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PERSPECTIVE

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Risk-based thinking for extreme events: What do terrorism and climate change have in common?

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Abstract

Terrorism and climate change debates are often characterized by worst-case thinking, cost neglect, probability neglect, and avoidance of the notion of acceptable risk. This is not unexpected when dealing with extreme events. However, it can result in a frightened public, costly policy outcomes, and wasteful expenditures. The paper will describe how risk-based approaches are well suited to infrastructure decision-making for extreme events. Risk management concepts will be illustrated with current research of risk-based assessment of climate adaptation engineering strategies including designing new houses in Australia subject to cyclones and extreme wind events. It will be shown that small improvements to house designs at a one-off cost of several thousand dollars per house can reduce damage risks by 70%–80% and achieve billions of dollars of net benefit for community resilience—this helps offset some the predicted adverse effects of climate change for a modest cost. The effect of risk perceptions, insurance, and economic incentives is explored for another climate adaption measure. The paper will also highlight that there is much to be optimistic about the future, and in the ability of risk-based thinking to meet many challenges.

1 | INTRODUCTION

Cyclones, earthquakes, tsunami, and floods are natural hazards that cause significant loss of life, and economic and social losses. Added to this are "man-made" hazards such as climate change and terrorism. These hazards are low probability—high consequence events which in recent times are more commonly referred to as "extreme events." There is much hyperbole in the media and other sources that terrorism and more recently climate change are (or can be) reaching dangerous levels, are apocalyptic, or even existential. This characterization of extreme events can result in a frightened public, costly policy outcomes, and wasteful expenditures. Hence, extreme events illicit extreme reactions—risk aversion, probability neglect, cost neglect, worst-case thinking—that may distort the decision-making process in an effort by policy-makers to be seen to be "doing something" irrespective of the actual risks involved.

Many terrorism and climate change "risk" and "risk management" reports dwell on lists of vulnerabilities and consequences. There is seldom mention of probabilities, or quantitative measures of vulnerability, or the likelihood of losses. While useful for initial risk screening, intuitive and judgment-based risk assessments are of limited utility to complex decision-making since there are often a number of climate or threat scenarios, adaptation or counterterrorism options, limited funds and doubts about the cost-effectiveness of protective measures. In this case, the decision-maker may still be uncertain about the best course of action. For this reason, there is a need for sound and rational risk management that integrates the performance of infrastructure systems with the latest developments in stochastic modeling, structural reliability, economic assessment, and decision theory.

Risk-based approaches are well suited to optimizing decisions related to extreme events (e.g., Stewart & Rosowsky, 2022). Stochastic methods may be used to model threat likelihood, vulnerability, resilience, effectiveness of protective strategies, exposure, and costs. Probabilistic terrorism risk assessment methods have been developed to assess the risks of terrorism, and effectiveness of risk reducing measures (Mueller & Stewart, 2011, 2015). Risk-based assessments of climate adaptation measures have also been developed (e.g., Bastidas-Arteaga & Stewart, 2019). While the risk management jargon may differ, the decision support approaches to counterterrorism and climate adaptation measures have much in common, as are the challenges. This paper aims to draw out these issues in more detail, with a particular focus on the pitfalls often encountered when assessing technological, financial, and societal risks. There is clearly a need for risk leadership (e.g., Hofmann, 2022). The paper will also highlight that there is much to be optimistic about the future, and in the ability of risk-based thinking to meet many challenges.

2 | CLIMATE ADAPTATION ENGINEERING

In recent years climate change seems to have displaced terrorism as the extreme event of most concern to public and governments. There is increasing research that takes into account the changing climate risks and life-cycle costs in engineering to reduce carbon emissions and/or reduce the vulnerability or increase the resiliency of infrastructure—this may be referred to as "climate adaptation engineering." Climate adaptation engineering is defined as measures taken to (see Figure 1):

(i) reduce CO_2 emissions during the life cycle of design, construction, operation and end-of-life of infrastructure that may include decarbonization measures such as more sustainable

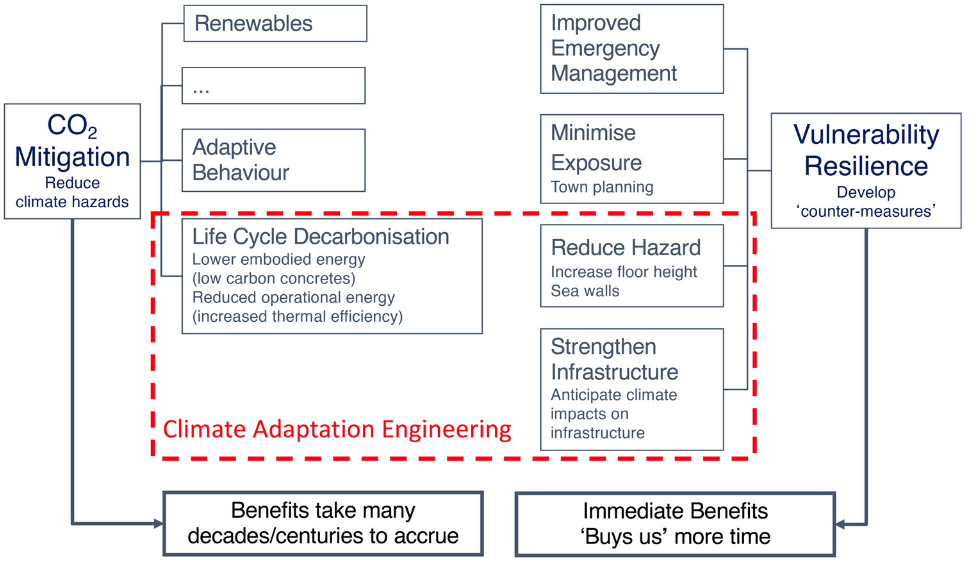

FIGURE 1 Illustration of climate adaptation engineering.

