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LITERATURE REVIEW ON DECISION SUPPORT SYSTEMS FOR OPTIMISING LONG-TERM NATURAL HAZARD MITIGATION POLICY AND PROJECT PORTFOLIOS

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ABSTRACT

In this report, literature pertinent to the development of natural hazard mitigation decision support systems is reviewed across four areas:

1. Evidence for the increased frequency of natural hazards and the benefits of mitigation are reviewed. Modelling indicates that natural disasters will become more frequent and of higher impact into the future, when mitigation is not implemented. However, these changes have not been observed in economic loss data from disasters over the last decades. Mitigation is found to be effective and economically justifiable based on benefit-cost ratios. When mitigation measures are strategically selected, benefit-cost ratios above 8 are possible.

2. Mitigation planning is reviewed, with the presentation of mitigation planning frameworks and classifications of mitigation options. Mitigation options include projects, policies and other activities that are implemented before a disaster event, which work to reduce hazard, reduce exposure, reduce losses during response, and reduce impact over the recovery period. These options include structural works, management techniques, and land use planning tools. While land-use planning tools have generally become preferred by government policy makers, there has been little study in the literature regarding their effectiveness.

3. The decision support system (DSS) literature is surveyed to understand current research thrusts in this field. It was found that more research effort is needed for strategic decisions, with greater use of techniques, such as optimisation, to provide higher levels of decision support. In addition, end-user engagement was found to be critically important for DSS adoption. Based on this, a DSS development approach, as found in the literature, was described.

4. The development of emergency management DSSs since the early 1980s is surveyed, with a particular focus on DSSs for mitigation. It was identified that the use of optimisation and taking a multihazard approach are important components of mitigation DSSs. However, no previous research has incorporated both of these aspects into DSSs, nor have previous studies considered changes in climate change, demographics, land use, or economics into the future.

Consequently, this report concludes that the development of decision support systems that (i) use state of the art methodologies, (ii) incorporate the use of optimisation within a multihazard approach, (iii) consider changes in climate, demographics, land use and economics, and (iv) assess land-use related mitigation measures in addition to structural and management measures, is both important and novel.

1. INTRODUCTION

The impact of natural disasters on society is of great concern due to their impact on economies, communities and the environment. According to the World Economic Forum, water crises and the greater incidence of extreme weather events (such as floods and storms) were the third and fifth highest risks of concern to their multistakeholder communities, respectively (World Economic Forum, 2014).

The impact of natural disasters on economic systems can also be investigated through analysing the reported costs of natural disasters in the past. This is often done using databases of reported losses, such as those maintained by Munich Re (the NatCat database) and Swiss Re (The Sigma database), both of which are large reinsurers, and the public domain EM-DAT database, maintained by the Centre of Epidemiology of Disasters. Of these, the NatCat database is largest (Guha-Sapir and Below, 1999).

According to the NatCat databases, there were 890 loss events in 2013, worldwide, that resulted in 20,500 fatalities (excluding famine), and US$135 billion in losses (of which US$35 billion were insured losses). Although these losses are a small portion (less than 0.2%) of the US$87 trillion global GDP, natural disasters are localised and may have severe impact on local economies and communities, and recovery may take a very long time.

Estimates can be much greater than those calculated from aggregating records from the NatCat database. For example, based on different assumptions and methods, Clarke and Munasinghe (1995) estimated that losses in 1991-1992 were approximately US$100 billion (compared to US$39 and US$55 billion in 1991 and 1992 respectively, from the EM-DAT database). If indexed at 4% per annum, this would equate to approximately US$230 billion per year in 2013 values, almost double that estimated from the NatCat database for natural disasters in 2013.

The possible losses from natural disasters are much greater. Natural disasters are low likelihood, high impact events. Therefore, potential losses from events that are more infrequent than those experienced in recent years are huge. Shah (1994) predicted that a magnitude 7 earthquake hitting Los Angeles, at the present time, would cause over US$170 billion in economic losses, over US$95 billion in insured losses, over 3,000 deaths and up to 20,000 injuries. Likewise, a repeat of the 1906 San Francisco earthquake would result in similar losses, and the repeat of the 1923 Tokyo earthquake would cause over US$2.0 trillion in economic losses, over US$30 billion in insured losses, and over 40,000 deaths (See also Grossi and Muir-Wood, 2006).

