risk level	*Average value of life*
10^{-3}	\$168,000
10^{-4}	\$1,068,000
10^{-5}	\$1,963,000
10^{-6}	\$6,746,000

The value of life of \$351,000 in Table 10.1 with regard to smoke detectors for residences has taken into account the purchase price of the detector, the replacement cost of batteries and the changes in the probabilities of death and injury. This author (Dardis, 1980) estimates the average value of life as changing from \$274,000 to \$428,000 depending on whether non-fatal injuries are weighted as equal to one-half a fatality or zero, respectively. Two shortcomings which bias this estimate in opposite directions are the omission of installation costs and

Table 10.1 Values of life from implicit and contingent valuation

Source of evidence	*Authors*	*Value of life (1980 US$'000)*[a]	*Risk reduction*
Implicit values from labour market activity			
Blue-collar workers in manufacturing and construction	Dillingham, 1980	378	10^{-4}
Workers in risky occupations	Thaler & Rosen, 1973	494	10^{-3}
Males in manufacturing industries	Smith, 1979	2,785	10^{-4}
Blue-collar workers	Viscusi, 1978	2,820	10^{-4}
Implicit values from consumption activity			
Residential housing market	Portney, 1981	180	10^{-4}
Residential smoke alarms	Dardis, 1980	351	10^{-5}
Highway speed	Ghosh, Lees & Seal[b], 1975	419	10^{-4}
Auto seat belt use	Blomquist, 1982	466	10^{-4}
Contingent values			
Air travel	Frankel, 1979	57	10^{-3}
		3,372	10^{-6}
	Jones-Lee, 1976	10,120	10^{-6}
Heart attack prevention	Acton, 1975	59	10^{-3}
Nuclear power	Mulligan, 1977	62	10^{-3}
		428	10^{-4}
		3,576	10^{-5}

Source: Blomquist (1982)

Notes
a All values are converted to June 1980 dollars using the Consumer Price Index.
b Since the risk reduction is not specified, it is assumed to be of the same order of magnitude as that in the Blomquist study.

the treatment of household size. The inclusion of installation costs means that the amount which residents are giving up to obtain more safety is greater than estimated and that the implied value of life is higher than estimated by Dardis. Since there will usually be more than one person per household the implied value of life per person is perhaps one-half to one-third of the household value.

Graham and Vaupel (1981) have compared the costs and benefits of 57 life-saving programmes. Quoting surveys of expressed willingness-to-pay for small reductions in the probability of death, these authors have shown that values of a life ranged from \$50,000 to \$8 million (1978 values). Nine labour market studies of wage premiums have produced a narrower but still disparate range of values spread from \$300,000 to \$3.5 million. Graham and Vaupel conclude that within a broad range the monetary value assigned to the benefits of averting a death usually does not alter the policy implications of the analyses.

Future risks can be discounted to the extent that people are willing to take immediate risks (for example, a surgical operation) to avoid greater risks at a future date. The rate of discount is equivalent to a rate of interest and would also reflect the fact that people tend to value the earlier years of their lives more highly than the later years. Alternatively, future risks can be discounted because the money required to reduce them can be obtained by investing a smaller sum beforehand. Dawson (1971) obtained values of life by calculating discounted future earnings plus a fixed subjective loss, assuming 6 per cent per annum rate of discount. Melinek (1974) updated these figures using average annual earnings of £1,920 for men and £1,060 for women and obtained a figure of £14,740 for average discounted earnings; this estimate is considerably less than the value of £50,000 provided by the willingness-to-pay approach. Average discounted consumption, assuming annual consumption of £600 and a rate of discount of 6 per cent per annum, was £7,800. Average discounted earnings less consumption was thus estimated as £6,940 (at 1973 prices). This sum represents the average net economic value of an individual to his family. Melinek (1974) has produced estimates for discounted earnings for different age groups and for males and females separately.

Schelling (1968) estimated the subjective value of life to be 10–100 times a year's income, giving a value of £20,000 to £200,000 assuming an annual income of £2,000. The average value of £50,000 obtained by Melinek is near the geometric mean (£60,000) of the limits estimated by Schelling.

Court awards in the UK for damages for fatal (or potentially fatal) injuries are based on loss of earnings plus a small sum for reduction of life expectancy. Figures for court awards and sums assured for life insurance are not readily available but can be obtained for purposes of comparison.

Discussing a paper presented by Jones-Lee to a workshop on accident modelling, Maycock (1986) has reproduced figures (in Table 10.2) which give estimates (in US dollars at 1979 prices) of the value of a fatality arising from the various valuation methods (based on data from developed countries). The table includes a sixth approach not discussed on pp. 167–9. The 'appropriate' valuation depends upon the economic or social objectives of the particular country applying the technique. If national output is the key objective, then 'gross output' measures are the most appropriate for accident valuation. If a country's objectives are related to broader social welfare considerations, then willingness to pay would seem more appropriate.

Since 1985 several research studies carried out in the United Kingdom adopted the willingness-to-pay (WTP) approach for determining a single monetary value or range of monetary values for human life. These studies, reviewed by Ball (1996), included sectors such as industrial safety, radiological

Table 10.2 Estimates of the cost of a statistical fatality (or value of the avoidance of a statistical fatality) by costing/valuation methods

Costing/valuation method	*Cost/value of one statistical fatality (1979 US$)*
1 Gross output approach:	
(a) including subjective component (Dawson, 1971)	120,000
(b) including subjective component but increased 50% and with reduced discount rate applied (UK Dept of Transport, 1979)	225,000
2 Net output approach:	
(a) excluding subjective component (Reynolds, 1956)	25,000
(b) including subjective component (Dawson, 1971)	76,000
3 Life insurance basis (Fromm, 1965)	930,000
4 Court-awards basis	
(a) Abraham and Thedie (1960)	83,000
(b) Shepherd (1974)	1,000,000
5 Implicit public sector valuation: (Mooney, 1977)	3,000–60,000,000
6 Willingness-to-pay approach	2,100,000

Source: Maycock (1986)

protection, road safety and railway safety. Figures in Table 10.3 have been reproduced from Ball's paper; these are based partly or wholly on WTP method.

As pointed out by Ball in his concluding remarks, while there is little apparent argument among UK economists over the proper way of eliciting the value of life (i.e. expressed preference WTP), the methodology continues to exhibit serious and intractable difficulties. A recent study (Ives *et al.,* 1993) of WTP for food risk reductions confirmed that contingent valuation responses remain subject to serious biases. Given the problems with contingent valuation, it would be a mistake to rely unduly upon any single method of arriving at the value of life for decision purposes. It would be better to make use of as many techniques as possible and avoid any inclination to over-sophistication in determining or presenting the results. The most important thing is to arrive at a value which is more or less in tune with what society can afford and to use it as a guide while recognising fully its frailties.

Cost-benefit analysis

The main purpose of estimating a value for human life is to use it in a cost-benefit decision analysis of measures aimed at increasing safety or reducing risk. As a first example, consider the decision analysis carried out by Helzer *et al.* (1979) to evaluate alternative strategies to reduce residential upholstered furniture fire losses. Three alternatives were evaluated: no action; mandatory

Table 10.3 Recent UK estimates of the value of preventing a fatality

Source	*Value of life (£)*
Health & Safety Executive (Davies & Teasdale, 1994)	620,000[a]
Royal Society (1992)	2,000,000–3,000,000[a]
Centre for Environment & Risk Management, University of East Anglia (Ives *et al.*, 1993)	1,600,000[b]
Department of Transport (1993)	820,000[a,c]
Jones-Lee *et al.* (1985)	1,000,000–2,000,000[d]
Dalvi (1988)	500,000[e]

Source: Ball (1996)

Notes
a 1992 prices
b Median value at 1990 prices
c Comprising £541,000 as willingness-to-pay component, £277,000 for lost output and £2,000 for medical costs
d 1985 prices
e 1987 prices

smoke detector installation; and an upholstered-furniture standard under consideration by the Consumer Product Safety Commission. The alternatives were evaluated on the basis of minimising the total cost plus the loss to society over time. Figure 10.1 shows how the comparison of alternatives was affected by the value assigned to life.

According to Figure 10.1, if no value were placed on preventing the loss of life, no action is the most attractive alternative. At a value of approximately \$60,000 per life saved, the smoke detector alternative became the most attractive strategy and at approximately \$300,000 per life saved, the proposed standard became the most attractive alternative. The proposed standard was the most attractive strategy for all values greater than \$300,000 per life saved. At a value of \$1 million per life saved the proposed standard resulted in a reduction in present value of cost plus loss of 7 per cent over the detector alternative and 16 per cent over no action. These sensitivity studies showed that the smoke detector alternative and the proposed standard were the most attractive over a wide range of values assigned to life.

Chandler and Baldwin (1976) carried out a statistical study of fires in the United Kingdom during 1970 involving the ignition of furniture and furnishings in the home. The total cost of furniture fires for this year was estimated by combining property damage, deaths and injuries. A value of £50,000 was used for each life loss and a value of £1,000 for each injured case. The latter value was based on hospitalisation costs, although for more serious injuries involving permanent disability a value in excess of £1,000 would have been appropriate. Based on some unpublished data the following values were adopted for property damage:

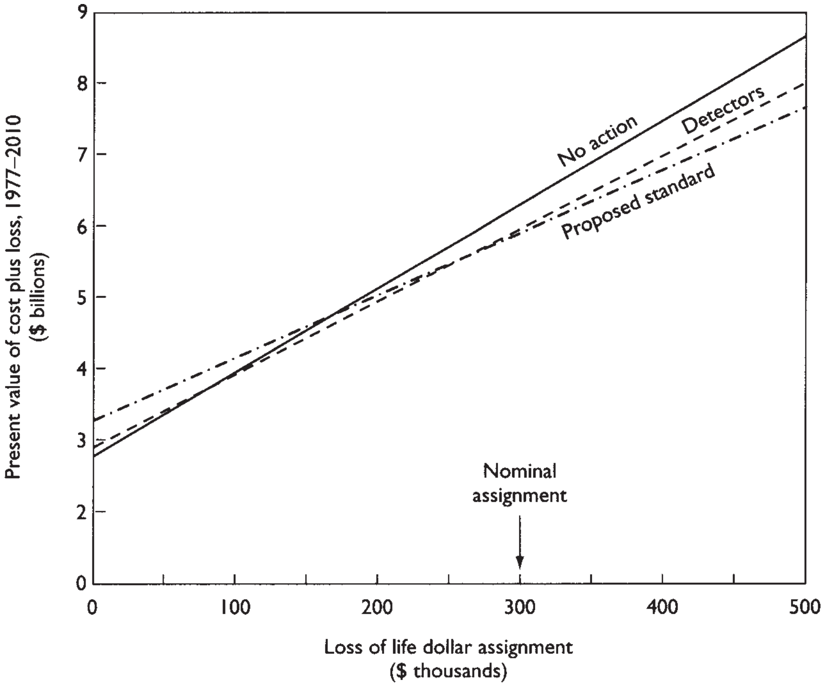


Figure 10.1 Sensitivity of results to dollar assignment on loss of life
Source: Helzer et al. (1979)

Fire confined to object ignited first	£50
Fire spreading beyond object ignited first but confined to the room of origin	£300
Fire spreading beyond the room of origin	£2,000

Using the values mentioned above it was estimated that for the year 1970 the total costs were £18.8 million for furniture fires and £54.5 million for all dwelling fires.

