Evaluation of the justifiable investment in residential sprinkler system installations using the J-value methodology

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ABSTRACT

It is common for agencies around the world to conduct some form of cost-benefit analysis (CBA) when proposing an investment in a safety measure. Since resources are limited, expenditure on one particular safety measure effectively means that there are not the resources available for other measures. Due to finite financial resources, an investment in a safety scheme will require a trade-off elsewhere. As such, the objective of a CBA is to assess whether the proposed measure provides a net benefit to society or whether resources would be better directed elsewhere.

Fire safety measures, such as sprinkler systems, are one means to mitigate the risk posed by fire in buildings. Sprinkler systems have a long record of property and life protection but there is a cost associated with their installation and ongoing maintenance. For many years various agencies have examined whether sprinkler systems should be mandated in some or all buildings within their jurisdiction, and as a result have conducted different forms of CBA. However, there are a number of challenges when carrying out such assessments particularly when it comes to placing an economic value on human life.

This paper revisits three previous CBA available in the literature for the installation of residential (domestic) sprinkler systems in single family dwellings. The paper applies recent work to extend the J-value methodology which employs the life quality index (LQI) concept as a mean of valuing the benefit of increasing life expectancy through the mitigation or reduction in the occurrence rate of a hazard. Similar to the previous studies investigated, the paper finds that the unilateral installation of sprinkler systems in single family homes does not provide a net benefit to society. This conclusion is reached through the adoption of a novel and objective judgement scalar that is easy to implement and interpret.

KEYWORDS

cost-benefit analysis, residential sprinkler systems, J-value, life quality index
INTRODUCTION

In the light of events, such as the Grenfell Tower incident, there has been considerable discussion in the UK regarding the installation of sprinkler systems into high-rise residential buildings. Some parties, such as the London Assembly Planning Committee [1], suggest that national building regulations be changed to mandate that sprinkler systems are fitted in such buildings if they meet specific criteria related to their height, etc. Although sprinkler systems are not fully reliable [2], there is little doubt that sprinklers can have a beneficial impact on mitigating the fire hazard to people and property [3], [4]. However, the installation of sprinkler systems has various costs that need to be accounted for, such as installation and maintenance. It is therefore reasonable to suggest that any proposal to mandate widespread installation of fire protection measures should assess whether that investment provides a net benefit to society, or whether finite financial resources would be better invested elsewhere.

Recent work by Hopkin, et al. [5] has extended the J-value methodology [6] to fire safety investments. The work examined how the costs and benefits associated with the reduction in fatalities, injuries and fire damage can be included as part of a life quality index (LQI) assessment [7]. The study also shows how discounting of the investment cost can be incorporated into the analysis. An exemplar evaluation of a fire safety scheme was included in the work but it was not specific to a particular type of system or jurisdiction. This paper revisits three cost-benefit analysis (CBA) studies from the literature and applies the J-value methodology to the values previously employed in those studies to examine whether the installation of sprinkler systems provides a net benefit to society. In the process, the limitations of some of these studies, specifically the value of a statistical life, are addressed through the LQI and in cognisance of society’s capacity to commit resources.

J-VALUE

In simple terms, the J-value provides a scalar measure of the efficacy of a safety investment through normalising the life-time cost of a scheme against the benefits realised in terms of improving life expectancy for those affected, reducing injury and loss of assets / damage. The total (implying an interest beyond solely improving life expectancy) J-value is

\[
J = \frac{C}{\Delta D_f + \Delta D_i + M_R \cdot \Delta D_d} \approx \frac{C}{\Delta D_f + \Delta D_i + \Delta D_d}
\]

where \( C \) is the cost of the safety scheme, \( M_R \) is a risk scalar [-], \( \Delta D_i \) is the change in losses due to injury, \( \Delta D_d \) is the change in losses due to damage, and \( \Delta D_f \) is the safety investment that is warranted to protect people’s lives. The parameter, \( M_R \), will begin at approximately unity for an organisation with assets large enough to dwarf a financial loss. However, it will rise to a higher value if the loss that may occur is comparable with its total assets. For the former case, \( J_{f,T} \) simplifies to the right-hand formulation.