Consequently, there is much benefit in reducing net losses from natural disasters, if there are mechanisms to do so. The reduction of natural hazard losses is the focus of a research project being conducted as part of the Bushfire and Natural Hazards CRC, entitled “Decision Support System for Assessment of Policy and Planning Investment Options for Optimal Natural Hazard Mitigation”. This report forms part of this project, and aims to review the pertinent literature relevant to this research project.

This report is set out as follows:

In Section 2: The case for natural hazard mitigation is made, by summarising our knowledge on how the frequency of natural disasters may change into the future, and evidence on the extent to which losses can be reduced through mitigation efforts. Subsequently, impediments to mitigation planning are identified.

In Section 3: Frameworks for mitigation planning that have been published in the literature are reviewed. Implications for the design of decision support systems are then made based on these frameworks.

In Section 4: The decision support system (DSS) literature is surveyed to understand current research thrusts in this field. In addition, classification systems for DSSs are summarised. These classifications are used in

Section 5 to organise previous work on natural hazard decision support systems, in order to make conclusions about research need.

In Section 5: The development of emergency management DSSs since the early 1980s is surveyed, with a particular focus on DSSs for mitigation. Subsequently, research conducted on the use of multihazard and optimisation approaches are presented.

2. MITIGATION - A POTENTIAL ANTIDOTE TO INCREASING LOSSES FROM NATURAL HAZARDS

This chapter provides an overview of our knowledge on natural hazard mitigation. To proceed, the definition and scope of mitigation is first presented. Then, we review the debate on whether natural hazard losses are expected to increase into the future, and what the main drivers for these changes are. Subsequently, we consider how these losses may be minimised (or in other words, mitigated). Finally, the question of why mitigation has not become more prevalent is addressed, despite the fact that, as substantiated within this section, mitigation is very effective at minimising losses.

2.1. A definition of "mitigation"

The definition of "mitigation" is vague. While there is a tendency to view mitigation as the 'prevention' in the prevention, preparedness, response and recovery (PPRR) continuum of emergency management, the common English definition of mitigation is synonymous with abatement, alleviation, diminution, moderation, and reduction of severity. Therefore, mitigation involves more than just hazard prevention, as many non-prevention planning activities, for example, also reduce the risk of losses (Hunter, 1996). For example, response planning enables faster disaster response, and faster responses reduce losses.

Texts on emergency management also differ in their usage of *mitigation*. For example, Smith (2013) lists three categories of disaster reduction strategies, being protection, mitigation and adaptation, whereby mitigation is defined as "financial measures to modify the loss burden" and includes measures such as emergency aid and insurance. On the other hand, Lindell (2013) defines mitigation as "pre-impact actions that protect passively against casualties and damage at the time of hazard impact". While there is good sense in using mitigation to only refer to activities before an impact, mitigation is also commonly associated with disaster recovery, as recovery provides the opportunity for rebuilding in ways that prevent similar damages in future events, whilst mitigation is high on the political agenda (Godschalk et al., 1998). In addition, it could also be argued that activities performed during response reduce further losses, and consequently mitigate losses. However, these activities would not normally be termed "mitigation" (e.g. The Australian National Emergency Management Committee agreed to preclude these activities from their definition of mitigation; Hunter, 1996)

Based on this discussion, this report uses *mitigation* to refer to any project or process that is implemented before a natural hazard event, such that the hazard or the losses/impacts resulting from a natural hazard event are reduced.

2.2. Risk may increase into the future

Three factors are thought to be causing natural hazard losses to increase over time. First, climate change is increasing the frequency and severity of natural disasters. Second, economic growth continues, which means more wealth is vulnerable when natural disasters strike. Third, populations and investments are being concentrated in cities, which are often situated in vulnerable locations, which also cause larger magnitude of losses when natural disasters strike.