The cost associated with a particular type of fire represented the maximum potential benefit if all fires of that type were prevented. Using this criterion Chandler and Baldwin (1976) concluded that action to reduce fatalities would have the greatest benefit, particularly deaths resulting from smokers' materials. For furniture already in use the remedy suggested was to either reduce or eliminate the likelihood of ignition or to reduce the toxic hazard in the immediate vicinity of the object ignited. This action would be preferable to prevention of spread as most fatalities were found in the room of fire origin.

A few fires led to much controversy over the use of foamed plastics as a building material and it was proposed that such materials be replaced by more traditional materials, such as plasterboard. This suggestion was subjected to a cost-benefit analysis by Appleton (1977) who investigated the following three types of remedial action:

1 replace foamed plastic by plasterboard;
2 install plasterboard below the foamed plastic;
3 lay fibreglass above the foamed plastic.

The upper (most dangerous) bounds for the total discounted losses (at 1976 prices) were obtained for the following two typical dwellings:

1 A top-floor flat consisting of hall, kitchen, living/dining room, two bedrooms and a bathroom/wc: total discounted loss-£52.6.
2 A large bungalow consisting of hall, kitchen, living room, dining room, three bedrooms and a bathroom/wc: total discounted loss-£77.0.

For these two types of dwellings the average costs of remedial action per dwelling ranged from £130 to £930 at 1976 prices. Hence the discounted losses (maximum benefits) were considerably less than the costs of remedial action even when taking the most pessimistic view of the effect of foamed plastics ceilings. Hence no remedial action was advocated on a cost-benefit basis.

In the analysis mentioned above a value of £100,000 was used for each life saved. In order to test the sensitivity of this parameter the calculations were repeated with the implied value of life as a variable (see Figures 10.2 and 10.3). It was estimated for a bungalow that the replacement of foamed plastic by plasterboard would cost £920. If reality lay at the upper limit of possibilities and this replacement proceeded, then that decision would imply that the value of life was £5 million. Alternative propositions would yield figures of £4.2 million, £7.5 million and £11 million. Since such large values for life were unacceptable, the remedial actions were economically unjustifiable.

General discussion

The value of life discussed in the previous sections included only items of concern to the individual and hence it is a private, as opposed to a social, assessment. Distress to those not killed or injured including those not at risk is an additional consideration to the extent that people are willing to pay for the safety of others. People feel some concern for the safety of others. Such concern increases the value to be placed on life in calculating safety expenditure acceptable to the community as a whole. The distress and financial loss that an individual's death would cause to his or her family are included in his or her private evaluation in so far as the individual takes account of these factors in deciding which risks are worthwhile. The financial loss to the rest of society can be considered an additional factor in the value of an individual's life. The social value of life is the sum of the individual's value of an improvement in his or her

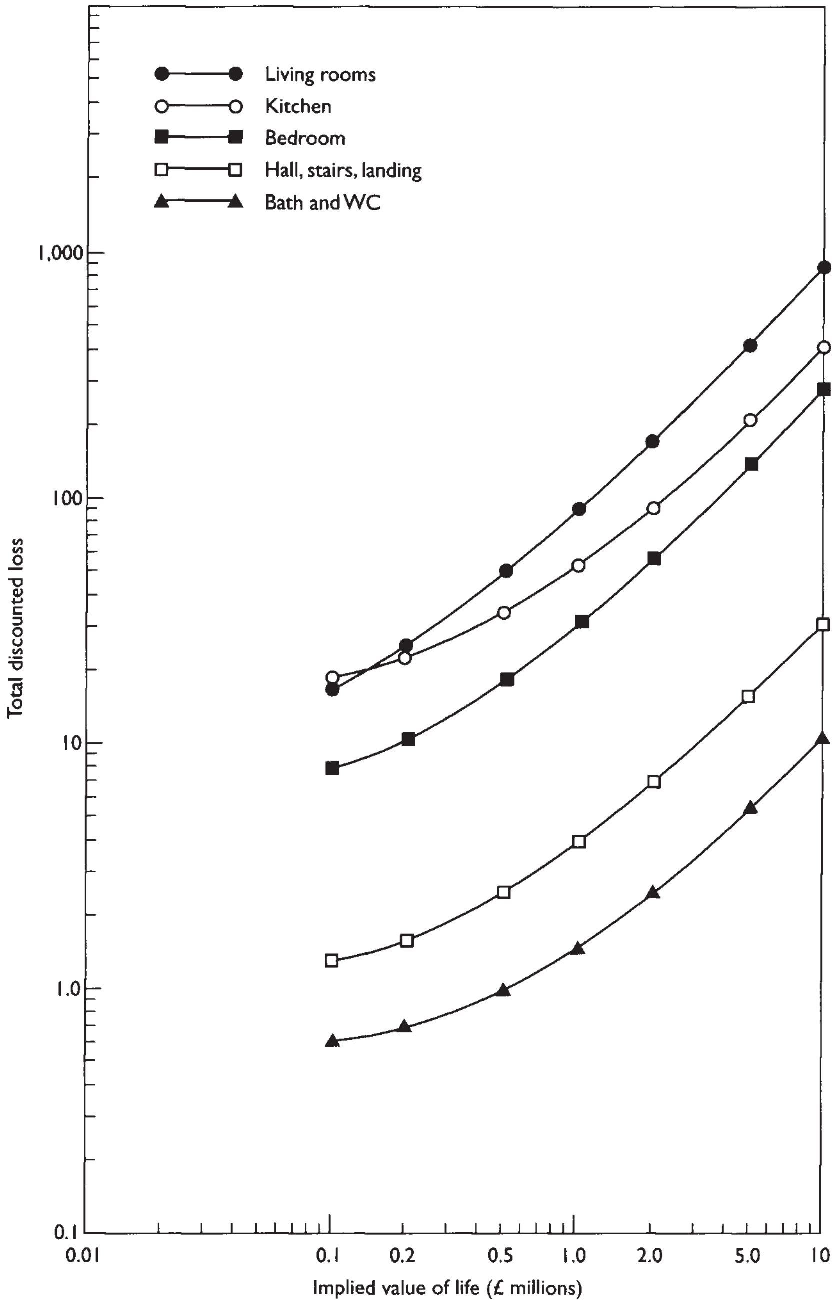


Figure 10.2 Total discounted loss versus implied value of life (a)
Source: Appleton (1977)

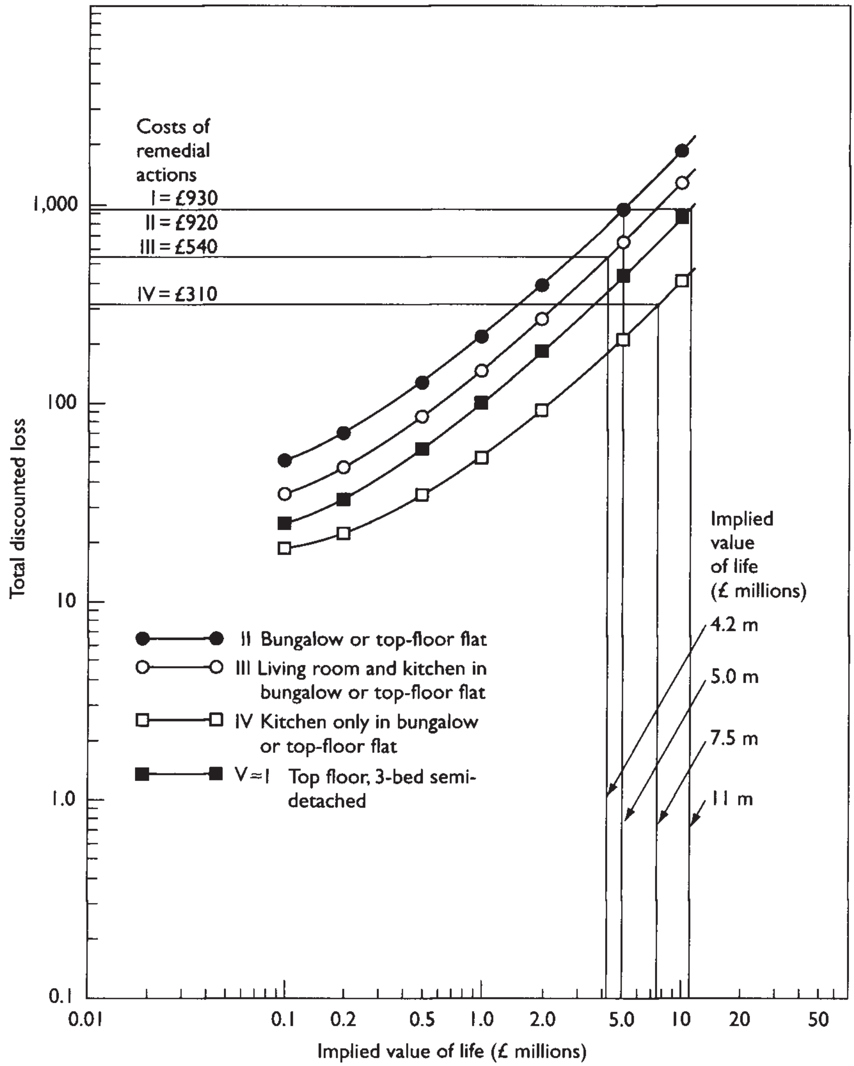


Figure 10.3 Total discounted loss versus implied value of life (b)
Source: Appleton (1977)

safety and the value to others of that improvement. Bailey (1980) estimates several components of this externality such as imprecise insurance classifications including social security, indirect business taxes and medical costs borne by others. As estimated by Bailey, the total adjustment for these external factors increases Blomquist's private (willingness-to-pay) valuation of $466,000 by 17.5 per cent to $548,000.

In a safety problem such as fire protection, all such externalities should be carefully enumerated and their values included if necessary in order to derive the social values of life which are more relevant for public policies than individual implied values. A citizen's valuation of individual safety will understate its value to society as a whole.

A problem arises in an organisational evaluation of mortality risks to several individuals; this pertains to the manner in which individual implicit values should be aggregated. Because the responses about willingness-to-pay concern funds of the individual at risk and the institutional problem concerns funds of some other entity, a direct aggregation of the individual responses would be likely to be inappropriate in many circumstances. For example, the implied life values of the occupants cannot be simply added in order to provide the manager of an hotel with an appropriate level of fire safety expenditure for the establishment. Other factors such as the assets and profits of the firm would have to be taken into consideration.

Many ethical issues become entwined in the life valuation by a government organisation for safety expenditure. It may have to spend less on some sections of the population in order to be able to spend more on other sections. Most fire victims are, for example, either young children or old people, particularly those who live alone. Also, although a person is poor that life should not receive a lower valuation when, for example, pollution and fire control decisions are made.

Governments should also give serious consideration to the social disutility or consequences due to deaths in fires. Disutility would be low for small fires or single-death fires in the mortality context. Disutility is high for multiple-death fires. It is important to consider not only the number of deaths but also whether they occur singly or as a result of catastrophes involving many deaths. Catastrophes normally have social and political consequences which an equal number of deaths occurring singly (in separate events) would not have. Representing this symbolically:

$$D(10)>10.D(1)$$

where $D(x)$ is the disutility associated with x deaths. The disutility associated with a multiple-death fire would be high and hence not desirable. A small probability of a catastrophic loss of life is worse than a larger probability of a smaller loss of life, given that the expected number of fatalities are the same for each case.

Chapter 11

Fire insurance

Introduction

The spread of a fire in a building is a complex phenomenon involving timevarying multiple interactions among physical and chemical processes evolved by a variety of burning materials. Hence, the damage likely to be sustained in a fire is a random variable fluctuating widely around an average value. It is, therefore, difficult to provide a sound statistical basis for fire insurance business although actuaries have attempted to develop such a basis during the past three decades. The object of this chapter is to briefly review the statistical problems involved in fire insurance and discuss the calculation of rebates in insurance premiums for deductibles and fire protection measures in industrial fire insurance. The interaction between fire protection and insurance has not received sufficient attention in actuarial literature.