At the core of the J-value is a need to quantify the benefit of improving life expectancy through investments in safety provisions. In the past many CBA studies have adopted the value of a preventable fatality (VPF) concept. However, VPF is based upon so-called ‘revealed preferences’ where Sunstein [8] emphasises that there are large variations in ‘observed’ VPF with respect to gender, race and social status. In the J-value, this is achieved via a proportionality metric derived from the LQI, described as the societal willingness to pay (SWTP) value, given by

\[
SWTP \approx GC_x q
\]

where \( G \) is the societal wealth, as measured by GDP per capita, \( q \) represents work-life balance [-], and, \( C_x \) a proportionality constant [-] specific to a given demographic profile. Simply, SWTP is the investment that should be made to avert a single fatality in cognisance of the given society’s capacity to commit resources. Such is the LQI’s traction over dated and subjective concepts like VPF, SWTP values can now be found in international standards such as ISO 2394 [9]. It follows that the SWTP can be multiplied according to the number of fatalities averted to arrive at a valuation \( \Delta D_f \) of the benefits of improving the life expectancy of a given group (of size \( N \)) affected by a potential hazard. The change in annual expected number of fatalities \( \Delta f \) arising from the fire safety measure is

\[
\Delta f = \frac{N_f_{fatal} \cdot \chi_f}{N_{units}} \quad \text{and} \quad \Delta D_f = SWTP \cdot \Delta f
\]

where \( N_f_{fatal} \) is the number of fatalities per fire before the safety investment, \( \chi_f \) is the reduction in fatalities due to the fire safety measure and \( N_{units} \) is the number of properties (e.g. buildings or apartments etc.)
affected. Correspondingly, the annual injury $\Delta D_i$ and damage reduction benefits $\Delta D_d$ are similarly derived as

$$\Delta D_i = \frac{N_{\text{injury}} X_i}{N_{\text{units}}} \zeta_i \quad \text{and} \quad \Delta D_d = \frac{N_{\text{fires}} X_d}{N_{\text{units}}} \zeta_d$$

where $\zeta_i$ and $\zeta_d$ are the costs of the prevented injury and property damage, respectively. $X_i$ and $X_d$ are the corresponding reductions in injuries and property damage as a result of the safety investment.

As the safety investment relates to the reduction of future risk, the J-value analysis requires that future costs and benefits incurred at different times are annualised using a continuous discount rate ($\gamma$) over the service life ($L$) of the safety scheme. Where the safety investment relates to a single upfront investment, then the future benefit terms need to be discounted such that

$$\Delta D_\gamma = \frac{\Delta D_f + \Delta D_i + \Delta D_d}{\gamma} \cdot (1 - e^{-\gamma L})$$

The total discounted cost ($C$) of the associated safety investment typically includes an upfront sum ($c_0$) and a maintenance sum ($m$). For sprinkler systems, this work has accounted for the costs for its installation ($c_{\text{ins}}$) and the connection to the water supply ($c_{\text{wss}}$) as separate items, leading to a combined value in $c_0$

$$C = c_0 + \sum_{t=1}^{L} m \left(1 + \frac{\gamma}{1 + \gamma}ight)^t \quad \text{and} \quad c_0 = c_{\text{ins}} + c_{\text{wss}}$$

The corresponding total fire safety J-value is then given by

$$J_{fLT} = \frac{C}{\Delta D_\gamma}$$

If the value for $J_{fLT}$ exceeds unity then the safety measure is deemed to result in a net dis-benefit to society as the realised benefits would be less than a society’s capacity to commit resources. Correspondingly, a $J_{fLT}$ less than unity implies that the safety investment is justified, leading to a net benefit to society. Where a safety scheme is solely motivated by improved mortality, $\Delta D_i + \Delta D_d$ can be disregarded. However, this generally leads to a lesser need to invest as other societal benefits that are not linked to mortality are disregarded.