(low carbon) materials, enhanced operation efficiency (e.g., more thermally efficient buildings), and changes to inspection and maintenance regimes, and/or

(ii) reduce the vulnerability or increase the resiliency of built infrastructure to storms, floods, fire, heat and other climate hazards, this may include, for example, enhancement of design standards (higher design loads or flood levels), retrofitting or strengthening of existing structures, or use of hazard resistant materials such as fire-resistant cladding.

The political imperative to "act" on climate change is to reduce CO_2 emissions with a recent push for renewable energy, electric vehicles, and other sustainability measures. However, while these measures are needed, their impact on the near to midterm climate-related losses will be relatively low. Whereas measures to reduce vulnerability and enhance resiliency of infrastructure provides a more immediate reduction in climate-related losses.

3 | DECISION CHALLENGES: TERRORISM AND CLIMATE CHANGE

There are a number of issues and questions related to controversial and emotive issues such as terrorism, climate change, and other extreme events, and are discussed as follows. These relate to management of technological, financial, and societal risks.

3.1 | Worst-case thinking

The media are replete with stories and articles that the world has never been more dangerous, and this is exacerbated by worst-case thinking and hyperbole expressed by many climate change and terrorism experts. In 2008, Department of Homeland Security (DHS) Secretary, Michael Chertoff proclaimed the "struggle" against terrorism to be a "significant existential" one. In 2021, US President Joe Biden said that climate change poses a "global existential crisis." These are not isolated examples, as similar remarks have been made by Boris Johnson, the United Nations General Secretary, and other world leaders and senior government officials. However, with the exception of all-out nuclear war or an asteroid impacting earth, other threats existential to humanity are hard to fathom.

If business-as-usual predictions are biased toward impending doom, then this justifies any response no matter the cost in loss of civil liberties, quality of life, and treasure. It can lead to wasteful expenditures for a threat or hazard that is possible, not probable. Sunstein (2007) notes that "For public officials no less than the rest of us, the probability of harm matters a great deal, and it is foolish to attend exclusively to the worst-case scenario." A more rational approach is to focus on estimating the likelihood of costs and benefits when assessing the need for protective measures. This of course, is the essence of risk management.

Worst-case thinking can also lead to excessive spending on programs with little benefit, and ignoring other programs with large benefits. The current US budget for domestic homeland security is approximately $120 billion per year (Stewart & Mueller, 2018). Mueller and Stewart (2011) estimated that US counter-terrorism costs are 5–75 times higher than any benefits—that is, one dollar buys less than 20 cents in benefits. An over $1 billion per year enterprise, the Federal Air Marshal Service (FAMS), is found to reduce terrorism risks by only 0.2% leading to a benefit-to-cost ratio of only 0.05 (Stewart & Mueller, 2018). A policy mix of adding an Improvised Physical Secondary Barrier to cockpit doors, doubling the Federal Flight Deck Officer Program (armed pilots), and reducing FAMS by 75% would increase risk reduction by 0.6% together with cost savings of over $700 million per year, a win-win policy mix.

A panel of more than 40 international experts assembled by Bjorn Lomborg found that a $2 billion investment could save more than 1.5 million lives by expanded immunization coverage and community-based nutrition programs (Lomborg, 2009). Hence, if a mere $2 billion were redirected from the homeland security budget to these more effective risk reducing measures, the likelihood and consequences of terror attacks would hardly change, but 300–60,000 times more lives would be saved (Mueller & Stewart, 2011).

3.2 | Cost neglect

While it is not difficult to list threats and vulnerabilities, what is more challenging is to ascertain the cost to reduce these threats and vulnerabilities. And to decide who pays, and when. There is a notion that safety is infinitely good, then no cost is too high. There is no attempt to compare costs against benefits.

For example, it is not unusual for books on counter-terrorism to provide exhaustive lists of vulnerabilities and the need for enhanced security measures such as explosive detection systems, surveillance cameras, armed guards, and so on—yet often there is no entry for cost in the index (e.g., see Mueller & Stewart, 2011).

3.3 | Probability neglect

Many analysts base their findings on threats or scenarios that they assume will occur. There is no consideration of the likelihood of a terrorist attack, that a specific CO_2 emission scenario will occur, or that adaptation will be effective. For example, a US 2014 climate risk assessment report predicts trillions in dollars of damage due to climate change for the business-as-usual scenario—that is, the world continues on its current path assuming a RCP8.5 (known more recently as SSP8.5) emission scenario (Risky Business, 2014). This IPCC emissions scenario assumes that emissions will continue unabated for the next 85 years including 6.5 more coal being used in 2100 as it is today. This is very much a worst-case scenario and might be better characterized as unrealistic and implausible as it ignores that CO_2 mitigation measures will be implemented, that adaptation measures are implemented, or the impact of improved or game-changing technologies. Sunstein (2003) terms this as "probability neglect" and that "people's attention is focused on the bad outcome itself, and they are inattentive to the fact that it is unlikely to occur."

Predictions are also inherently unreliable, especially those that rely on assumptions about technological advances. In 1894, The Times newspaper in London reputedly predicted "In 50 years, every street in London will be buried under nine feet of manure" (e.g., Johnson, 2013). This became known as the "Great Horse Manure Crisis of 1894." This is not without foundation. For example, at the time London had 300,000 horses, producing something like 1000 tonnes of manure daily. A population boom in London and a business-as-usual scenario meant more horses for transportation of people and goods, more horses to clear more manure, leading to more manure, and so on. This seemingly vicious cycle was broken by the invention of the horseless carriage—the motor vehicle. This is a nice analogy of the pitfalls of placing too much confidence in predictions, nicely summed up by physicist Niels Bohr: "Prediction is very difficult, especially if it's about the future."