Fire insurance provides protection against financial losses from fire and is intended to 'indemnify' a property owner. A claim payment should restore the property owner's original status but not leave him or her better off. While a life insurance policy may be written with as large a benefit as the buyer wishes to pay for, a fire insurance company will only reimburse a property owner for an amount no greater than the repair or replacement cost of the property if a fire occurs. The number of fires likely to occur in a building and the amounts of fire damage are random variables.

The underlying principle of insurance is that of a pooling process. Individuals or corporate entities who own properties which are subject to damage or destruction from random fires enter into an agreement with others similarly at risk by which they pay certain sums into a pool in exchange for reimbursement of their losses should their properties be damaged by fires. The pooling arrangement may be a mutual activity or it may be organised by an insurance company or association of underwriters such as Lloyds. For the purpose of this chapter, it is sufficient to discuss the statistical problems with reference to a fire insurance company.

The object of a fire insurance company is to secure that in the aggregate the total premiums received will provide for its fixed outgoings (i.e. commission and expenses) and meet average current claims, leaving a small margin for catastrophic claims and profit. Furthermore, the company seeks to ensure that the deviations of the claims about the average in an accounting period are reasonable compared with its free reserves. If the company charges a high rate of premium (per £100 of insurable value) in order to secure a large profit margin, it may lose its business because of the competitive situation in the market. If the premium rate is too low, other influences will put the company out of business.

To run the fire insurance business successfully, the premium rate for any type or group of building should reflect reasonably well the fire risk to which it is exposed. Statistical models discussed briefly in the next section provide the basis for calculating the 'risk premium' for any type or group of buildings. Two loadings are generally added to the risk premium when estimating the total premium payable by a property owner: safety loading (pp. 190–2) and an additional loading to cover the insurer's operating costs, which include profits, taxes and administrative expenses.

The premium rate should also be adjusted for any self-insurance (deductible) agreed between a fire insurance company and a property owner. When a deductible is introduced in an insurance contract, the insured is expected to take greater interest in adopting loss prevention and reduction measures. With adequate fire protection, particularly sprinklers, the insured can take the risk of accepting a large deductible which will minimise the total cost of insurance and protection. In order to promote this concept it is necessary for an insurance company to establish statistically sound rebates on insurance premiums for different levels of deductibles, taking sufficient account of the reduction in loss due to a fire protection measure (see pp. 192–5). In calculating the rebates it may be worthwhile considering the maximum amount a group of risk-averse policy holders can spend or are willing to spend to avoid the risk due to large fires (see pp. 195–7).

Statistical models

Risk theory

Actuarial risk theory is concerned with the application of probabilistic techniques and models to the risk process involved in the operation of an insurance business. The risk arises due to the fact that an insurance company agrees to meet the claims of its policy holders to compensate their losses due to the occurrence of events such as motor accidents, deaths and fires. The company would face ruin during a period if the total claim amount to be paid by the company during that period exceeded its assets, consisting of 'free reserves' (capital) and total premiums received. Uncertainties are associated with the total claim amount and hence the occurrence of ruin is a random event, estimation of whose probability requires the application of risk theory.

The number or frequency of claims and the size of claims are the two components constituting the total claim amount. Models based on risk theory recognise that both these components are random variables and the actual amounts arising from several successive periods will fluctuate around an expected value within confidence limits expressed in probabilistic terms. In conventional actuarial techniques the fluctuation phenomenon is disregarded and the random variables are replaced by the expected value of the total claim amount.

The financial structure of an insurance firm depends on management costs and investment of capital in addition to the claim aspects, but these two factors are not subject to random fluctuations. Hence, an application of risk theory is restricted to the probabilistic estimation of the number of claims and the 'risk premium' based on the expected size of a single claim. An insurance company generally adds two types of loadings to the risk premium (see pp. 190–2). Easy-to-follow textbooks on actuarial risk theory are those by Beard *et al.* (1969) and Daykin *et al.* (1993). Seal (1969) has written a more advanced book on this subject.

The average number of claims expected to occur in any period (usually one year), q, can be estimated from the probability distribution of a number of claims which gives the probability, $p_k(t)$, of exactly k claims occurring during t periods. The claim number process can be regarded as a Poisson function such that:

$$p_k(t) = \exp(-q\,t)\,(qt)^k/k! \qquad (11.1)$$

The average number of claims during t periods is given by

$$\Sigma\, k\, p_k(t) = q.t \qquad (11.2)$$

which is equal to q for unit period (t=1). In spite of certain limitations (Beard *et al.,* 1969) the Poisson function gives a good approximation particularly for short time periods.

The probability that the number of claims equals k is given by equation (11.1) and the conditional probability that, if k claims occur, their sum is $\leq x$ is given by $S_k(x)$. The (cumulative) distribution function $V(x)$ of the total claim amount is then given by:

$$V(x) = \sum_{k=0}^{\infty} p_k(t)\, S_k(x) \qquad (11.3)$$

$V(x)$ is known as the generalised Poisson function which plays a central role in actuarial risk theory.

If the claims are assumed to be mutually independent, the function $S_k(x)$ is the kth 'convolution' of the distribution function $G(x)$ of a single claim. $G(x)$ gives the probability of the amount of a single claim being less than or equal to x. It is possible to apply the 'convolution' method if $G(x)$ is exponential. Unfortunately, this is not the case with fire insurance since, as discussed in the next section, G*(x)* is generally of Pareto or log normal nature. It is, however, possible to obtain the distribution function V(x) by Monte Carlo simulation. Beard *et al.* (1969) have also discussed other methods of estimating V*(x)*.

Fire loss distribution

In a simple model, an estimate of the total amount of claims during a period is given by the product of the mean number of claims for the period (equation 11.2) and the average amount, $\bar{x}$ per claim. An estimate of $\bar{x}$ is provided by the probability distribution of the amount of loss or claim, x, in a (single) fire. For any building, the magnitude of x would vary randomly between 0 and the total financial value, V, at risk in the building which includes the structure, fittings and contents.

The nature of the probability distribution of fire loss amount has been investigated in detail by Ramachandran (1972, 1974a, 1975b) and Shpilberg (1974) and other authors mentioned in these papers. According to these studies, fire loss x has a skewed (non-normal) distribution and the variable z denoting the logarithm of x has a distribution of the exponential type. This type has been defined by Gumbel (1958) with reference to the limiting (asymptotic) behaviour of a random variable at the tail (large or small values). Statistical properties which are exactly true for the exponential distribution are asymptotically (approximately) valid for a distribution of the exponential type. Exponential type includes exponential, normal, log normal, gamma, chi-square and logistic distributions. Among these distributions exponential for z or Pareto for x has been considered by some actuaries for modelling fire insurance claims but normal for z or log normal for x has been more widely recommended.

According to Pareto distribution, the probability of loss in a fire in a building exceeding x, denoted by Q*(x)*, is given by:

$$Q(x) = (x/m)^{-\lambda} = m^{\lambda} x^{-\lambda} \tag{11.4}$$

where m is the minimum loss and λ a constant depending on the fire risk category of the building. For any risk category, the value of λ. for a building with sprinklers can be expected to be greater than that for a building without sprinklers since the sprinklers, if they operate satisfactorily, would extinguish a fire or restrict the extent of fire spread.

Figure 11.1 is an example of Pareto distribution relating to an industrial building. It is based on data obtained in confidence from an insurance source. The figure is applicable to losses exceeding £100 such that m=100. The value of λ is 0.6 for a building without sprinklers and 0.8 for a building with sprinklers. The figure, which shows straight lines for the two cases, has been drawn on a log scale since log Q(x) has a linear relationship with log x. It may be seen that sprinklers reduce the probability of loss exceeding any specified value.

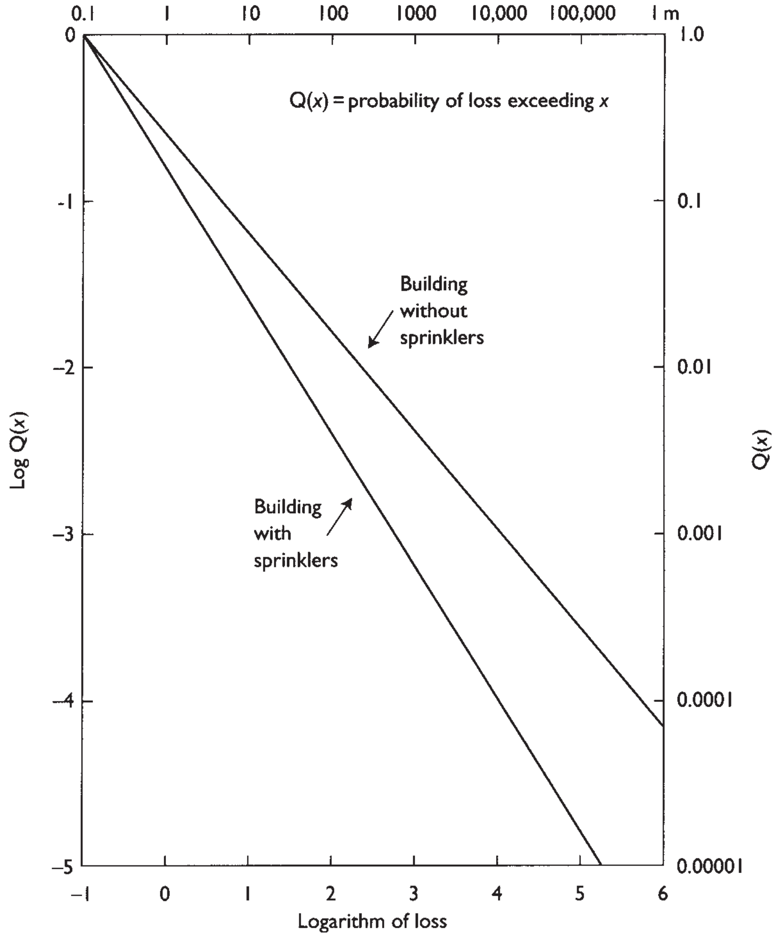


Figure 11.1 Pareto distribution of fire loss, industrial building, United Kingdom

The cumulative distribution function given by

$$F(x)=1-Q(x) \tag{11.5}$$

expresses the probability of loss in a fire being less than or equal to x. The derivative of $F(x)$, denoted by $f(x)$, is known as the probability density function:

$$f(x) = m^{\lambda} \cdot \lambda\, x^{-\lambda-1} \tag{11.6}$$

Using a 'curtailed' version of a Pareto distribution, if the maximum value of the random variable x is V, the expected (average) value of x in the range (m, V) is given by:

$$\bar{x}_V = \frac{1}{F(V)} \int_m^V x\, f(x)\, dx$$

$$= \frac{1}{F(V)} \frac{m^{\lambda}\lambda}{1-\lambda} \left(V^{1-\lambda} - m^{1-\lambda}\right) \tag{11.7}$$

For example, if m=£100 and V=£1,000,000, the average loss $\bar{x}_v$ in this range is likely to be £5,840 for a non-sprinklered building with λ=0.6 and £2,120 for a sprinklered building with λ=0.8.

As discussed in Chapters 7 and 8, fire loss, x, can have a log normal distribution. In this case the probability density function of $z=\log_e x$ is given by

$$f(z) = \frac{1}{\sqrt{2\pi}\,\sigma} \exp\left[-\frac{1}{2}\left(\frac{z-\mu}{\sigma}\right)^2\right] \tag{11.8}$$

where μ and σ are the mean and standard deviation of z. The variable z has a normal distribution. The expected value of x in the range (o, V), $\bar{x}_V$, is given by equation (7.3) (p. 122). If the value V at risk in a building is very high, that is, V=∞, the loss expected, $\bar{x}$, tends to exp [$\mu+\sigma^2/2$]. An example based on log normal distribution has also been discussed in Chapter 7 which shows the value of sprinklers in reducing fire loss.