Concerning climate change, the 5th IPCC assessment report concludes that climate change is increasing the hazards associated with storm surges, heat stress, extreme precipitation, inland and coastal flooding, landslides, drought, aridity, water scarcity, and air pollution. These increased risks will have widespread negative impacts on communities, economies and ecosystems (IPCC, 2014a). In particular, the IPCC report assesses the evidence on whether climate change is increasing hazard levels in regard to a number of natural phenomena, with the following findings:

- There is strong evidence that the frequency of extreme temperatures and heat waves in some regions is increasing, even at a faster rate than mean temperatures, due to human influence on climate systems (IPCC, 2013). In Australia, there is medium-high confidence that the frequency and intensity of extreme climatic events is increasing (IPCC, 2014b).
- There is medium confidence that observed values in heavy precipitation events have increased, on a global basis, since the mid-twentieth century. As such, extreme precipitation will very likely be more intense and frequent due to climate change, particularly in mid-latitude land masses and over wet tropic regions (IPCC, 2013). In regard to flooding, evidence is lacking that the magnitude and frequency of floods has increased over the instrumental record (although see Hallegatte et al., 2013; Hirabayashi et al., 2013; and Jongman et al., 2014 for model based evidence of increased flooding into the future). However, the annual economic losses from large extreme events, including floods and droughts has increased tenfold from the 1950s to the 1990s (IPCC, 2014a), although this claim does not take into account the change in value of money over time due to factors such as inflation.
- The risk of drought is likely to increase in regions that are presently dry (IPCC, 2013). Together with changes in precipitation and evaporation, this will have severe implications in regard to water scarcity (Schiermeier, 2014). These factors are expected to bring increased economic losses and risks to human life caused by wildfires in most of southern Australia (IPCC, 2014b).
- Sea level extremes are very likely to increase significantly, as a result of global sea level rise (IPCC, 2013). Therefore, coastal areas, particularly those that are low-lying, will increasingly experience submergence, coastal flooding and coastal erosion. However, there is only low confidence in projections of storm surge changes in tropical and mid-latitude regions (IPCC, 2014a). Nevertheless, the recent IPCC report estimates the benefits of mitigating coastal flooding and land loss to be greater than the costs of inaction, on a global scale.
- Projections show that the frequency of tropical cyclones will likely decrease or remain unchanged, although the wind speed and rainfall rates associated with cyclones will likely increase. However, some regions will experience a higher frequency of cyclones, which may be caused by a global shift in cyclone tracks (IPCC, 2013).

Concerning the concentration of population and investments in vulnerable locations, this is largely caused by economic and population growth in urban areas (Changnon et al., 2000; Deloitte Access Economics, 2013; Neumayer and Barthel, 2011). Urban areas are often situated in vulnerable regions. For example, cities often grow adjacent to rivers and oceans that form the backbones of navigation/transport systems, and populations often congregate around fertile basins often formed through alluvial flood deposition or soils of volcanic provenance. In addition, as cities grow, supply of land to facilitate growth reduces, which results in developments using more vulnerable land.

Despite the concentration of wealth in urban areas and climate change, there is a lack of empirical evidence that suggests economic losses have increased from natural hazards in the last several decades. Although the costs of response and recovery to disaster events have increased, there is debate as to whether the costs in real terms have increased (Neumayer and Barthel, 2011). This is because monetary values tend to increase over time due to inflation, without any change in real worth. In addition, per capita wealth has also increased, on a global basis, and it may be better to analyse changes in the relative cost of response/recovery against wealth, rather than to track changes in economic losses in absolute terms. Consequently, studies have sought to normalise monetary values to take this into account (Barredo, 2009; Brooks and Doswell, 2001; Pielke and Landsea, 1998; Pielke et al., 2003). The majority of evidence suggests that, on a global basis, the economic costs of natural disasters are not increasing (Neumayer and Barthel, 2011). However, Schmidt et al. (2009) found that tropical cyclone losses were increasing in the USA in real terms. Using an alternative methodology, where econometric models that include socio-economic and meteorological factors are calibrated to historical data, Schmidt et al. (2010) found that socio-economic factors were three times more influential in losses from tropical cyclones than climate factors. Therefore, this methodology, while indicating that socio-economic factors are mostly responsible for changes in monetary values of losses, also indicate that climate change is a factor.

It may seem contradictory that the frequency and intensity of natural hazards are, on a global basis, increasing, yet losses are not. However, losses are also dependent on the exposure and vulnerability of the social and economic systems that natural hazards affect, in addition to climatic and other natural factors. Therefore, these two results can be explained by increased investment in mitigation activities that reduce vulnerability and exposure. Vranes and Pielke (2009) found that investment in mitigation measures of at least 1% per annum of the average yearly natural hazard loss amount would be sufficient to prevent growth in natural disaster losses.