3.4 | Opportunity costs

Policy-makers that act before they carefully consider the implications of their actions can result in undesirable or unintended outcomes which are often referred to as "opportunity costs." For example, increased delays and added costs at US airports due to new security procedures following the 9/11 attacks provided incentive for many short-haul passengers to drive to their destination rather than flying, and, since driving is far riskier than air travel, the extra automobile traffic generated has been estimated to result in 500 or more extra road fatalities per year (Blalock et al., 2007).

A CO_2 mitigation strategy that reduces economic growth, particularly in developing countries, may reduce their ability to adapt and other indirect impacts. In the 50 years since 1970, the natural hazard fatality rates have reduced by over 90% for low-income countries (Ritchie et al., 2022a). This shows that economic development is a key driver in reducing the impact of natural hazards, and climate change mitigation or adaptation measure that reduce economic growth may have a significant opportunity cost.

Further, according to the charity ActionAid, the increased use of industrial biofuels (fuels made on an industrial scale from agricultural crops) have been a major cause of the food and hunger crisis in the developing world—filling an SUV with one tank of biofuel requires over 450 pounds of corn, which contains enough calories for a person for a year (ActionAid, 2010). Rising energy costs also mostly affects the poor.

3.5 | Acceptable risk

The notion of acceptable risk is rarely raised in public discussions. The world is not risk free. Hence, the generally accepted level of annual fatality risk (AFR) is 1 in a million (e.g., Stewart & Melchers, 1997), and also see Figure 2.

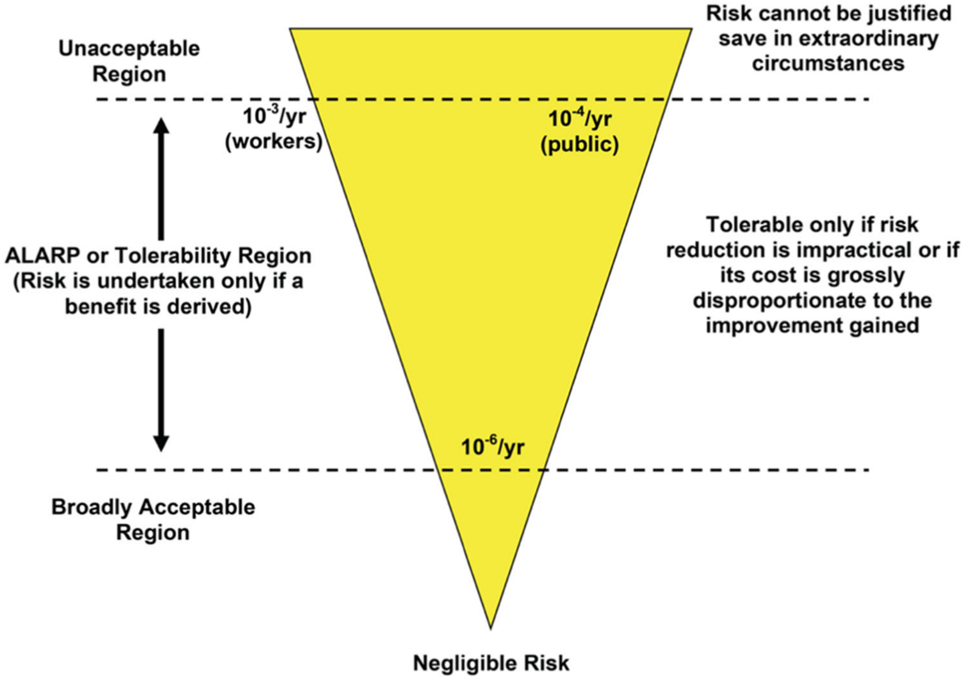

FIGURE 2 Fatality risk criteria (adapted from HSE, 2013).

The concept of as low as reasonably practicable (ALARP) describes the level to which safety risks are expected to be controlled. The UK Health and Safety Executive use this principle when setting fatality risk criteria (see Figure 2), and many counties have similar criteria. The practical implementation of these concepts involves considering a risk in terms of the trouble, time, and money needed to control it. The three regions shown in Figure 2 are:

- *Unacceptable region*: If the safety risk is assessed as unacceptable then risk treatment is mandatory except for extraordinary circumstances.
- *Tolerable (or ALARP) region*: allows safety risks to be tolerable only if risk reduction is impractical (absence of a feasible protective measure) or if the cost is grossly disproportionate to the risk—for example, a cost–benefit analysis.
- *Broadly acceptable region*: At the other end of the scale, risks may be broadly acceptable if they are low or negligible, where risk reduction is not likely to be required (unless costs are low) as any benefits are likely to be outweighed by the costs.

The probability that an American will be killed by a hurricane stands at about one in 7 million per year, and one in 2.8 million per year for a heat-related death. The probability that an American will be killed by a terrorist in the United States, with the events of 2001 included in the count, stands at about one in 4 million per year (Mueller & Stewart, 2015), and is one in 39 million since 9/11. In Western Europe the odds are higher at one in 9 million, but still considerable lower than one in a million. The annual likelihood worldwide that a person will be killed in an airliner by a terrorist is approximately 1 in 320 million for the period since 9/11. To put some of these data in context, a person would need to fly once per day for 30,000 years before being involved in a terrorist attack (Stewart & Mueller, 2018). By comparison, an

American's chance of being killed in an automobile crash is about one in 9500 a year, the chance of being a victim of homicide is about one in 20,000, and the chance of being killed by lightning is one in 10 million (Stewart & Mueller, 2018). How much should we be willing to reduce a risk, and is the risk reduction worth the cost?