Fire protection measures such as sprinklers are designed to reduce the damage in the event of a fire occurring in a building. They are not designed to prevent the occurrence of a fire, which depends on the nature and number of ignition sources, human and non-human, present in the building. Hence, in an insurance assessment concerned with the comparison of the economic value of different fire protection measures, it is only necessary to consider the probability distribution of fire loss and not the distribution of the number of claims.

Extreme value techniques

Large claims fall at the tail of the probability distribution of fire loss and pose special problems. These claims exercise a critical effect on the financial performance of an insurance company which has not covered the risks due to large losses through any reinsurance arrangement. A reinsurance company, on the other hand, has to face the consequences due to fluctuations in the claims arising from the large risks it accepts.

Statistical methodology for large claims has been discussed by several authors (see Tiago de Oliveira, 1977; Teugels, 1981, 1983, 1984; Beirlant and Teugels, 1992; Gomes and Pestana, 1986). The techniques developed by these authors are based on complex statistical theories and are not easily applicable to the practical problems in fire protection and insurance. On the other hand, the models developed by Ramachandran (1974a, 1975a, 1975b, 1976, 1982b) are simpler for practical applications. These models based on the statistical theory of extreme values are aimed at making the best use of all the data available for large losses or claims.

The models developed by Ramachandran are applicable to a random variable with a probability distribution of the exponential type as defined earlier. Values with large magnitudes in a large sample generated by such a (parent) distribution are rearranged (ranked) in decreasing order of magnitude with the first rank assigned to the largest (maximum) value. The models predict the individual and collective behaviour of these ranked variables with large magnitudes.

Extreme value techniques developed by Ramachandran have been applied to the following problems in fire protection and insurance:

1 the behaviour of the tail (large losses) of the fire loss distribution over a period of time;
2 the construction of a control chart for a risk category based on large losses to judge the adequacy of fire prevention and protection measures;
3 estimating the average (and total) loss in all fires, large and small, assuming a specific form for the fire loss distribution and using data on large losses;
4 evaluation of the effects of factors enhancing or reducing the loss (multiple regression with extreme values);
5 reconstructing the entire claim distribution using only large claims data;
6 calculation of premium rates for reinsurance.

Rogers (1977) applied one of the extreme value models developed by Ramachandran for the third problem mentioned above, the generalised least squares method, to large losses which occurred in the UK during 1966–72. Each of these large fires cost £10,000 or more in direct material damage. He assumed specifically a log normal distribution for loss x such that $z=\log_e x$ has the normal probability density function described in equation (11.8). Rogers estimated the parameters μ and s for six types of occupancies further classified into four categories according to whether a building is provided with sprinklers or not and whether single-storey or multistorey. The values of μ and s were based on large losses corrected for inflation and expressed at 1966 prices with the aid of retail price indices. Using the parameters μ and s and equation (7.3), Rogers calculated the average loss in fires with losses less than the threshold level of £10,000 at 1966 prices. By combining this average with known losses in large fires exceeding the threshold level, he estimated the average loss in all fires, large and small.

Rogers's results, reproduced in Table 11.1, exclude very small fires that did not grow beyond the 'infant' stage. In the sprinklered classes, these were the small fires which were promptly extinguished by other means before the sprinklers operated. For these classes, an estimated number of fires (mostly small) extinguished by sprinklers but not reported to the fire brigades were

Table 11.1 Average loss per fire at 1966 prices, United Kingdom (£'000)

Industry	*With sprinklers*		*Without sprinklers*		*Overall*
	Single storey	*Multistorey*	*Single storey*	*Multistorey*	
Textiles	2.9	3.5	6.6	25.2	9.3
Timber and furniture	1.2	3.2	2.4	6.5	3.8
Paper, printing and publishing	5.2	5.0	7.1	16.2	10.9
Chemical and allied	3.6	4.3	4.3	8.2	6.4
Wholesale distributive trades	—	4.7	3.8	9.4	7.0
Retail distributive trades	—	1.4	0.4	2.4	1.9

included in the number (n) of all fires, a parameter used in the extreme value model. Such unreported fires constituted approximately one-third of all fires in sprinklered buildings.

Although based on large losses, the results in Table 11.1 are of economic importance. Large fires constitute only a small percentage, about 5 to 10 per cent, of the total number of fires but contribute more than 50 per cent to the total loss in all fires. The results in Table 11.1 clearly indicate the value of sprinklers in reducing the loss likely in a fire occurring, particularly in a multistorey industrial building. In a multistorey textile industry building, for example, the reduction is £21,700, at 1966 prices, which is 86 per cent of the loss expected in a building without sprinklers. This percentage may be called the 'loss reduction ratio'. The reduction is only 56 per cent for a single-storey textile industry building. The 'loss reduction ratio' can be used to calculate the rebates in the risk premiums per claim for full insurance cover for different types of buildings or risk categories.

The figures for average loss given in Table 11.1 are applicable to buildings with large financial values at risk, that is, V=∞. For buildings with smaller values at risk, the loss expected in a fire, $\bar{x}_V$, can be estimated with the aid of equation (7.3, p. 122).

Risk size

As discussed in the previous two sections, the loss expected in a fire, $\bar{x}_V$, depends on the financial value V at risk in a building. The magnitude of $\bar{x}_V$ can be expected to increase with V, as is apparent from equation (7.3) for a log normal distribution or equation (11.7) for a Pareto distribution. But the increase is not proportionate, i.e. $\bar{x}_V/V$ is not a constant. From equation (11.7), for example:

$$(\bar{x}_V/V) = K [\nu^{-\lambda} - (C/V)] \tag{11.9}$$

where K and C are constants.

It may be seen from equation (11.9) or from numerical calculations based on this equation that the ratio $\bar{x}_V/V$ decreases as V increases. This result, which is also true for a log normal distribution, may be verified by performing numerical calculations based on equation (7.3) for any given values of μ and σ. The following 'power' relationship is approximately valid for all practical purposes:

$$\bar{x}_V = KV^{\alpha} \tag{11.10}$$

Equation (11.9) tends to equation (11.10) with $\alpha=1-\lambda$ for large V since C/V will be very small. The value of α is generally less than unity as revealed by statistical studies carried out by Ramachandran (1970c) and actuarial studies in some European countries reviewed by Benktander (1973).

A fire in a large building is more likely to be discovered and extinguished before involving the whole building than is one in a small building. The proportion destroyed in a large building would therefore be expected to be smaller than the proportion destroyed in a small building. These arguments suggest that the loss rate $\bar{x}_V/V$ would decrease with increasing V such that the value of a is less than unity. This result pertaining to equation (11.10) is also supported by statistical studies on area damage in fires in which the size of a building has been expressed in terms of total floor area A (see equation 6.1, p. 90).

If, for any risk category, the average value at risk in a building is $\bar{V}$, the expected value of damage in a fire, $\bar{x}_V$, for a particular building in the category with value V is given by:

$$\bar{x}_V = \bar{x}_{\bar{V}} (V/\bar{V})^{\alpha} \tag{11.11}$$

where

$$\bar{x}_{\bar{V}} = K\bar{V}^{\alpha} \tag{11.12}$$

Equation (11.11) follows from equation (11.10). The value of $\bar{x}_V$ can be estimated as the average loss in all fires occurring in a risk category. If this is possible, equation (11.11) can be used provided information is available for the average value $\bar{V}$ at risk in the buildings belonging to the risk category considered. Equation (11.11) avoids the need to estimate the constant K in equation (11.10).

The value of α in equation (11.10) or (11.11) can be equated to the value of ß in equation (6.1) if it is assumed that the total value at risk, V, is spread uniformly over the total floor area denoted by A. This assumption may be satisfied by different parts of a building, for example, production area, storage area, etc., although it may not be valid for the entire building.

The parameter C in equation (6.1) represents the minimum area which is likely to be destroyed in a fire. This minimum can be assumed to be the area covered by the object initially ignited. Using an approximate figure for financial loss or value at risk per unit area, C can be converted to monetary terms to provide an estimate for the constant K in equation (11.10).

Consider Figure 6.1 (p. 91), which depicts the relationship in equation (6.1) between area damage expected in a fire and building size. Looking at this fig ure from an insurance angle, the damage expected in a building of 10,000 m^2 would be 1,200 m^2 with sprinklers compared with 2,300 m^2 without them. Such results converted to monetary values can be used for determining rebates on fire insurance premiums for buildings equipped with sprinklers.

The frequency or number of claims during a year has also a 'power' relationship similar to equation (6.4), (p. 95) with financial value, V, at risk (see Benktander, 1973). The power (exponent) in this relationship, also, is generally less than unity although the probability of a fire starting in a large building can be expected to be greater than the probability of one in a small building. This is due to the fact that all parts of a building do not have the same risk of fire breaking out. In an industrial building, for example, production, storage and administrative areas have varying levels of ignition sources.

In fire insurance, the normal practice for calculating the premium payable for a property is to multiply the insured value, V, of the property expressed in units of £100 by a fixed (constant) rate of a number of pence per £100 of value. This may not be a valid procedure according to the statistical studies discussed in this section. Since the value of α in equation (11.10) is not generally equal to unity, $\bar{x}_V/V$ is not a constant and might decrease with increasing V if α is less than unity. The premium rate (pence per £100 of value) for large buildings should, perhaps, be less than the rate for small buildings.

The methods described in this section would provide tools for adjusting the risk premium per claim to take account of variations in the value at risk and of the presence or absence of fire protection measures such as sprinklers. The model in equation (11.10) would provide approximate values for the adjustment factor while more accurate values could be derived by applying a curtailed version of the global probability distribution of fire loss for a risk category. This version for Pareto distribution is shown in equation (11.7) and for log normal distribution in equation (7.3).

Safety loading

The statistical methods described in the previous section provide an estimate of the 'risk premium' per claim for a fire risk category. Two loadings are generally imposed on the risk premium when calculating the total premium payable by a property owner. The first is known as a safety loading and the second is an additional loading to cover the insurer's operating costs which include profits, taxes and administrative expenses.

To calculate the safety loading per claim, one of the methods is based on the expected value of loss, $\bar{x}$, for a risk category provided by figures such as those in Table 11.1 or the formula exp $[\mu+(\sigma^2/2)]$ if loss x has a log normal distribution. (The parameters μ and σ are the mean and standard deviation of the logarithm z of loss x to base e.) In this method, a fixed proportion (p) of $\bar{x}$ is added to $\bar{x}$ to estimate the gross risk premium per claim including the safety loading as $\bar{x}$ $(1+p)$.

In another method, the safety loading is expressed as a multiple of the standard deviation of $\bar{x}$ such that gross risk premium per claim is given by:

$$R_p = \bar{x} + \frac{\lambda\sigma_x}{\sqrt{n}} \tag{11.13}$$

where n is the number of claims per year in a portfolio of similar risks. The standard deviation of x, σ_x, is given by the square root of:

$$\sigma_x^2 = E(x^2) - \bar{x}^2 \tag{11.14}$$

where

$$E(x^2)=\exp(2\mu+2\sigma^2) \tag{11.15}$$

if loss x has a log normal distribution. In equation (11.13) $[\sigma_x/\sqrt{n}]$ is the standard deviation of $\bar{x}$.