So far, this discussion has centred on expected global changes in natural hazards. However, some regions could be expected to be relatively less or more worse off than the global mean. While similar conclusions (that losses are not increasing) have been made for Australia based on normalised insured losses (Crompton and McAneney, 2008), studies also indicate that natural hazard risk will increase into the future (IPCC, 2014b). While the current average yearly cost of natural disasters in Australia is AU$6.3 billion per year, this is expected to grow at a rate of 3.5% annually in real terms. This growth rate is based primarily on economic development and concentration of wealth in urban areas, and does not take into account the impact of climate change, or projected implementation of mitigation measures (Deloitte Access Economics, 2013).

2.3. Benefits of mitigation

The previous subsection noted the lack of evidence that losses from natural disasters are increasing, which was surprising given the influence of climate change and the concentration of wealth in vulnerable areas. Therefore, it was proposed that mitigation was preventing a rise in losses. In this section, the reported economic benefits of mitigation projects are identified in the literature, to assess whether mitigation measures could be effective — and hence reduce, or even prevent losses into the future.

There have been a number of papers that have conducted benefit-cost analysis for disaster risk reduction measures, mainly at the community scale and mainly in developing countries (e.g., Eucker et al., 2012; Heidari, 2009; Holland, 2008; Holub and Fuchs, 2008; Khan et al., 2012; Khogali and Zewdu, 2009; Kull et al., 2013; Kunreuther and Michel-Kerjan, 2012; Mechler, 2005; Schröter et al., 2008; Shreve and Kelman, 2014; Venton and Burton, 2009; Venton et al., 2010a; Venton et al., 2010b; White and Rorick, 2010). The three most comprehensive publications that have quantified the benefits of aggregate mitigation measures include an analysis of mitigation projects funded by grants from the US Federal Emergency Management Agency (FEMA) by Rose et al. (2007), an analysis of potential flood and coastal mitigation measures by England's Environment Agency (UK Environment Agency, 2009), and an analysis of three mitigation case studies located in Australia for the Australian Business Roundtable for Disaster Resilience and Safer Communities (Deloitte Access Economics, 2013).

A benefit-cost analysis identifies all the costs incurred, and the benefits, resulting from a particular set of mitigation activities. In the context of natural hazard mitigation, the benefit is given by the expected reduction in losses (including the reduced response and recovery expenditure) that occurs due to implementing a set of mitigation activities, from the case where the mitigation activities were not carried out at all. Because of the stochastic nature of disaster events, benefits of a set of mitigation activities can be described using a probability density function (PDF). For use in benefit-cost analysis, the expected value of this pdf is used. Such analyses are conducted over a specified time frame into the future, with future costs and benefits discounted, to take into account time-preferences of costs and benefits.

The benefit-cost ratio, which can be calculated using the results of a benefit-cost analysis, was used by all three studies, and is calculated as:

$$BCR = \frac{\sum B}{\sum C} \qquad \text{Equation 1}$$

Where $\sum B$ is the present value sum of benefits and $\sum C$ is the present value sum of costs. Rose et al. (2007) found that the overall BCR across nearly 5,500 FEMA mitigation grants was about 4:1, although the actual ratio for individual events and different hazard types varied considerably from this. For example, the overall BCR for earthquake, wind (e.g. hurricane) and flood mitigation projects were 1.3:1, 7.0:1 and 5.1:1, respectively, and the BCR of mitigation activities amongst the grants ranged from 0.05:1 (that is, a large net loss) to 50:1. A sensitivity analysis indicated that projects that had expected BCRs above 1:1, remained so, under a very broad range of conditions.

The English Environment Agency tested five funding strategies for maintaining existing and investing in new flood risk management assets across England, and found that the benefit to cost ratio for these strategies ranged from 4:1 to 11:1, when the costs and benefits of managing coastal, tidal and river flooding, and managing coastal erosion were considered. The one hundred year net present benefit for these five options ranged from approximately £140 to £180 billion (UK Environment Agency, 2009).