3.6 | The world is more dangerous

There is a natural tendency to portray the world as increasingly dangerous. This is fed by worst-case thinking, probably neglect, and failure to acknowledge that the world is not risk free. Yet, there is considerable evidence for optimism—the line "I'm not dead yet!" from the movie *Monty Python and the Holy Grail* may provide some much needed comfort.[1]

Over the past century building standards have been developed and continually improved—with the prevention of building collapse and catastrophic loss the main driver for change. And while uncertainties and knowledge gaps still exist, disaster risks in the developed world are, in general, at an acceptable level. In the past decade, the chance of being killed in a natural disaster in the United States is one in a million per year, in Western Europe is one in 500,000. For the world, the odds are three times higher at one in 150,000 per year (Ritchie et al., 2022b). However, in the 50 years since 1970, the natural hazard fatality rates have reduced globally by 75%, and by over 90% for low-income countries (Ritchie et al., 2022a).

The United Nations Human Development Index (HDI) is a composite index based on life expectancy at birth, mean years of schooling, and gross national income per capita. The United Nations HDI shows steady improvement for every nation since its implementation in 1990 (see Figure 3) and the gap between developed and less developed countries is closing. Further, Cuaresma and Lutz (2015) predict that the HDI in 2075 will increase for all countries for all IPCC future scenarios. For the SSP2 (medium) scenario the HDI for Ethiopia will increase by 87%, while Pakistan's HDI is projected to increase by 62%.

There is also steady progress in many of the United Nations Sustainable Development Goals (SDGs). The proportion of those living below the international poverty line was 42% in 1981, but reduced to 10% by 2015. Child mortality rates have reduced by nearly 60% since 1990, and equal access to further education has increased more than threefold since 1970 to 34.5%, and the number of deaths, missing persons and directly affected persons attributed to disasters has dropped by 86% since 1990 (SDG, 2021). These are impressive gains in human welfare.

However, the trends are not always so positive—global urban air pollution has increased by 25% since 1990, the number of internally displaced persons associated with disasters in low-income countries has more than doubled since 2008, and fauna and flora are under threat in many regions of the world. The SDGs show there remain significant challenges, though strong improvements have been made in many of the UN goals.

In 2015 the OECD released a report *The Economic Consequences of Climate Change* (OECD, 2015). However, the OECD report did not present trends in gross domestic product (GDP) per capita, so GDP and population data from the World Bank allows the results in Table 1 to be calculated by the author. Despite the population increasing from 3 to 7 billion from 1960 to 2010 the GDP per capita increased globally by 154%. Not surprisingly, the baby

[1]The humor of Monty Python in TV and films is termed "Pythonesque"; it peculiarly blends satire with British surrealism (Wilkie, 2019).

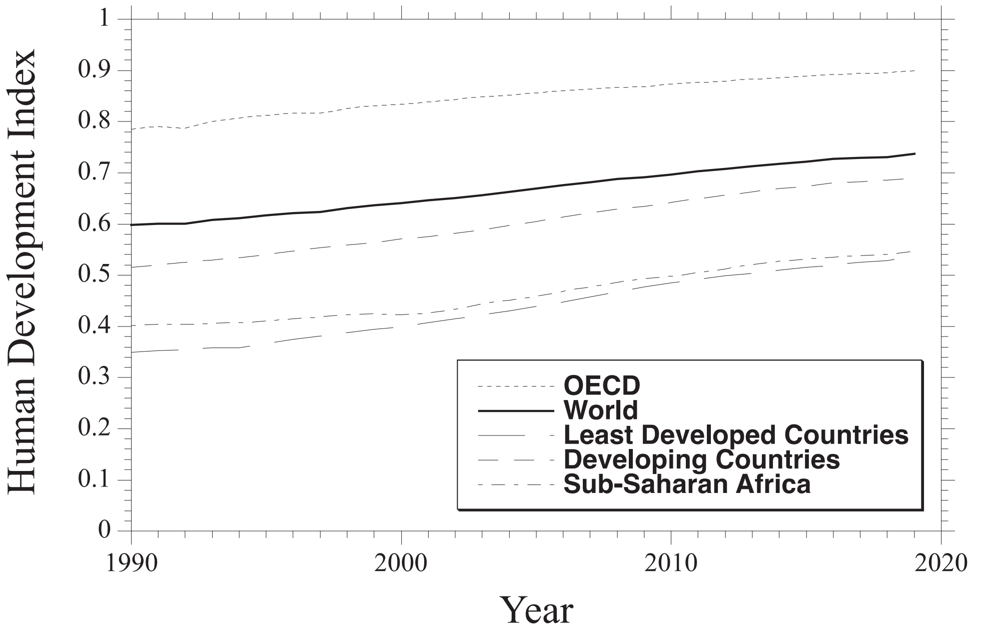

FIGURE 3 Human development index (adapted from Stewart, 2022).

TABLE 1 Increase in GDP per capita (adapted from Stewart, 2022).

	1960–2010	2010–2060	
	(%)	No climate change (%)	Climate change (%)
World	154	100	57
OECD	214	45	35
Sub-Saharan Africa	41	363	197

Abbreviation: GDP, gross domestic product.

boomer years post WWII led to very high economic growth in OECD countries, but also managed to increase by 54% for the 68 least developed countries according to a UN Classification, and 41% for Sub-Saharan Africa (see Table 1). The period 1960–2010 was not exactly a time of peace and tranquillity. There were economic and social disruptions including the Cold War, Middle East oil crisis, four global recessions including the GFC, numerous civil wars and coups in Africa, Asia, and South America, and military adventurism in many parts of the globe. Despite these setbacks, these growth rates are not surprising, and helps explain why the United Nations HDI shows steady improvement for every nation.