The exact safety margin provided by a particular value of λ depends on the probability distribution and standard deviation of $\bar{x}$, a discussion about which is beyond the scope of this book. However, for any distribution, according to Chebyshev inequality (La Valle, 1970), the probability of an insurance payment exceeding the amount given by equation (11.13) is less than or equal to $(1/\lambda^2)$. For example, $\lambda=3$ would guarantee a probabilistic safety margin of at least 89 per cent $(=1-1/3^2)$; in this case, the upper limit for the probability of a claim amount exceeding R_p is 0.11.

In the first method for safety loading based on the expected value principle, a constant factor is applied to the expected value $\bar{x}$. Hence the loss reduction ratio for sprinklers defined earlier remains unaltered although the risk premium for a property without sprinklers would be increased to a gross amount to include the safety loading. The ratio between the gross risk premiums for properties with or without sprinklers based on the second method involving the standard deviation would differ from the loss reduction ratio, depending on the standard deviation σ_x and the portfolio size n for the two cases. Both the methods described above briefly have been discussed in detail by Sterk (1980) with regard to the calculation of rebates for deductibles.

The methods described above provide an estimate of the gross risk premium per claim for a property. This premium can be converted to an annual premium by multiplying it by the annual probability of the occurrence of a single claim for a property.

Deductibles

As discussed in Chapters 7 and 8, the object of introducing deductibles (selfinsurance) in fire insurance contracts is to promote fire safety by making property owners responsible for part of the loss when a fire occurs in their property. Acceptance of a deductible instead of full insurance adds an extra dimension in the decision analysis carried out by a property owner who has to determine an optimum package of fire protection and insurance. This problem has been discussed in Chapter 7 with reference to a risk-neutral property owner and in Chapter 8 with reference to a risk-averse property owner.

The type of deductible discussed in Chapters 7 and 8 relates to the 'pure' kind of 'amount deductible'. Under this contract, a property owner is responsible for any material loss up to the deductible amount agreed with the insurer in advance. For any loss exceeding the deductible limit, the insurer would reimburse the insured the loss minus the deductible amount. If a property with a total value V at risk is insured with a deductible D, the insured would be responsible for a sum whose expected value is given by $\bar{x}_D$ in equation (7.4) (p. 122), if fire loss has a log normal probability distribution. In this case, the insurer is liable to pay the insured a sum whose expected value is given by $\bar{R}_D$ in equation (7.5). $\bar{x}_D$ and $\bar{R}_D$ add up to $\bar{x}_V$ in equation (7.3), which is the loss expected in a fire providing an estimate of the risk premium per claim for full insurance (no deductible).

For a property with a total value V at risk, $\bar{x}_D$ in equation (7.4) expresses the reduction in the risk premium per claim. The percentage reduction or rebate in the risk premium is given by the ratio:

$$r(\mathrm{V,D})=\bar{x}_D/\bar{x}_V \tag{11.16}$$

where $\bar{x}_V$ is given by equation (7.3). The risk premium per claim to be charged is given by $\bar{R}_D$ whose ratio with $\bar{x}_V$ is given by [1-*r* (V,D)]. For the example shown in Table 7.1, $\bar{x}_V$ or $\bar{R}_D$ for full insurance is £2,200 with sprinklers and £17,700 without sprinklers. For a £50,000 deductible, $\bar{x}_D$ is £1,400 for a sprinklered building and £10,000 for a non-sprinklered building. From equation (11.16), the rebate *r* (V,D) is 64 per cent and 56 per cent, respectively, for the sprinklered and non-sprinklered cases. For a £100,000 deductible, *r* (V,D) may be verified to be 77 per cent and 74 per cent for the two cases.

If V is very large, equation (11.16) reduces to:

$$r(\mathrm{D}) = \mathrm{G}\,(w-\sigma) + \frac{\mathrm{D}}{\bar{x}}\,[1 - \mathrm{G}(w)] \tag{11.17}$$

where, $\bar{x}$, the loss expected for large V, is given by:

$$\bar{x} = \exp\left(\mu + \frac{\sigma^2}{2}\right) \tag{11.18}$$

if fire loss has a log normal distribution. G(u) is the distribution function of a standard normal distribution and $w=(\log_e D-\mu)/\sigma$.

The result in equation (11.17) is the same as that obtained by Mack (1984). As proposed by Mack, it may be convenient to introduce:

$$t=D/\bar{x} \tag{11.19}$$

such that r(D) can be rewritten as

$$r(D) = G\left(\frac{\ln t}{\sigma} - \frac{\sigma}{2}\right) + t\left[1 - G\left(\frac{\ln t}{\sigma} + \frac{\sigma}{2}\right)\right] \tag{11.20}$$

where In stands for logarithm to base e.

Consider again, as an example, the national data for multistorey textile industry buildings discussed on pp. 123–6. For these data, fire loss has a log normal distribution and hence, using equation (11.18), the expected loss ($\bar{x}$) in a large building, at 1966 prices, is £4,400 if the building is provided with sprinklers and £34,200 if without sprinklers. These average losses differ from those in Table 11.1, which are adjusted figures taking account of known large losses.

For the data mentioned above, the rebate schedule for a building with a large value at risk is presented in Table 11.2 for three deductible levels. The figures in this table are based on equation (11.17). The results suggest that the rebates for deductibles for a sprinklered building are not significantly different from the corresponding rebates for a building without sprinklers.

According to the example discussed above, the risk premium per claim for full insurance is £34,200 at 1966 prices for a large building without sprinklers. Considering a deductible of £50,000 as an example, the owner of such a property has to bear an expected loss of £10,300 as given by:

Table 11.2 Rebate schedule for deductibles (1966 prices): multistorey textile industry building, with large financial value at risk, United Kingdom

	Full insurance RP per claim (£)	*Deductible rebate (%)*		
		£50,000	*£100,000*	*£200,000*
Sprinklers	4,400	34	42	51
No sprinklers	34,200	30	41	52

Note: RP = risk premium

$$G(w - \sigma)\,\bar{x} + D\,[1 - G(w)] \tag{11.21}$$

which reduces to equation (11.17) when expressed as a ratio of $\bar{x}$. The rebate is hence 0.30 (=10,300/34,200) as shown in Table 11.2 The risk premium per claim for this case is approximately £23,900 (=0.70×34,200). Based on past data, the risk premium per claim for full insurance cover for a large sprinklered building may be 13 per cent (=4,400/34,200) of the premium determined for a non-sprinklered building. An insurer would, of course, add to the risk premium the two loadings discussed above.

According to this analysis, the rebates for deductibles for a building with total value £500,000 are higher than the rebates for a building with very large total value. This is understandable since, as one would expect, the ratio between the deductible and the value at risk is a factor affecting the rebate. The higher this ratio, the larger will be the rebate percentage. The insurer will be taking a great risk in accepting a large building with a high value, and hence, cannot afford to give a high rebate for such a building.

The results based on equations (7.3) and (7.4) also indicate that the rebate ratio r (V,D) in equation (11.16) is not very sensitive to the presence or absence of sprinklers. Again, this ratio should be applied to the risk premium for full insurance cover for a building with £500,000 value. With sprinklers, this premium can be 12 per cent (=2,200/17,700) of the premium determined for the case without sprinklers (see Table 7.2, p. 125). This percentage is almost the same as that (13 per cent) estimated earlier for a building with a large value at risk. Hence, the rebate of about 87 per cent for sprinklers for full insurance cover does not appear to vary significantly with the total value V at risk.

The foregoing analysis indicates that the rebate schedule for sprinklers can be the same as that for the case without sprinklers. For the industry considered, the rebate schedule per claim for a building without sprinklers is given in Table 11.3 for three deductible levels and four total values of risk apart from a very large value. The schedule should be applied to the risk premium per claim calculated for full insurance. To be on the safer (cautious) side, the risk premium

Table 11.3 Rebate schedule for deductibles (1966 prices): multistorey textile industry building without sprinklers, United Kingdom

Total value at risk (V) (£)	*Full insurance RP per claim (£)*	*Deductible rebate (%)*		
		£50,000	*£100,000*	*£200,000*
500,000	17,700	56	74	89
1,000,000	21,700	47	63	78
2,000,000	25,300	41	55	69
5,000,000	29,100	36	48	61
Very large value	34,200	30	41	52

Note: RP=risk premium

for full insurance for a sprinklered building may be set at 13 per cent of the premium determined for a non-sprinklered building, which is the percentage estimated for a large building.

The risk premium per claim multiplied by the annual probability of a claim or fire occurring provides an estimate of the annual risk premium. As previously mentioned, the annual probability of fire starting, F(V), has a ‘power’ relationship with the size of a building expressed in terms of total floor area or financial value (V) at risk. Based on this relationship and the values of the parameters estimated by Rutstein (1979), the annual probability of a fire occurring in a multistorey textile industry building of value £500,000 has been estimated to be 0.12 (see pp. 123–6). With the exponent in the power relationship having a value of 0.35, F(V) for a building of value V is given by:

$$F(V) = 0.12\ (V/\ 500{,}000)^{0.35} \qquad (11.22)$$

Using equation (11.22), F(V) for four values of V are given in Table 11.4 together with the risk premiums for full insurance, per claim and annual, for a building without sprinklers. The premium rate per £100 of value may be seen to decrease with increasing value at risk. As mentioned earlier, using a constant value for premium rate does not appear to be a statistically valid procedure for determining the risk premium for any property. Only for the purpose of explaining decision analysis and utility theory techniques, constant annual rates (per £100) of 25 pence and 65 pence for sprinklered and non-sprinklered buildings have been used in the example discussed in Chapter 7 (pp. 123–6) and Chapter 8 (pp. 146–8).

Utility of deductibles: the insured’s point of view

Purely out of commercial interests, it may be necessary to assess the utility of deductibles from the insurer’s point of view (Mack, 1983). However, it may be

Table 11.4 Full insurance premium rate (1966 prices): multistorey textile building without sprinklers, United Kingdom

Total value at risk (V) (£)	*RP per claim*		*F (V)*	*Annual RP*	
	Premium (£)	*Rate per £100 (£)*		*Premium (£)*	*Rate per £100 (pence)*
500,000	17,700	3.54	0.12	2124	42
1,000,000	21,700	2.17	0.15	3255	33
2,000,000	25,300	1.27	0.19	4807	24
5,000,000	29,100	0.58	0.27	7857	16

Notes
RP = risk premium
F (V) = annual probability of fire starting

worthwhile to consider the problem from the point of view of the insured as well (Ramachandran, 1994). Most of the owners of industrial and commercial properties would prefer the certain loss of small sums of money towards fire protection and insurance every year to a small but uncertain chance of a loss greater than the expected mean value (EMV) in the event of a fire. The extra money over the EMV which a risk-averse property owner is willing to spend for 'financial security' and 'peace of mind' depends upon the shape of his/her, disutility function, which is the negative counterpart of the utility function. The mathematical structure of this function has been investigated in detail in Chapter 8.

In Chapter 8 we also discussed the use of the disutility function in a decision analysis aimed at identifying an economically optimum combination of fire protection measures and insurance/self-insurance. This analysis will lead to a clear and correct decision only if the rebate schedule for calculating the insurance premiums realistically reflects the economic value of fire protection measures and the reductions in the risk premium for different deductibles. The insurer should also take sufficient account of the ability or willingness of an insured to pay the premium required, which is the problem discussed in this section.

If the claim distribution is log normal and the disutility function has the structure described in equation (8.15), the certainty equivalent (CE) of self-insurance disutility to be suffered by a property owner for a deductible D, $\hat{x}_{DV}$ would be according to the formula in equation (8.18). The insured may be able to bear this disutility depending upon the degree (θ) of his/her risk aversion but may set an upper limit, $\hat{R}_{DV}$, to the insurance disutility given by the formula in equation (8.19). $\hat{R}_{DV}$ is the maximum amount the insured may be prepared or willing to pay per fire towards an insurance premium.