**PREVIOUS SPRINKLER COST-BENEFIT ANALYSIS STUDIES**

**Welsh case**

In 2012 the Welsh Government engaged the Building Research Establishment (BRE) to undertake a domestic sprinkler regulatory impact assessment. This was in response to changes in Welsh Law in 2011 requiring that domestic sprinklers be provided in all new and converted residential premises. The assessment took the form of a CBA, with consideration of reductions in fatalities, injury and property damage. In valuing a statistical life, road traffic accident figures were adopted by BRE due to noted limited alternatives at the time.

To derive the impact of sprinkler installations on mortality, injuries and damage, BRE adopted statistics from fire and rescue service incident report forms. An indirect computation of impact on mortality, damage and injury was adopted through correlating fire burn area, and the noted metrics. It was subsequently presumed that sprinklers, where successfully operational, capped the burn area, leading to a change in the observed fatalities, injuries and damage extent. A full explanation can be found in Fraser-Mitchell and Williams [10].

The BRE study considered a range of possible residential tenancies, such as single occupancy houses, flats, hostels, care-homes, etc. However, this study is limited to an analysis of single occupancy houses. As such, mean values for reduction in fatalities, injuries and damage of 90, 64 and 93%, respectively, are adopted. Valuations for the costs of injury prevented, and costs of fire damage are adopted per the BRE report, and represent mean values across all dwelling fire incidents.

At the time, the BRE study concluded that: (a) fitting sprinklers in all new Welsh residential premises was not cost beneficial, (b) mandating sprinklers in care-homes is cost effective, and (c) sprinklers may be marginally cost effective in new blocks of flats.

**New Zealand case**

A comparative analysis of the J-value is conducted using the study by Duncan, et al. [11]. Their study examined the cost-benefit of installing domestic sprinkler systems in New Zealand to the then current standard NZS 4515:1995 [12] and the implications of proposing a more cost-effective system design. Details of their
analysis and the proposed system designs are given in Duncan, et al. and not repeated here but they found that domestic sprinkler systems, constructed to NZS 4515:1995, were not cost-effective at a cost per life saved.

Duncan, et al. give costs for the installation, water connection and annual maintenance of systems. However, they do not express the total fatalities and injuries explicitly but quote values of 6 and 40 per 1,000 fires, respectively. Using a value of 5,967 fires from New Zealand Fire Service statistics over the five-year period from 1993 to 1997, results in 36 fatalities and 239 injuries per year. Similarly, the reduction in fatalities, injuries and property damage are not stated directly by Duncan, et al. but values for cases with and without sprinkler installation are given. Hence, values are derived for the analysis shown here.

**Australian case**

Beever and Britton [13] conducted research into the cost-effectiveness of various fire safety measures in buildings in Australia including the installation of residential sprinkler systems. The research made no recommendation to extend the building codes in Australia to require the installation of sprinkler systems in domestic dwellings. The Beever and Britton study was followed-up by Hasofer and Thomas [14] who carried out an analysis of the benefit-cost of installing sprinklers using the LQI method, similar to the work presented here. Hasofer and Thomas found that the installation of sprinklers in single family dwellings was not an economical proposition.

Although the work presented here is similar to that by Hasofer and Thomas, the exact formulation of the J-value and the necessary input parameters differ in their details. Thus, the original study from Beever and Britton has been examined in order to extract input parameters relevant to this study. Using data from the 1991 Australian census, Beever and Britton stated that 14,610,000 people lived in single family detached and semi-detached homes. Using the quoted average number of people per home of 2.99 suggests there were 4,886,288 single family homes in Australia at that time. Beever and Britton estimated that around 36,600 dwelling fires occurred over a four-year period from 1989/90 to 1993/4 which gives 9,150 fires per year. Using the number of single family homes, this works out to be 1.87 fires per 1,000 homes per year, consistent with Beever and Britton.

In dwellings without sprinklers there were 7 fatalities per 1,000 fires, i.e. 64 fatalities per year and 70 injuries per 1,000 fires, i.e. 641 persons per year. Beever and Britton assessed that the installation of sprinklers led to there being a reduction ranging from 3.89 fatalities to 1.46 fatalities per 1,000 fires. In order to give the highest benefit to the installation of sprinklers, this paper uses the lower 1.46 value giving a reduction in fatalities due to sprinklers of 79 %. With sprinklers installed Beever and Britton quote injury rates of around 15 to 30 per 1,000 sprinklered fires and again using the lower statistic gives a reduction of 79 %. Property damage with sprinkler and without sprinklers installed were taken to be $AU 3,900 and $AU 24,000 respectively, giving a percentage reduction of 84 %. Finally, Beever and Britton assumed a 20-year life for the sprinkler system, and also that the mains water pressure was sufficient and did not give a separate water connection cost.