It is clear that climate change for a "business-as-usual" scenario of no mitigation or adaptation will lead to high damages and a lowering of GDP. The question is—how does this affect future projections of economic growth? A good indicator is how GDP per capita will change in the future. The OECD (2015) report found that a 50-year period to 2060 that ignores the effects of climate change will lead to relative growth that will be much higher for the less developed parts of the globe. For example, Table 1 shows that Sub-Saharan Africa will increase their GDP per capita by 363%. If unmitigated climate change is now taken into account (i.e., business-as-usual scenario with a 50% growth in greenhouse gas emissions by 2060), Table 1 shows that economic growth will be slowed, but not halted. Even under the dire "business-as-usual" climate change projection the GDP per capita will increase threefold for Sub-Saharan Africa over the next 50 years. The GDP per capita is lowered to a growth of 57% for the world in which climate change occurs with no mitigation or adaptation measures. Even with such a pessimistic scenario the trajectory remains upward—ensuring a wealthier future for even those regions with high vulnerability to climate change. More importantly, the next 50 years will deliver dramatically stronger economic growth to Sub-Saharan Africa than was experienced in the preceding 50 years.

The above data shows that the world is not becoming any more dangerous or vulnerable. Where is the evidence of impending doom? There is evidence to suggest that the opposite holds true—it can be argued that the world has never been healthier, wealthier, and more educated leading to more resilient societies that can better cope with natural and manmade disasters (for a full discussion see Stewart, 2022). While vulnerabilities remain, people and infrastructure are showing increased resilience. Though staggering losses may still occur, they can be ameliorated with targeted strategies to reduce vulnerability, increase resilience, or reduce exposure of infrastructure and people to extreme events.

4 | RISK-BASED DECISION SUPPORT

4.1 | The world is not deterministic

The timing and severity of natural hazards, loads, deterioration, maintenance, repair, and so on associated with the life-cycle of infrastructure are highly variable and uncertain. Added to this is the uncertainty and incomplete knowledge of how infrastructure is vulnerable and damaged by these hazards, and the ability for economic or societal infrastructure to be resilient and for communities to recover.

Uncertainty and incomplete knowledge may be modeled by probabilistic (stochastic) methods. It provides a normative measure of uncertainty that may be quantified from field, laboratory, or historical data and/or advanced computer simulation models. While the former can help ascertain past or current vulnerabilities and resiliency, it has very little predictive capability if the network or system changes over time to suit increases in demand and shifting community demographics, or if the infrastructure degrades over time, or if the likelihood or severity of natural hazards increases due to climate change. These stochastic methods allow risk to be quantified, such as the likelihood and extent of infrastructure damage and recovery for future scenarios of hazard, vulnerability, or resiliency.

An area of particular difficulty for decision-making is where the potential consequences are extremely large or severe yet the probability of these consequences actually occurring is estimated to be extremely low. As discussed above, a probabilistic risk analysis based on sound system and probabilistic modeling is well suited to predicting life saving and damage risks for extreme events. This probabilistic framework provides practical guidance; for example, developing disaster risk reduction measures, safety and load rating assessment of bridges, asset management of pipelines, tunnel safety from vehicle fires, safety cases for offshore platforms and chemical process plants, reliability of electricity infrastructure, and it underpins the development of safety factors and design loads for civil engineering design codes and standards.

Not surprisingly, learned academies such as the Royal Academy of Engineering (RAE) and the Australian Academy of Technological Sciences and Engineering (ATSE) understands the importance of probabilistic thinking: "Regulations and design standards are evidently in need of revision to reflect the uncertain climatic conditions that will be experienced in coming decades, setting probabilistic standards rather than absolute requirements for performance" (RAE, 2011) and "The Academy considers evidence-based tools, such as probabilistic risk assessments... to be fundamental for building resilience into Australia's future planning processes" (ATSE, 2022). However, they note an understandable concern: "The lack of understanding of probabilistic scenarios by politicians and the media could be particularly problematic" (RAE, 2011). This is an ongoing challenge to the engineering profession, where engineers need to explain probabilistic concepts to the government, media, and the public in a way that allows for more informed and rational decision-making.

4.2 | Annual fatalities and cost–benefit assessment

Decision criteria for extreme events are typically based on (i) AFR, and (ii) cost-effectiveness of protective measures. Risk for a system exposed to a threat is

$$E(L) = \sum \Pr(T)\Pr(H|T)\Pr(D|H)\Pr(L|D)L, \tag{1}$$

where $\Pr(T)$ is the annual probability that a specific threat will occur (a terrorist attack, an emission scenario), $\Pr(H \mid T)$ is the annual probability of a hazard (wind, heat, explosion) conditional on the threat, $\Pr(D \mid H)$ is the probability of damage or other undesired effect conditional on the hazard (also known as vulnerability or fragility) for the baseline case of no extra protection (i.e., "business-as-usual"), $\Pr(L \mid D)$ is the conditional probability of a loss (economic loss, loss of life, etc.) given occurrence of the damage (resilience), and L is the loss or consequence if full damage occurs. In some cases, "damage" may equate to "loss" and so a vulnerability function may be expressed as $\Pr(L \mid H)$ which is equal to the product $\Pr(D \mid H)\Pr(L \mid D)$. The summation sign in Equation (1) refers to the number of possible threats, hazards, damage levels and losses. If the loss refers to a monetary loss, then $E(L)$ represents an economic risk. If the loss refers to fatalities, then $E(L)$ represents an AFR.