The insurer should, therefore, take into account the amount indicated by $\hat{R}_{DV}$ for determining the insurance premium, including loadings (see pp. 190–2), for any property of value V and deductible D. If, for example, θ=1.5 and the value of a sprinklered multistorey textile industry building is £500,000, the owner of this property would be willing to pay up to £5,700 per fire for insurance by accepting a deductible of £50,000 (see Table 8.1, where the figures are at 1966 prices). If the owner is risk averse to a lesser degree with θ=1.2, he or she will be prepared to pay only up to £2,100 per fire. These amounts are considerably higher than the risk premium per claim of £800 which does not include the loadings. The premium per claim including loadings should not, therefore, exceed £5,700 if θ is estimated to be 1.5 or £2,100 if θ is 1.2. With the risk premium per claim estimated at £7,700, the premium per claim (including loadings) for the property considered, if not protected by sprinklers, should not exceed £14,500 if θ=1.2 or £26,500 if θ=1.5.

The figure for the maximum insurance premium per claim including loadings indicated by $\hat{R}_{DV}$ may be converted to an annual amount by multiplying it by the annual probability, F(V), of fire starting. For the example discussed, F(V) is equal to 0.12 according to Table 11.4. For this example, if θ=1.5 and sprinklers are not installed, the maximum annual premium acceptable to the property owner is £3,980 (=33,200×0.12) for full insurance cover and £3,180 (=26,500 ×0.12) for £50,000 deductible. Hence, based on these figures, the maximum annual premium for £50,000 deductible can be 80 per cent (=3,180/3,980) of the maximum annual premium determined for full insurance cover. This percentage is the same as that based on the ratio (26,500/33,200) between the maximum insurance premiums per claim. The annual probability of fire starting, F(V), gets cancelled when figures for $\hat{R}_{DV}$ are expressed as percentages of those for full insurance. For £100,000 deductible, the percentage may be calculated to be 63 (=21,100/33,200).

It should be emphasised again that $\hat{R}_{DV}$ indicates the maximum premium acceptable to a property owner including loadings whereas the figures in Table 11.3 are based on risk premiums excluding loadings. According to Table 11.3, with a rebate of 56 per cent, the risk premium per claim for a property of value £500,000 without sprinklers can be 44 per cent of the premium for full insurance if a deductible of £50,000 is accepted. According to the analysis discussed earlier, the maximum premium for this property including loadings should be 80 per cent of the maximum premium for full insurance, if θ=1.5.

The foregoing analysis indicates that, for the example considered, if θ=1.5, the insurer should fix the premium per claim for full insurance, including loadings, at an amount not exceeding £33,200. This maximum is equivalent to an annual premium of £3,980 or a rate of 80 pence per £100 of value at risk. The annual risk premium of £2,124 at a rate of 42 pence per £100 of value shown in Table 11.4 does not include the loadings. On the basis of θ=1.5, the maximum premium for £50,000 deductible should be £26,500 which is equivalent to an annual premium of £3,180 at a rate of 64 pence per £100 of value. This amount, as discussed earlier, is 80 per cent (=80×0.8) of the maximum premium for full insurance.

As discussed in this section, utility theory provides a method for considering the insured's ability or willingness to pay for insurance and determining the maximum limit for the insurance premium. Subject to this limit the loadings for safety and administrative expenses can be added to the risk premium based on the loss expected in the range above the deductible level. By carrying out a survey the value of θ quantifying the degree of risk aversion may be ascertained for a group of property owners.

Chapter 12

Fire protection economics

Summary of analytical methods

Components of total national fire cost

Fires occur only rarely in a particular building. But in a population of buildings in a country fires occur frequently and cause destruction to life, property and economic welfare. Every year, a small number of large fires inflict considerable financial damage on building structures and their material contents. The occupants of buildings involved in some large fires sustain fatal and non-fatal injuries, resulting in financial loss and distress to the families of the victims. Large fires occurring particularly in industrial and commercial properties can cause indirect/consequential losses arising from loss of production, of profits, of employment and of exports and thus destroy a significant percentage of the economic wealth of a country.

Apart from the direct and indirect losses mentioned above, the total national cost due to fires includes expenditure incurred by fire brigades or departments run by the government and major industrial firms, administration costs of fire insurance companies and costs incurred by property owners in providing passive and active fire protection measures for their buildings. The total cost also includes other costs such as those incurred by government bodies in developing and enforcing requirements for fire safety.

International comparison of fire costs

Global estimates for most of the components of total fire cost are available for some years for some countries. Direct and indirect fire losses and other fire costs are usually expressed as percentages of gross domestic product (GDP) for purposes of international comparisons, although GDP is not a satisfactory measure of the total burnable value at risk. A more satisfactory measure is gross fixed capital stock (GFCS) relating to fixed assets such as plant and machinery, although it does not include consumer durables. It may be difficult to obtain an estimate of GFCS whereas information on gross fixed capital formation (GFCF) is available for some years for some countries. The number of fire deaths per 100,000 persons can be used to compare loss of life due to fires in different countries.

Figures for financial losses and deaths due to fires in different countries are not strictly comparable for various reasons. First, there are differences between countries in methods of collecting, classifying and estimating fire loss data. Second, the living standards, social and cultural patterns, economic conditions and technological development vary from country to country. Third, there are physical differences between countries with regard to building design and construction, contents and utility systems of buildings and weather conditions. Fourth, there are differences in the organisation, functioning and fire fighting methods of professional fire brigades. Lastly, the severity with which fire safety codes are enforced and the influence of fire insurance in promoting fire safety also vary from country to country.

However, the fire cost figures for any country for several years provide trends which can indicate whether fire prevention, protection and fighting methods are sufficiently effective in reducing the frequency of occurrence of fires and the amount of damage caused. This effectiveness can be assessed on a global scale or for each occupancy type by correcting fire losses for inflation and calculating corrected loss per fire. Inflation and the increasing frequency of fires, particularly large fires, appear to be major factors contributing to growing fire losses in some countries. This indicates the need to increase fire prevention activities, although fire protection and fighting methods may be effective in reducing property damage in fires which occur.

The economics of fire protection—decision-makers

In order to reduce the national wastage caused by fires, large amounts of money are required to be spent on fire prevention and protection activities at all levels of a national economy. These levels in the fire safety field are mainly the owner of a property, the fire brigade, the national government, the fire insurance company and the manufacturer of a fire protection system. People involved at these levels are ‘decision-makers’ who have to determine the amount of money which can be spent on appropriate fire safety activities.

As required in any business venture, the costs involved in installing and maintaining a fire protection system or in carrying out a fire safety activity should not exceed the benefits due to the system or activity. Since the costs and benefits are spread over a period of several years, the annual ‘rate of return’ pertaining to the benefits should be such that it would be possible for a decision-maker to recover the costs within a reasonably short period. This criterion can be applied in a number of ways to establish the economic justification for incurring expenditure on any fire protection measure. These methods depend on the decision-maker and the accounting procedure adopted.

In the fire safety field, most of the costs involved are known expenditures which have to be ‘certainly’ incurred. Examples are money spent in installing a fire protection system and the fire insurance premium. But damage sustained in a fire is an ‘uncertain’ cost which depends on the likelihood (probability) of a fire occurring and the 'probable damage' if a fire occurs. This unknown or probable cost has to be included in the financial plans of a property owner, partly if the property has some self-insurance cover and fully if it has none. This cost need not be considered if a property is fully insured since, in this case, the insurer will reimburse the property owner almost the entire cost of the fire damage.

The probable reduction in fire damage due to a fire safety measure is an 'uncertain' benefit. A property owner has also 'certain' benefits such as tax allowances and savings on insurance premiums which are offered as inducements for adopting a fire safety measure. Due to these benefits, the costs incurred towards a fire safety measure can be recovered during a short period of time. At the national level of decision-making, the probable reduction in fire damage is the only benefit that needs to be considered in order to recommend the adoption of a fire safety measure or to incorporate this measure as mandatory in fire safety codes and regulation (see p. 15). This benefit should exceed the costs involved for economic justification. Tax allowances and savings on fire insurance premiums are somewhat extraneous to the national economic level.

The costs and benefits, therefore, depend on the decision-maker considered in an economic analysis. The methods and statistical techniques which can be adopted by two main decision-makers in the fire safety field are summarised in the following two sections of this chapter. The decision-makers discussed are the property owner and the national government. We also discuss the estimation of indirect/consequential losses and summarise statistical techniques which aid insurers in the calculation of appropriate fire insurance premiums.

National level

Cost-benefit analysis

At the national level, the economic criterion to be applied is that the probable reduction in fire damage due to a safety system should exceed the costs involved in installing the system and maintaining it in satisfactory working order. If sufficient data are available, this benefit may be calculated as the sum of reductions expected to be achieved in all the components of fire damage: life loss, property damage and social costs. Indirect/consequential losses (Chapter 9) may not be relevant at the national level and hence need not be considered.

Consider, for example, the figures in Table 11.1 (p. 188). Judged against fire damage in buildings without sprinklers, the expected reduction in property loss per fire due to sprinklers is significant for multistorey buildings although it varies from industry to industry. The reduction is considerable in multistorey textile industry buildings. The average reduction revealed by figures in Table 11.1 for any industry applies to a building of average size. This benefit due to sprinklers should be multiplied by the annual probability of a fire occurring in a building of average size in order to express it on an annual basis (see pp. 20–1).

Consider, for example, the figures in Table 11.1 for multistorey textile industry buildings. The average saving per fire due to sprinklers is about £22,000 at 1966 prices or about £250,000 at 1997 prices. The current average size of the buildings considered is not known but let us assume that it is a total floor area of 20,000 m2. It may be further assumed that a fire can occur in such a building once in three years, with an annual probability of 0.33. The average annual saving due to sprinklers is hence about £83,000. At £17 per m^2, the cost of installing sprinklers in this building is £340,000.

Over a forty-year period, at 10 per cent interest rate, with a capital recovery factor (Table 3.1 on p. 23) of K=0.1023, the annual amortised value of the capital cost of sprinklers is £34,800 against which the annual benefit is £83,000. This gives a benefit-cost ratio of 2.39 (=83,000/34,800) which is greater than unity and, hence, the installation of sprinklers is economically justifiable in this case. Following the alternative method, the net present value of the annual benefit may be seen to be £811,342 (=83,000×W) where W in equation (3.6) (p. 24) has the value 1/K=1/0.1023=9.7752. This also gives a benefit-cost ratio of 2.39 (=811,342/340,000).

If, as in Table 3.3, the discount factors for successive years at 10 per cent discount rate are applied to the annual benefit, it may be calculated that the cost of sprinklers can be recovered in about six years. At the end of this period the net present value of the annual benefits (equation (3.5)), assumed as constant at £83,000, will be £361,500, which exceeds the cost (£340,000) of sprinklers. The NPV of (benefits-cost) is £21,500 at the end of six years and -£25,400 at the end of five years. The recovery period of six years is known as the payback period, which should be short for the economic acceptance of any investment project (see pp. 26–8 and 30–1).

Let us assume that parts of the sprinkler system have to be replaced or repaired at the end of 15 and 25 years at costs of £100,000 and £200,000 respectively. At an interest rate of 10 per cent, the present values of these costs are £23,940 and £18,460 applying the discount factors of 0.2394 and 0.0923 given in Table 3.2 (p. 25). Hence, it will be necessary to set apart at the time of installation a total sum of £42,400 towards such repairs and replacements. If this sum is added to the installation cost, the total cost of £382,400 can be recovered in seven years.