Deloitte Access Economics (2013) were commissioned by the Australian Business Roundtable for Disaster Resilience and Safer Communities to analyse three Australian mitigation case studies (raising the Warragamba dam wall height to reduce flooding in the Hawkesbury-Nepean basin; specifying stronger building requirements and land-use planning to mitigate cyclone and flooding in South-East Queensland; and retrofitting existing housing, and improving fuel management to reduce potential loss in bushfire prone areas in Victoria). All three mitigation projects were found to be beneficial. Deloitte Access Economics (2013) found that BCRs greater than 1, and up to 9 were possible when mitigation investments are made that target high risk locations with appropriate combinations of structural and non-structural mitigation options.

There are other benefits that arise when planning mitigation. Burby (1998a) and May (1996) both argue that natural hazard planning provides information on the location and nature of the various types of natural hazards. This helps provide information on the most appropriate use of land, and when linked to other high-priority goals (such as climate change mitigation, economic development, and improvements to environmental amenity), can lead to increased political will and impetus for supporting mitigation measures.

The benefits of mitigation planning are often most noticeable after a disaster occurs. For example, in reviewing foreknowledge regarding the hazard and risk of the 2011 Tohoku earthquake and tsunami (which caused the Fukushima nuclear accident) and the 2008 economic recession due to the US housing and financial market collapse, Stein and Stein (2014) concluded that these events, although rare, could have been predicted, and therefore avoided through more careful assessment and mitigation.

To summarise, it is clear that mitigation can be very cost effective, if targeted on projects and processes that lead to high benefit-cost ratios. However, there has been little research on how long such high BCRs can be maintained. For the sake of illustration, consider a yearly budget for mitigation that is set over an extended time period. In choosing what mitigation activities to invest in for each year, it would be wise to spend on those projects that had the highest BCR. This leaves activities with lower BCR values to be selected in future years. Therefore, with time, the benefits of mitigation dwindle. Vaziri et al. (2010), Legg et al. (2012), Xu et al. (2007), and Tesfamariam (2010) have investigated such long-term dynamics in optimising the ratio between mitigation and recovery spending into the future, but only for earthquake and hurricane risk. Such dynamics indicate the importance of temporal planning to reap the full benefit of mitigation strategies.

2.4. Difficulty of mitigation

If mitigation is so cost effective, then this gives rise to the question, *why does investment in mitigation seem to be lacking?* Although there are likely to be many answers to this question, reasons given in the literature include:

- In natural hazard mitigation, the costs of the mitigation activities are concentrated, while the benefits are broadly dispersed. Wood (2004) explains that this is the reason why scientific advances in regard to natural hazard mitigation are not quickly, or routinely, incorporated into tangible public policy and regulations. Therefore, Wood (2004) concludes that groups with entrepreneurial characteristics are needed to bring about policy change for mitigation, as entrepreneurial behaviour can break down policy subsystems, is effective in introducing and promoting policy innovation and has the ability to galvanise support from an otherwise detached and apathetic electorate.

- Wood (2004) also found that commitment to risk reduction at local-level government was correlated to commitment at the state level, and also to vulnerability to natural hazards and economic conditions in the local government region. Therefore, impediments to mitigation would include lack of leadership at state and federal levels, lack of funding, low economic development, and low natural risk from natural disasters in a region.

- At the level of organisations, Sadiq and Weible (2010) found that the greatest obstacle preventing the adoption of mitigation activities was a lack of information. They found that financial resources were relatively less significant barriers to mitigation.

- Natural hazard mitigation is, in essence, planning for the occurrence of events and circumstances that occur in sequence or simultaneously, which result in system failure (failure chains). However, planning for failure chains is difficult, as identifying system vulnerabilities in advance is challenging (Stein and Stein, 2014).

- Decisions are generally made using human intuition, formed by experiences, expectations, beliefs, and goals of the stakeholders, rather than an analysis of trade-offs between options, which are time consuming and costly. Human intuition works well for when decision makers have much experience, but for low probability and high consequence natural disasters, this does not work well. In such cases, intuitive decision making likely results in maintaining the status quo and focussing on recent events (IPCC, 2014b).

- Decision makers have limited information on what the best options and highest priorities are for mitigation investment (Hennessy et al., 2014).