If we modify Equation (1) where ΔR is the reduction in risk caused by protective measures (e.g., climate adaptation or counterterrorism measures) then expected loss after protection is

$$E_{\text{protect}}(L) = \sum(1 - \Delta R)E(L) - \Delta B, \tag{2}$$

where ΔR is the reduction in risk caused by the protective measure, $E(L)$ is the "business-as-usual" expected loss (risk) given by Equation (1), and ΔB is the co-benefit such as reduced losses to other hazards, increased energy efficiency of new materials, and so on. If there is an opportunity cost associated with a new measure, then ΔB becomes a negative value. Protective measures should result in risk reduction (ΔR) that may arise from a combination of reduced likelihood of the hazard, damage states, safety hazards, and/or people exposed to the safety hazard.

The challenging aspect of risk-based decision theory is predicting values of $\Pr(T)$, $\Pr(H \mid T)$, $\Pr(D \mid H)$, $\Pr(L \mid D)$, and ΔR. This information may be inferred from expert opinions, scenario analysis, and statistical analysis of prior performance data, as well as system and reliability modeling. Since there is uncertainty associated with such predictions, the use of probability distributions to describe mean, variance, and distribution type is recommended.

If the AFR lies in the generally tolerable region (e.g., 1×10^{-4} to 1×10^{-6}—see Figure 2) then several criteria may be used to assess if the benefits of protective measures exceed their cost:

1. Net present value (NPV),
2. Probability of cost-effectiveness or Pr(NPV > 0).

These criteria may also be used to optimize the economic performance of infrastructure, which will be illustrated in Section 5.

Figure 4 shows that the "benefit" of a protective measure is the reduction in damages or losses associated with the protective strategy, and the "cost" is the cost of the protective strategy. The net benefit or NPV is equal to benefit minus the cost. The decision problem is to maximize the net present value

$$\text{NPV} = \sum E(L)\Delta R + \Delta B - C_{\text{protect}}, \tag{3}$$

where C_{protect} is the protection cost that reduces risk by ΔR.

Figure 5 shows how protective costs increase exponentially with risk reduction, while benefits only increase linearly with cost. The optimal protection occurs when NPV is a maximum, leading to optimal risk reduction. Relevant is what level of expenditure and risk reduction gives the greatest benefit and when does the law of diminishing returns kick in. The first dollars spent on protective measures are likely to be worthwhile, even if the last is not.

Governments and their regulatory agencies normally exhibit risk-neutral attitudes in their decision-making as described by the above equations. Utility theory can be used if the decision maker wishes to explicitly factor risk attitudes such as risk aversion or proneness into the decision process (e.g., Qin & Stewart, 2021; Stewart et al., 2011).

If the input parameters are mean or best-estimate values, then Equation (3) gives an expected NPV. However, if input parameters are random variables then the output of the

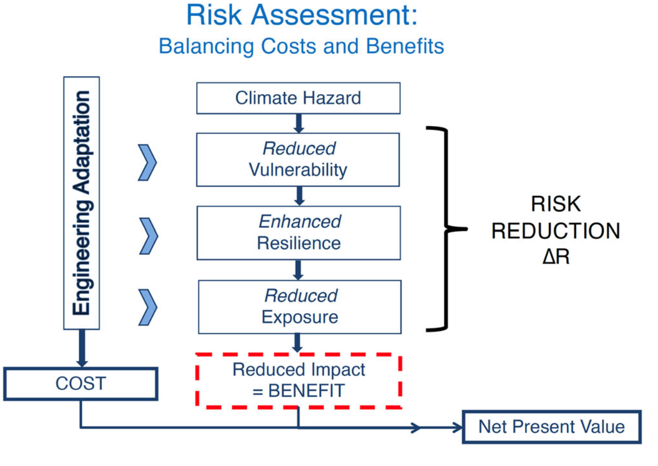

FIGURE 4 Balancing costs against benefits.

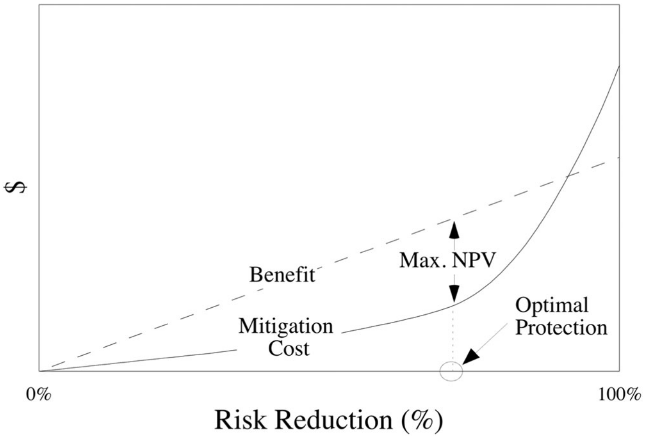

FIGURE 5 Schematic of net present value (NPV) showing optimal protection.

analysis (NPV) is also variable. This allows confidence bounds of NPV to be calculated, as well as the probability that an adaptation measure is cost-effective denoted herein as Pr(NPV > 0). If NPV > 0 then there is a net benefit and so the protective measure is cost-effective. Other notations and formulae can be used to provide optimal protection, but ultimately these also mostly rely on maximizing NPV. The above equations can be generalized for any time period, discounting of future costs and more detailed time-dependent cost and damage consequences.

Ultimately, the outcomes of risk-informed decision analysis will be to inform decision makers as not all decisions can be made on technical merits alone. It also helps to inform government, infrastructure asset and network owners and operators, community, and individuals of the trade-offs between risk, benefits, and cost when making decisions on how best to protect communities. For a fuller discussion see Stewart and Deng (2015).

5 | CASE STUDY: HOUSING DESIGN FOR EXTREME WIND EVENTS IN AUSTRALIA

5.1 | Wind damage and adaptation cost-effectiveness

This section summarizes a detailed assessment of damage to Australian housing due to extreme wind, and how a simple adaptation measure to strengthen new construction can be cost-effective for a changing climate, see Stewart et al. (2014) for a full description of the study. Figure 6 shows typical timber-framed house construction in Australia.