An analysis of the kind described above would provide economic justification for incorporating in fire safety codes mandatory requirements for sprinklers in multistorey industrial and commercial buildings. The annual benefits (reduction in damage) due to sprinklers would generally increase with the building size. Hence, for any type of occupancy, a threshold size can be determined such that buildings larger than that size may be required to be equipped with sprinklers (see pp. 59–60).

The two methods described above, benefit-cost ratio (BCR) and net present value (NPV) technique, are useful for comparing different fire protection measures and selecting the one which is economically the best. The 'best' measure is the one with the highest BCR or one with the shortest payback period as estimated by the NPV method. There is a third method, known as internal rate of return (IRR) (see pp. 26–8), according to which criterion a safety measure which has the highest IRR for a given payback or planning period is economically the best. For a specified payback period, the NPV of (benefits—costs) will be zero at a particular discount rate. The IRR for this period may be determined graphically (Figure 3.1, p. 27) by interpolating between two rates of interest within which the value of the ratio K=B/C (equation 3.8, p. 27) falls. In this context, B is the value of annual benefit and C the initial and not annual cost. For the example considered earlier, this ratio has the value 0.244 (= 83,000/ 340,000) which for a payback period of ten years lies between 20 per cent and 25 per cent rate of interest (see Table 3.1, p. 23). The IRR is approximately 21 per cent. The IRR method is more appropriate for an analysis at the level of a property owner.

In principle, fire safety can be improved by spending more and more money on various protection measures but a limiting stage can be reached at which decreasing 'marginal' (or additional) benefits may be almost equal to increasing 'marginal' (or additional) costs. Beyond this stage the 'marginal' costs may exceed the 'marginal' benefits (see pp. 34–7 and Figure 4.1). The economically optimum level of fire protection is given by the point of intersection of the marginal cost and marginal benefit curves.

The fire protection strategy whose marginal benefits are equal to marginal costs is the same as the strategy which minimises the total annual cost. The strategy providing the minimum total annual cost is generally referred to as the optimum level of fire safety. Using equation (4.9) (p. 36) and figures in Table 11.1 (p. 188), the total annual cost for the example discussed earlier in this section at 1997 prices is £96,000 for a building without sprinklers and £48,000 for a building equipped with sprinklers. The former figure is the annual fire damage while the latter is the sum of annual fire damage of £13,000 and the annual amortised cost of £35,000 for installing sprinklers. It may be seen that the annual saving in fire damage due to sprinklers is £83,000. These figures are based on an annual probability, 0.33, of fire occurrence and damage in a fire which was estimated to be £290,000 for a building without sprinklers and £40,000 for a building with sprinklers. The results and conclusions for economic justification are very sensitive to the value estimated for the probability of fire occurrence (see pp. 126–7).

Decision trees

The objective in an economic analysis is to consider all fire safety strategies which provide levels of safety greater than a minimum acceptable level and to select a strategy among them which minimises the total annual cost. The strategies considered would include combinations of fire safety measures and insurance options, discussed in the next section. Such combinations would involve interactions between fire safety measures and interactions between these measures and insurance/self-insurance options (see Chapter 6).

Selection of a fire protection strategy yielding an optimum level of fire safety subject to economic, regulatory and other constraints will be facilitated by following a decision tree approach (Chapter 7 and Figure 7.3). The branches of this tree represent strategies selected for comparison. On each branch, the estimated value of the total annual cost for the corresponding strategy is shown to facilitate the comparison (see the example in Figure 8.3, p. 149). Probabilities associated with fire losses and their range are also shown in a decision tree. Calculation of the expected monetary value (EMV) and certainty monetary equivalent (CME) given in Figure 8.3 is discussed in Chapter 8, a summary of which is given on pp. 205–6.

Loss of life

Sprinklers are generally installed in industrial and commercial buildings where few people are killed in fires. Most fire deaths occur in residential occupancies. However, if life safety also is to be considered for any type of occupancy, it will be necessary to estimate the number of fire deaths that can be prevented by installing sprinklers and other safety measures and evaluate the monetary value of these deaths. For this purpose, one of the methods discussed in Chapter 10 may be followed, but willingness-to-pay is the widely recommended approach. The saving in loss of life can then be added to the saving in property loss and the cost-benefit analysis carried out. As suggested in Chapter 10, a sensitivity analysis may be performed with a range of values for human life. It is not appropriate to assign a single value for life. Incorporation of loss of life would enhance the economic justification for installing sprinklers or any other safety measure.

Property owner level

Cost-benefit analysis

The methods described in the previous section are also applicable to economic analyses of fire safety measures at the property owner level, but the components of total annual loss relevant to this level are different from those at the national level. If a property is insured for fire for its full value of building structure and contents, the insurer will reimburse the property owner almost the entire amount of loss sustained in a fire. In this case, fire damage with its associated probability of fire occurrence will not be a component of total cost.

If a certain level of self-insurance (deductible) is negotiated and accepted for a property, the owner of this property will have to bear any loss less than the deductible level in the event of a fire occurring. If a loss exceeds the deductible level, the insurer will only pay the difference between the loss and the deductible level. Hence, in financial planning the property owner has to make a provision for a loss likely to occur below the deductible level.

Calculation of the expected value of a loss below the deductible is a somewhat complex statistical problem based on the probability distribution of fire loss (see pp. 122–3 and equation (7.4)). If a fire occurs, the entire amount of loss, whose expected value is given by equation (7.3), will have to be borne by the property owner if insurance cover, part or full, is not obtained. Equation (7.3) can also be used to estimate the average financial loss per fire required for an analysis at the national level. Equations (7.3) and (7.4) are based on a log normal distribution for fire loss which is a skewed (non-normal) distribution. Another skewed distribution recommended for fire loss is Pareto (see pp. 184–6).

If a property is fully insured, the owner has to bear annually the insurance premium applicable to this full coverage and not the fire damage as mentioned earlier. If self-insurance is accepted for part of the damage, a reduced insurance premium is payable for obtaining cover above the deductible level.

Apart from an insurance premium, a property owner has to bear the costs involved in installing and maintaining a fire protection system. To offset these costs, the property owner is entitled to benefits such as savings on insurance premiums and tax allowances. Calculation of tax allowances involves somewhat complex procedures, as discussed on pp. 60–3, where a method has been proposed for estimating the average annual benefit due to these incentives given by a government for promoting fire safety. If necessary, tax allowances can be calculated for each year and used to apply the net present value technique to total benefits including saving on insurance premium(see the example in Table 5.4, p. 64).

As explained above, the total annual cost to a property owner is mainly the sum of three components as shown in equation (7.6) (p. 126). These are: self-insured loss, insurance premium and cost of fire protection. The expected value of the loss below the deductible level is multiplied by the annual probability of fire starting to express it on an annual basis. The second and third components are also expressed on an annual basis. An average annual estimate towards tax allowances can be subtracted from the annual cost of fire protection to provide a net annual cost for this component. The costs for repair or replacement of parts of the fire protection system during the planning period or life of the building, as mentioned earlier, can be added to the initial cost of installing the system and the total of all these costs amortised to provide an estimate of the annual cost of fire protection (the third component). An accountant may have a different method for including repair and replacement costs. Comparatively, the annual cost for maintaining the fire protection system may not be a significant amount.

Selected fire protection and insurance/self-insurance strategies and their total annual costs can be represented on the branches of a decision tree (Chapter 7). This approach enables a decision-maker to identify the strategy with the minimum total annual cost.

Utility theory

Financial constraints may set an upper limit to the amount a property owner may be able to spend on fire protection and fire insurance. Also, he or she may not be willing to spend large sums of money for these purposes: the maximum amount will depend on attitude to fire risk, as well as economic factors such as assets and consequential losses (Chapter 9).

Property owners can be classified into three broad categories in regard to their attitude to fire risk: risk-neutral, risk-averse and risk-preferer or -taker. A risk-neutral property owner would be indifferent to risk and only willing to spend the expected monetary value (EMV) of the total annual cost. EMV has been used in the conventional cost-benefit analysis discussed in Chapters 1–7 and summarised so far in this and the previous section. In such an analysis, the decision-maker has been assumed to be risk-neutral. But most decision-makers would be keen to avoid risks and adopt a risk-averse attitude; they would be prepared to spend more money than the EMV for fire protection and insurance. Some people may prefer to take risks and spend less money than the EMV.

The three categories of attitude to risk described above can be quantified by considering first three types of utility functions which measure the intrinsic values of positive monetary outcomes, i.e. gains (see pp. 133–6 and Figure 8.1). Risk-neutrality (EMV) is represented by a straight line while the other two are represented by curves—concave curve for risk-aversion and convex curve for risk-taking attitude. The shape of these curves depends on the degree of risk-aversion or risk-taking attitude. These curves provide estimates of certainty monetary equivalent (CME) and the risk premium (RP)=EMV-CME (see equation (8.1), p. 135). RP is positive for a risk-averse decision-maker who is willing to pay a premium less than EMV in order to avoid participating in a game involving gains. RP is negative for a risk-taker who is prepared to pay a premium greater than EMV in order to participate in the game. RP is zero for a risk-neutral person. Mathematical problems involved in the calculation of CME for utility functions are discussed on pp. 136–8.

In fire protection problems, the monetary outcomes are negative quantities such as fire loss and costs. For these problems, disutility functions, the negative counterpart of utility functions, are more appropriate. For disutility functions, RP is negative for a risk-averse decision-maker who is prepared to spend an amount (CME) greater than EMV for fire protection and insurance. A few disutility functions (discussed on pp. 138–46) show how disutility for a risk-averse property owner would increase with increasing fire loss. The risk-averse disutility function proposed in equation (8.15) (p. 140) is simple in structure and computationally easy to use in conjunction with a log normal probability distribution for fire loss. The value of the parameter in this function quantifies the degree of risk aversion.

The formula for calculating the CME of self-insurance disutility for a given deductible level and property value is given in equation (8.18) (p. 142). The maximum insurance premium per claim (fire) acceptable to a property owner for a given deductible is given by the formula in equation (8.19). Based on this formula the maximum premiums in terms of CMEs are shown in Table 8.1 (p. 144) for an example involving two degrees of risk-aversion and two deductibles, for buildings with or without sprinklers. These figures do not take into account the probability of fire occurring.

The use of utility/disutility functions and CME in a decision analysis is discussed on pp. 146–51. In this analysis the CME of total annual cost is evaluated and used instead of the monetary value of the total annual cost. The object of this analysis is to select a fire protection plus insurance package which will have the minimum total disutility. An application of this method is explained with examples based on assumed figures for insurance premiums. The values of CMEs given in Table 8.2 (p. 147) relate to the total annual cost and take into consideration the annual probability of fire occurring.

The figures in Table 8.2 indicate that, by installing sprinklers, property owners can take a risk and accept a large deductible provided they are moderately risk-averse. If they are very risk-averse, full insurance will be the best option. For a property without sprinklers, full insurance is the best option whatever may be the degree of risk aversion of the property owner.

Construction of an appropriate utility/disutility function for a particular type of decision-maker is a difficult problem. One method is to carry out surveys on the perception of and attitude to fire risk of people of different socioeconomic backgrounds; this is an expensive and time-consuming exercise. A less expensive method may be to ascertain from a property owner an estimate of the maximum amount, M, a loss in excess of which might put him or her out of business permanently or temporarily for a long duration. A minimum amount, m, may also be ascertained, a loss less than which will not cause any disruption to the business activity. By choosing values of loss between m and M to denote minor disruption, major disruption, etc., a disutility function involving loss can be constructed according to formula in equation (8.22) (p. 152). The value of the parameter θ in this equation depends on the degree of risk aversion of the property owner and other economic factors. Estimates of probable consequential losses due to fires can also be used in the construction of an appropriate disutility function.