- Finally, mitigation budgets are always limited (Vaziri et al., 2010). In addition, as is the case in Australia, mitigation budgets tend to be drawn from local governments, while recovery from major disasters is heavily subsidised from federal government. This separation of the recovery and mitigation budget does little to incentivise risk reduction.

Therefore, there are serious challenges to mitigation, ranging from the distribution of costs and benefits across a community, to a lack of political will and the lack of analytical and transparent techniques for providing information for mitigation decision making.

3. MITIGATION PLANNING

This chapter deals with how mitigation measures might be identified, classified and incorporated into emergency management plans. First, a classification scheme is developed, based on categorisations found in the literature. This classification is helpful for identifying potential mitigation measures to compare when developing mitigation plans, and will also be used in Section 5 to analyse previous research efforts towards developing analytical techniques for mitigation planning. Next, three previously published mitigation planning frameworks are compared before the section closes by showing that the literature encourages multicriteria, integrated approaches to planning mitigation programs.

3.1. A taxonomy of mitigation measures

In this report, a classification of mitigation measures is developed with reference to Figure 1. This figure describes the linkage between environmental forces that give rise to natural hazards, and the physical losses and social impacts that result from them, as now described:

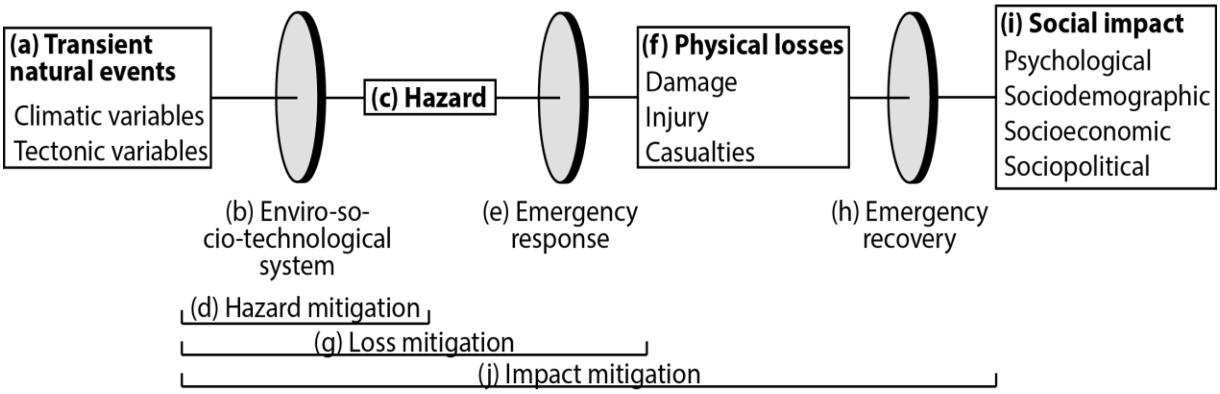

Figure 1. The linkage between hazard, losses and impact, with the enviro-socio-technological system, emergency response and recovery, and with different types of mitigation.

As shown in Figure 1(a), all natural disasters are caused by extreme combinations of transient natural events. Examples of these events include rainfall for floods, seismic activity for earthquakes, and heightened solar radiation for heat waves. These events are transient, in that they are relatively short lived and are extreme in combined intensity. Ultimately, these events cause hazard, as shown in Figure 1(c). Hazards are here defined as exposure to physical conditions that cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption or environmental damage, this being an adaptation of the definition given by the United Nations International Strategy for Disaster Reduction (UN/ISDR, 2009).

As shown in Figure 1(b), the level of hazard exposure one is subject to is dependent on the enviro-socio-technological system. For example, in flooding, the depth and velocity of flood waters is a hazard, and exposure to this is not only dependent on the duration and intensity of rainfall, but is also dependent on catchment characteristics, such as topography, land cover, geology and constructed storages. Consequently, one means of mitigating disaster losses is through modifying the enviro-socio-technological system. These are called hazard mitigation measures in Figure 1(d).

As shown in Figure 1(e) and (f), the losses resulting from disaster events are not only related to the severity of the hazard, but also to how natural hazards are responded to. This is because faster responses may prevent casualties, and reduce the duration of hazard exposure. This is an important consideration when planning mitigation, as it is regularly observed that preparation, planning and coordination of response services are inadequate, leading to more intense short-term suffering that could have been avoided (Burby, 1998a). Consequently, another means of mitigation is through improving response capability, which has the effect of improving response time and effectiveness. While these measures do not mitigate hazard, they do mitigate the short-term losses from disaster events (Figure 1g).