Tropical cyclones and storms are responsible for considerable damage to houses in the Australian state of Queensland. A climate adaptation strategy is to design new houses to a 20% higher design wind speed resulting in stronger connections to the metal roof cladding, roof truss, and walls. The Australian Standard AS, 1684.2,84.4 (2010) Residential Timber Framed Construction specifies that for current design, for example, a 3.05 mm plain shank nail is needed to connect roof battens to the roof truss. However, if the wind classification is increased due to a 20% increase in wind speed, then AS, 1684.2,84.4 (2010) recommends that 2 × 3.05 mm plain shank nails are needed. Other connections in a timber framed house would similarly be

FIGURE 6 Typical timber-framed house construction in Australia.

strengthened, resulting in an increase in house construction cost of approximately 1% of the cost of a new house—or about $3500.

Insurance and loss data, as well as expert judgment, was used to assess the wind vulnerability of a house to damage and loss, see Figure 7 that shows $\Pr(L \mid H)$. The same methods were used when a house is designed to a higher wind classification. At the design wind speed of 50 m/s, Figure 7 shows that adaptation can reduce the damage vulnerability by 75%—this is a significant risk reduction (ΔR) for a modest cost of adaptation. The question then becomes, is this a cost-effective climate adaptation measure when climate change is expected to increase wind speeds?

Extreme wind speed predictions due to climate change are highly uncertain. Hence, a scenario-based approach was selected for time-dependent changes in wind speed:

- Moderate Climate Change by 2100
  - 25% reduction in cyclone frequency
  - 10% increase in mean wind speed
- Significant Climate Change by 2100
  - no reduction in cyclone frequency
  - 20% increase in mean wind speed.

A third scenario was also analyzed, a 4° poleward shift in cyclones to South East Queensland by 2100. This is viewed as a very unlikely scenario, however, results are included for completeness, but they will not be discussed any further.

The average replacement value of a house is $320,000. Economic loss modeling considered (i) direct losses (damage to building and contents), and (ii) indirect losses (clean up, alternative accommodation, disaster response, injuries/fatalities, business disruption, and other social losses).

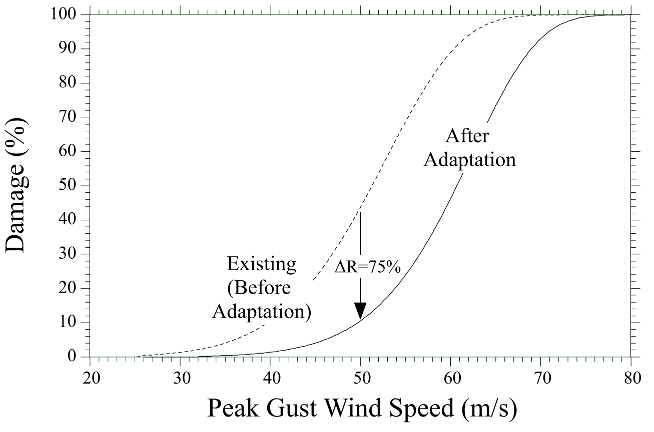

FIGURE 7 Damage vulnerability for houses.

A Monte-Carlo simulation analysis considered the cumulative losses from 2015 to 2100 for:

- Current (2015) building stock of 1 million homes in the Queensland cities of Brisbane, Cairns, Townsville, and Rockhampton.
- 1% growth of new house construction per year.
- 0.2% of existing houses per year being renovated and thus need to comply to new building regulations.
- Adaptation measure from 2015: All new and renovated construction designed to increased wind classification.
- Discount rate of 4%.

Hence, by 2100 it is predicted that only 5% of housing stock will have been built before 2015. Hence, the vulnerability of the housing stock will reduce over time, and the cost of adaptation is spread equally over time. This may be an attractive option for policymakers as there is no need for large upfront costs.

Figure 8 shows the economic impact of climate change, that is, the increase in direct and indirect losses for three climate change scenarios. The climate impact is highest at 2100 for significant change ($13.5 billion), reducing to $4.7 billion for moderate change. These are significant losses, and indicate that business-as-usual approach to housing design and construction can increase losses by 50%–150% by 2100.

The mean NPV is then calculated as well as 10th and 90th percentile bounds by allowing for the natural uncertainty in wind speeds and variability in housing vulnerability (see Figure 9), and assuming a risk-neutral decision-maker. It is observed that mean NPV is a high $7.3 billion for significant change, and $3.4 billion for moderate change to 2100. In both cases, the lower 10th percentile shows a positive NPV, and the probabilities of a positive NPV are 92% and 100% for moderate and significant change to 2100, respectively. The corresponding mean benefit-to-cost ratios (BCR) are a high 3.0 and 5.4. These results strongly suggest that modest strengthening of new housing construction has strong benefits that easily outweigh the costs – the net benefit is considerable.

It is also worth noting that even if there is no change in wind field, the mean NPV is $1.5 billion with a BCR of 1.9 billion, with a 70% likelihood that a net benefit will occur. Hence,

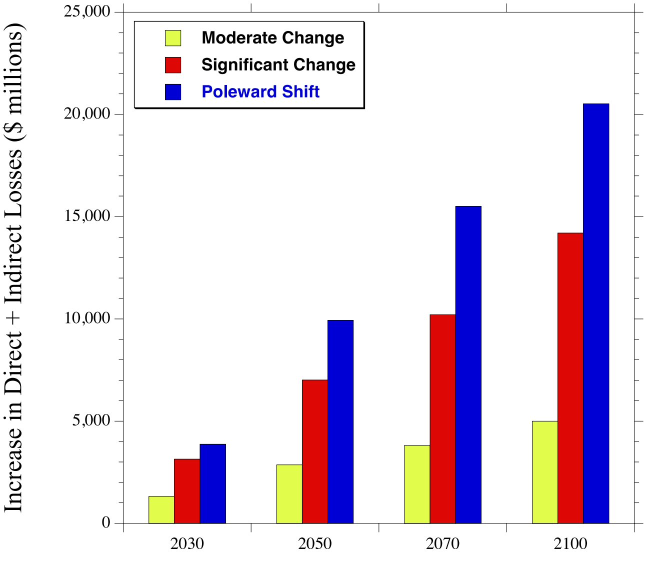

FIGURE 8 Increase in mean losses (adapted from Stewart et al., 2014).