**ANALYSIS**

Table 1 summarises the J-value input values that have either been directly sourced from the original reports or derived, as necessary. Currency values are given in the local unit for which each original study was conducted (where conventionally the scarab symbol ∞ is used to designate a general currency unit), namely pounds sterling (£) for the Welsh study, New Zealand dollars ($NZ) and Australian dollars ($AU), respectively. SWTP values for Wales (UK) and Australia are taken from ISO 2394 [9], with the change in mortality due to life risk reduction uniformly distributed across the age distribution. A 3 % discount rate is applied, with SWTP expressed within ISO 2394 in terms of common purchasing power parity (international dollars). For New Zealand, the UK value has been used, adjusted for the currency exchange rate, since the two countries have a similar GDP and demographic profiles. Care should be taken comparing costs since exchange rates and inflationary adjustments have not been made herein. The New Zealand case includes inputs from Duncan, et al. [11] for sprinkler system installations to NZS 4515:1995 and for the proposed revisions.

Table 2 shows the derived quantities using the previously presented equations and the appropriate values from Table 1 where it is noted that the reduction in fatalities for all three cases are of the same order of magnitude. Hasofer and Thomas expressed their result as benefit to cost ratio of 0.122 which is equivalent to 8.20 as a cost to benefit ratio similar to the 9.04 result found in this study for the Australian case. For the New Zealand case, a J-value of 6.16 is obtained for a system designed to NZS 4515:1995 compared with 3.56 for the proposed draft revisions. For the Welsh case, the J-value is 5.93, which is similar to the NZS 4515 result. As all values are in exceedance of unity, this implies a net dis-benefit to society in all evaluated cases.
### Table 1. Input values to J-value analysis.

| Input                                                                 | Symbol | Metric                                      | Wales          | New Zealand\(^1\) | Australia       |
|-----------------------------------------------------------------------|--------|---------------------------------------------|----------------|--------------------|-----------------|
| Number of single occupancy units (dwellings)                         | \(N\)  | \(\approx 1,200,000\)                      |                | 1,318,800          | 4,886,288       |
| Number of fires in single occupancy dwellings (fires / yr)           | \(N\)  | 1.421                                       |                | 5,967              | 9,150           |
| Fatalities due to single occupancy dwelling fires (persons / yr)     | \(N\)  | 14                                          | 36             | 64                 |
| Injuries due to single occupancy dwelling fires (persons / yr)        | \(N\)  | 345                                         | 239            | 641                |
| Cost of injury prevented \((\pound)\)                               | \(\zeta\) | 19,960                                      | 30,000         | 21,100             |
| Cost of damage per unsprinklered fire \((\pound)\)                  | \(\zeta\) | 8,800                                       | 17,200         | 24,000             |
| Reduction in fatalities due to sprinkler introduction in single occupancy dwellings (%) | \(\chi\) | 90                                          | 80             | 79                 |
| Reduction in injuries due to sprinkler introduction in single occupancy dwellings (%) | \(\chi\) | 64                                          | 63             | 79                 |
| Reduction in damage due to sprinkler introduction in single occupancy dwellings (%) | \(\chi\) | 93                                          | 83             | 84                 |
| System installation cost \((\pound)\)                               | \(c\)  | 1,950                                       | 6,500 (4,070)  | 2,550              |
| Water supply costs \((\pound)\)                                     | \(c\)  | 1,125                                       | 200            | n/a                |
| Annual maintenance cost \((\pound)\)                               | \(m\)  | 96                                          | 635 (280)      | 500                |
| Discount rate (%)                                                    | \(\gamma\) | 3                                           | 8              | 5                  |
| Average sprinkler system life (yrs)                                  | \(L\)  | 45                                          | 50 (30)        | 20                 |
| Societal willingness to pay \((\pound)\)                            | \(SWTP\) | 2,260,272                                   | 5,321,904      | 5,807,698         |

\(^1\) Values in brackets are for changes to NZS 4515:1995 proposed by Duncan et al. [11].