Indirect/consequential losses

Factors affecting consequential losses

Damage caused to a building, its contents and occupants (fatal or non-fatal casualties) during the course of a fire are known as direct losses. Costs associated with a fire after it is extinguished are indirect or consequential losses. According to this definition the distress and financial loss that an individual's death or injury would cause to family are an indirect loss. This component of indirect loss is, however, not discussed in Chapter 9, which is only concerned with consequential losses such as loss of production, of profits, of employment and of exports and costs towards extra imports. These losses mainly occur in industrial and commercial properties.

Consequential losses are very difficult to estimate, particularly at the national level, due to lack of data and well-developed techniques. However, factors affecting these losses have been identified in many research and case studies and are discussed on pp. 154–63. They include destruction of specialised plant and equipment, laboratory facilities for testing and quality control, fatigue testing facilities of aircraft structures, components and assemblies of specialist equipment (e.g. aircrafts, cars) and electronically or computer controlled equipments. Loss of any such items of the kind mentioned above and their repairs or replacement could cause significant interruption to some industrial and commercial activities and delay the restarting of these activities. Some of the firms involved in these activities might suffer bankruptcy as a result of serious fires. Delay in restarting a business or bankruptcy can lead to loss of production, profits, etc.

National level

At the national level, the loss of a specific unit of production capacity may be spread among the remaining capacity in the nation such that competitors may seize the opportunity to enter the market and maintain the national rate and volume of manufacture. Consequently, it is likely to be only a small incremental loss to the national economy due to fires. This is also because of the redistribution or 'netting out' effect of some of the losses at the societal level.

The observations mentioned above are supported to some extent by two research studies (unpublished) carried out by the Home Office in the UK during 1970–80. In the first study, an input-output type model was adopted and consequential losses were measured by the net present values of streams of annual outputs lost by a fire-hit firm and by supplying firms and purchasing firms. Separate calculations were made for three alternative cases depending on the level of employment and pressure of demand in the economy: slack, middle and tight conditions. Results were given for each of fifteen industries.

The second study attempted to verify the assumptions employed and the results obtained in the first study and to carry out an in-depth investigation of ten fires in the first stage and seventy-five fires in the second stage. In all, twenty fires were identified where the fire-hit firms had reported significant effects on one or more of the following: suppliers, customers, competitors, employment, investment and foreign trade. The study assumed full capacity utilisation of resources and that market values of the resources reflected their true worth. Insurance estimates of losses were used as measures of assets destroyed in fires and, by the application of national capital output ratios, these asset losses were translated into losses of output.

The second study also produced estimates of the ratios of consequential to direct losses to the economy for 'off-peak' and 'peak' years and for each industry and service sector. The main conclusion was that most fires, except those in the chemical and allied industries, produced no consequential losses to the national economy. According to national (global) estimates for all occupancies compiled by the Geneva Association, indirect fire losses in European countries, except Switzerland, were less than 25 per cent of the direct losses.

Private sector level

Only one research study (Hicks and Liebermann, 1979) appears to deal with costs and losses due to fires in the private sector. This study only included commercial occupancies separated into four types: mercantile, non-manufacturing, manufacturing and warehouses. The study employed a regression model based on a 'power' relationship between indirect and direct fire loss. Statistical data provided by insurance sources and case studies were used in the analysis. The results cast doubts on the use of a constant value for the ratio between indirect and direct fire losses.

Role of fire protection

As discussed previously (pp. 163–5), the need for fire prevention and protection measures reaches its maximum level of importance in particular for parts of an industrial or commercial property that have potentially high risks of consequential losses. It is necessary to identify such parts or areas of a property and provide appropriate safety measures. Factors affecting consequential losses have been mentioned on p. 207 and discussed in detail in Chapter 9.

In the pharmaceutical industry, for example, high levels of fire detection and protection are justified for production areas of patented products which provide the bulk of the profits. Adequate fire precautions are necessary for sites to which bulk chemicals and other raw materials are supplied from outside and stored. Drums containing highly flammable liquids should be stored in a properly designed drum park.

In buildings used for aircraft assembly, deluge systems actuated by fast fire detectors would be required in order to achieve response times shorter than those of conventional sprinklers. Deluge systems are also desirable for the protection of buildings with large volumes of flammable solvents. In tall buildings fitted with sprinklers and which contain high values and in areas where fuels are present, detectors would enable fires to be contained more quickly, possibly before sprinklers were activated. Resin plants may require the installation of flame-proofed or intrinsically safe electrical equipment and sprinkler systems. For paint and ink manufacturing industries, sprinkler protection would be useful for storage areas, particularly where non-aqueous products are stored. Indirect losses arising from electrical cable fires suggest fire barriers for cable trenches or cable tunnels, fire detection systems, water spray systems, particularly where multi-layers of cable trays are involved, and gas flooding systems (halon or carbon dioxide).

Fire insurance

At present, the calculation of premium rates for fire insurance does not appear to be based on sound statistical techniques. In actuarial literature, fire insurance has not been discussed sufficiently, compared with life insurance and other nonlife areas. Market forces seem to exercise considerable influence on the determination of fire insurance premium rates and rebates on premiums for fire protection devices and deductibles. Outdated or incorrect schedules for premium rates and rebates which do not adequately reflect the economic value of fire protection measures can lead to incorrect decisions, particularly by owners of industrial and commercial properties.

The central problem in fire insurance is to determine the total amount expected to be paid by an insurer during a year towards claims for fire incidents. This amount is the product of two components: the frequency or number of claims per year and the size of each claim. Both of these components are random variables fluctuating around their average values. The claim amount for a fire can be of any magnitude below the value at risk in a building and its contents. Recognising these uncertainties, actuarial risk theory has been developed to some extent for fire insurance problems (see pp. 182–4).

In a simple model, an estimate of the total amount of claims during a period is given by the product of the mean number of claims for that period and the average amount per claim. The average amount per claim or expected loss in a fire depends on the probability distribution of loss. This distribution (as discussed on pp. 184–6) is skewed (non-normal), due to the fact that most of the fires are small and only few fires cause large losses. Skewed distributions such as Pareto and log normal have been widely recommended by actuaries for modelling fire insurance claims (see equation (11.6) (p. 185) for Pareto and equation (11.8) (p. 186) for log normal.

Assuming a log normal distribution, the expected value of loss in a fire in a particular building with specified financial value at risk is given by the formula in equation (7.3) (p. 122). The parameters of this distribution are the mean and standard deviation of the logarithm of loss which has a normal distribution. An example based on log normal distribution has been discussed in Chapter 7 (pp. 123–6) which shows the value of sprinklers in reducing fire loss.

Large claims (losses) fall at the tail of the probability distribution of fire loss and account for a high percentage of the total claim amount. Thus, they exercise a critical effect on the financial performance of an insurer who has not reinsured such large risks. A reinsurance company, on the other hand, has to face the consequences due to fluctuations in the claims arising from the large risks it accepts. Statistical methodology (extreme value techniques) for dealing with large claims in insurance and reinsurance problems have been reviewed briefly on pp. 186–8. One of these models has been applied to large losses in calculating the figures in Table 11.1 (p. 188) which are average losses per fire in all fires, large and small.

Both the claims frequency (number of fires) and amount (loss) in a single claim (fire) have approximately 'power' relationships with the size of a building expressed in terms of financial value at risk or total floor area. These formulae have been discussed in Chapter 6, equations (6.1) (p. 90) and (6.4) (p. 95) and Chapter 11 (pp. 188–90). Equation (6.1) expresses the relationship between area damage and size of building or compartment. This model, as discussed in Chapter 6, can be used to provide a justification for allowing an increase in the size of a sprinklered building or compartment (see Figures 6.1 and 6.2; pp. 91, 93).

The statistical properties of a log normal distribution can be utilised to calculate the expected value of the amount for which an insured accepting a deductible would be responsible if a fire occurs in his or her property. A formula for this calculation is given in equation (7.4) (p. 122). In this case the insurer is liable to pay the insured a sum whose expected value is given by equation (7.5) (p. 123). These formulae are applicable to a risk-neutral property owner while those in equations (8.18) and (8.19) (p. 143) provide estimates of certainty monetary equivalents of self-insurance disutility and insurance disutility likely to be suffered by a risk-averse property owner accepting a deductible. Equation (8.19) gives an estimate of the maximum amount an insured with a deductible may be prepared or willing to pay per fire towards insurance premium. This amount should be taken into consideration by an insurer in calculating an appropriate premium (see pp. 195–7).

As mentioned in the introduction to this section, it is necessary for an insurer to apply sound statistical techniques when calculating rebates on premium for fire protection devices and deductibles. Formulae for this problem have been presented on pp. 192–5 which have been used to derive the results in Tables 11.2–11.4 for the example considered. Fire insurance firms may find it useful to apply these formulae and those relating to safety loading discussed on pp. 190–2.

System models

As discussed in Chapters 5 to 7, loss of life and property damage are major components of the total annual cost in an economic analysis of different fire protection strategies at the national or community level of decision-making. For some strategies, the expected (average) values of these two components can be estimated by analysing data on actual fires collected from insurance, fire brigade and other sources. These sources would only provide estimates for major types or groups of buildings, from which estimates for a particular building belonging to a type or group can be obtained by applying appropriate statistical models. Such estimates would be sufficiently accurate for economic analysis and other practical applications.

However, data from these sources are unlikely to provide information on reduction in damage to life and property due to the satisfactory operation of some fire protection measures, such as fire doors and smoke ventilation systems. Moreover, authorities involved in developing and enforcing fire safety regulations, codes and standards would require a critical evaluation of the effectiveness of fire safety measures and the 'trade-offs' between measures for individual buildings. The authorities need a sound assessment technique to relax the requirements specified in prescriptive codes and to permit the provision of alternative fire protection strategies likely to produce 'equivalent performance' in actual fires. With this objective, 'performance-based' fire safety codes are being developed in many countries.

The problem is how to assess the performance of a fire safety strategy in an actual fire in a particular building. For this purpose, system models are being developed to take account of complex interactions between many phenomena such as fire initiation, fire growth and spread, the response of building components to fire, the behaviour of occupants in the presence of a fire and the response of fire brigades to the fire. In the system model proposed by Yung and Beck (1995), the interactions are quantified by a series of stochastic state transition models and interrelated deterministic models. This system model incorporates a number of submodels dealing with fire growth, smoke movement, fire detection, evacuation of occupants, fire brigade action and some other aspects. Probabilistic outputs from these submodels are used in two other submodels to estimate the expected number of deaths and property loss, and these estimates are then used in three submodels which deal with economic aspects: expected fire costs, expected risk to life and fire-cost expectation. The system model of Yung and Beck has been applied to evaluate the performance of various fire protection designs for office buildings in Australia and apartment buildings in Canada.

A number of stochastic models, such as state-transition models, have been developed to predict the extent of fire spread in a building in probabilistic terms (see Ramachandran, 1995b, for a review of these models). Simulation models are another type of system model and are being developed to allow for continuous interactions between the processes involved in the event of a fire occurring in a building. In these models, uncertainties quantified by probabilities are estimated by introducing stochastic elements. Estimates of risk for different building designs are derived by Monte Carlo simulation techniques. Philips (1995) has reviewed simulation models applicable to fire protection engineering. Recent developments in virtual reality are expected to facilitate more realistic interaction between a simulation model and its user and also to provide inputs for probabilistic models. I shall discuss various models and techniques developed for a probabilistic assessment of fire risk in a building in another book currently in preparation.

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