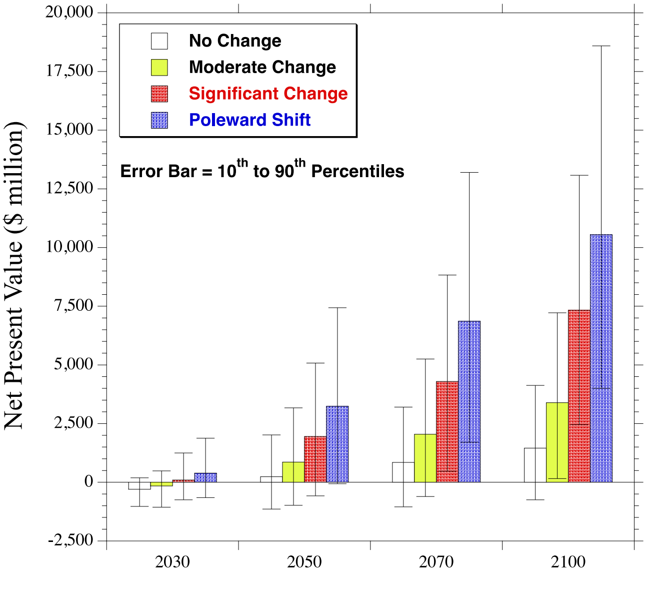

FIGURE 9 Mean and 10th and 90th percentile net present values (adapted from Stewart et al., 2014).

reduction in vulnerability, at modest cost, is a worthwhile endeavor even in the absence of climate change effects on the wind field. This is a no regrets policy even if climate predictions or scenarios are incorrect. It also shows that current design and construction standards may be suboptimal.

In summary, an adaptation strategy implemented at a modest cost to new construction will offset some the predicted adverse effects of climate change over time as more of the building stock is adapted, and can lead to significant net benefits to the homeowner and society. For a fuller discussion of results, including sensitivity analyzes, see Stewart et al. (2014). Wind-rated garage doors can also be a cost-effective climate adaptation measure (Stewart, 2016).

5.2 | Risk perceptions, economic incentives, and insurance

Another adaptation measure is installing cyclone-rated roller window shutters on contemporary housing built in Brisbane—this can reduce the expected damage costs by more than 95%, at an adaptation cost of $6,000 or 2% of the value of a house. The question is what economic incentives make this adaptation (risk mitigation) measure financially attractive to the homeowner, government, and/or the insurer. This can motivate homeowners to invest in mitigation which potentially leads to a more resilient residential community against windstorms, and a cost reduction for disaster management and recovery in the future. Rank-dependent utility theory (Quiggin, 1982) was utilized to quantitatively model risk perceptions in the life-cycle cost analysis (Qin & Stewart, 2021).

The claim costs to an insurer can be significantly reduced if homeowners are encouraged to install window shutters, and therefore it may be desirable for the insurer to provide a reduction in insurance premium to promote window shutters among homeowners. Without any incentives, even a risk-averse homeowner would select not to install window shutters considering a time horizon of 10 years, but would do so only if considering a longer time horizon of 30 years. On the other hand, for a 10-year horizon, if insurers offered a 27% discount on their insurance premium, then a risk averse homeowner would be willing to install window shutters as this then would become financially attractive to them, as well as the insurer (see Table 2). By comparison, a risk-neutral homeowner would only install window shutters if the insurance premium discount was increased to 31%. A higher discount for the insurance premium is needed to motivate homeowners with a shorter planning time horizon. In other words, homeowners are more likely to invest in risk mitigation measures if their planning horizon is longer than 10 years.

An alternate means of incentivisation is for government or insurers to provide homeowners with a rebate to help offset the upfront cost of shutter installation, see Table 2. For homeowners with a shorter planning time horizon, a higher rebate for shutter installation cost is needed, which is expected as the risk reduction (benefits) provided by window shutters increases with

TABLE 2 The minimum discount for the insurance premium and minimum rebate for shutter installation cost that are financially attractive to homeowners with different risk perceptions (adapted from Qin & Stewart, 2021).

Time horizon	Risk averse (%)	Risk neutral (%)	Risk loving (%)
Insurance premium discount			
10 years	27	31	n/a
30 years	0	3	4
Rebate			
10 years	59	72	80
30 years	0	8	12

Note: "n/a" means a discount for insurance premium is not enough to make shutter installation cost-effective.

time. For a typical planning time horizon of 10 years, a rebate for shutter installation cost or a discounted insurance premium have been found to be feasible economic incentives. For more details see Qin and Stewart (2021).

6 | CONCLUSIONS

Terrorism and climate change are extreme events that engender fear and anxiety in the community. Policymakers are also susceptible to these emotions, yet there is a need for risk leadership where rational thinking should trump emotions. Risk-based approaches are suitable to assess the acceptability of risks, and the cost-effectiveness of measures to reduce terrorism and climate impact risks. There is no need to overreact. Moreover, climate adaptation solutions for the built environment exist that are effective and can provide multibillion dollar benefits at low cost. There is much to be optimistic about the future, and in the ability of risk-based thinking to meet most challenges.

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