A sensitivity analysis on the input values shows that, similar to Hasofer and Thomas, varying the injury rate from 15 to 30 per 1,000 fires made almost no difference to the Australian J-value analysis, only changing the result by 0.05. However, using the upper value of 3.89 fatalities per 1,000 fires where sprinklers are installed changes the reduction in fatalities to 44% and consequently the J-value increases to 12.29.

### Table 2. Derived quantities.

| Derived quantity (unit) | Symbol | Metric                                      | Wales          | New Zealand\(^1\) | Australia       |
|-------------------------|--------|---------------------------------------------|----------------|--------------------|-----------------|
| Reduction in fatalities through safety measure (per / dwelling / yr) | \(\Delta\) | \(1.1 \times 10^{-5}\)                      |                | \(2.2 \times 10^{-5}\) | \(1.0 \times 10^{-5}\) |
| Life preservation utility (\(\pound\) / yr)                           | \(\Delta D\) | 23.73                                       | 115.58         | 60.25              |
| Injury reduction utility (\(\pound\) / yr)                            | \(\Delta D\) | 3.67                                        | 3.39           | 2.17               |
| Damage reduction utility (\(\pound\) / yr)                            | \(\Delta D\) | 9.69                                        | 64.25          | 37.64              |
| Discounted benefit over life, \(L\) (\(\pound\))                      | \(\Delta D\) | 916                                         | 2,248 (2,083)  | 1,265              |
| Upfront investment in safety measure (\(\pound\))                     | \(c\)  | 3,075                                       | 6,700 (4,270)  | 2,550              |
| Discounted cost of safety measure (\(\pound\))                        | \(C\)  | 5,429                                       | 13,849 (7,422) | 8,887              |
| J-value for sprinkler system installation (-)                          | \(J\)  | 5.93                                        | 6.16 (3.56)    | 9.04               |

\(^1\) Values in brackets are for changes to NZS 4515:1995 proposed by Duncan et al. [11].

#### DISCUSSION AND CONCLUSIONS

Conducting any CBA can be a challenging exercise since the assessment needs to identify who is incurring the costs and/or accruing the benefit, and have all of the costs and benefits been considered. For example, considering sprinklers as a provision in isolation inherently presumes that other precautions are effective in the manner intended. Beever and Britton [13] discuss the potential reduction in domestic insurance claims if sprinkler systems were installed and conclude any savings would be insignificant compared to the other costs.
such as the annual maintenance. Hasofer and Thomas [14] note that insurance is the transfer payments from one group in society to another group which does not affect a benefit to cost ratio societal indicator.

Beever and Britton include in their study a consequent reduction in the fire brigade response if sprinkler systems were installed. Here they recognised that only a proportion of fires would be in single family homes, that the brigade would still likely be called to sprinklered buildings and that less than half of brigade callouts are to fires. Clearly any change in regulations, whether applied to new buildings or to a retrofitting programme, can take many years to have an effect. Even if it was accepted there was a case to reduce the fire brigade’s capability with the installation of sprinklers, this would not be possible until some future date.

In this work there has been no assessment of water damage from accidental sprinkler activations as well as the difference in potential water damage from fire brigade hose streams in the event of a fire. In a wider context, there is the issue of the potential for trade-offs that come with over investment in a safety scheme. That is, given a society’s finite resources, where are cost-cuts made to subsidise widespread sprinkler adoption? Whilst not the subject of this paper, the acknowledgement of trade-offs is an important CBA consideration.

This paper shows that applying the J-value methodology to the installation of sprinkler systems into single family dwellings does not provide a societal benefit for the three cases evaluated. This result is consistent with Fraser-Mitchell and Williams [10], Duncan, et al.[11], Beever and Britton [13], Hasofer and Thomas [14]. Work is ongoing to apply the J-value assessment methodology to the proposal made by the London Assembly Planning Committee [1] for high-rise residential buildings to understand its economic implications.

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