As shown in Figure 1(h) and (i), the long-term social impact of a natural disaster is related to how recovery is managed, in addition to hazard and emergency response. One of the most common ways of improving recovery is through insurance. As insurance is a measure to improve recovery, it does not minimise losses or hazard, but ensures finance is available for the recovery effort. Consequently, the third means to mitigate losses is through improving recovery capability, which mitigates long term impact (Figure 1j).

Concerning the use of insurance, it can be argued that this does not mitigate losses. Insurance only redistributes the costs of disasters over time and across a greater population. In fact, insurance actually increases the cost of disasters, as insurance companies need to ensure their profitability.

However, insurance is generally considered to be a mitigation option. Insurance does help mitigate disasters in the local region, and insurance can also modify behaviour. If insurance premiums are calculated based on the risk that policy holders are exposed to, then this will create incentive to not develop in risky areas. In addition, this would encourage landowners to reduce their exposure in an attempt to lower their insurance premium. However, people can be unwilling to purchase insurance against natural hazards (Burby, 1998b). In addition, policy holders are not normally conditioned to reduce exposure on purchasing insurance, and are generally not rewarded by reduced premiums when they do. Therefore, insurance can induce unhelpful signals by giving incentive to building in hazard-prone areas when premiums are not appropriately calculated according to risk.

Often, governments provide, what is, in effect, insurance (although often not labelled as such). After disasters, governments are often called on to help the rebuild process, through relief payments. This favours the community and favours politicians' approval ratings. Unfortunately, the 'premiums' that finance such recovery payments are 'tax', which are not paid in proportion to risk. Therefore, this also sends unhelpful signals, even if governments do not need to make profit.

Hazards can be mitigated by modifying the enviro-socio-technological system, as shown in Figure 1. These measures can be further categorised into structural works, management techniques, and land use planning tools.

A list of structural works for mitigating hazard is given in Table 1

Table 1. Structural measures for hazard mitigation for different hazard types.

Hazard	Structural measures
Coast surge and inland flooding	Elevating, protecting and strengthening structures, early warning systems, sea walls, dikes, groins, dams, levees, and open space in low lying areas.
Storm (e.g. Tropical cyclone)	Protecting and strengthening structures
Earthquake	Protecting and strengthening structures
Heatwave	Installing air conditioning, building insulation

Bushfire	Protecting structures, forming fire breaks.

Management techniques are related to how landscapes and structures are managed and maintained. For example, fuel load reduction, and maintenance of fire retarding measures constructed into buildings are management techniques to abate bushfire risk.

In recent decades, land use planning has become a favoured means of mitigating natural hazards. Land use planning tools have been classified into six categories (Olshansky and Kartez, 1998), being:

1. Building standards that include building codes, flood and seismic design standards, and retrofit requirements for existing buildings.
2. Development regulations that include zoning and subdivision regulations, which may include details regarding permissible development in flood-zones, and setback requirements from faults, steep slopes, coastal erosion areas, and areas that require high specification development standards.
3. Public facility policies that could involve capital improvement plans and plans/criteria for locating public infrastructure such as schools, emergency services, and transport and utility networks.
4. Land and property acquisition whereby the state purchases titles in high risk areas.
5. Taxation and fiscal policies that steer behaviour toward disaster resilience[1] through shifting the distribution of costs across society. For example, governments may increase rates on properties held in high risk areas, or provide grants to landholders for retrofitting buildings at risk.
6. Information protocols/policies that intend to influence behaviour through informing communities of risk (e.g. through hazard disclosure statements on property transfers).

3.2. Frameworks for developing mitigation plans

There have been a limited number of published works that developed an overarching framework to steer the formation of mitigation plans. In this section, three of these frameworks are reviewed. But first, it is helpful to define what a mitigation plan encompasses.

Mitigation plans are statements of mitigation intent, which have the following purposes (Godschalk et al., 1998).

- Facilitate the systematic and comprehensive review of community goals with respect to natural hazards;
- Provide a basis for action that is legally and politically defensible;

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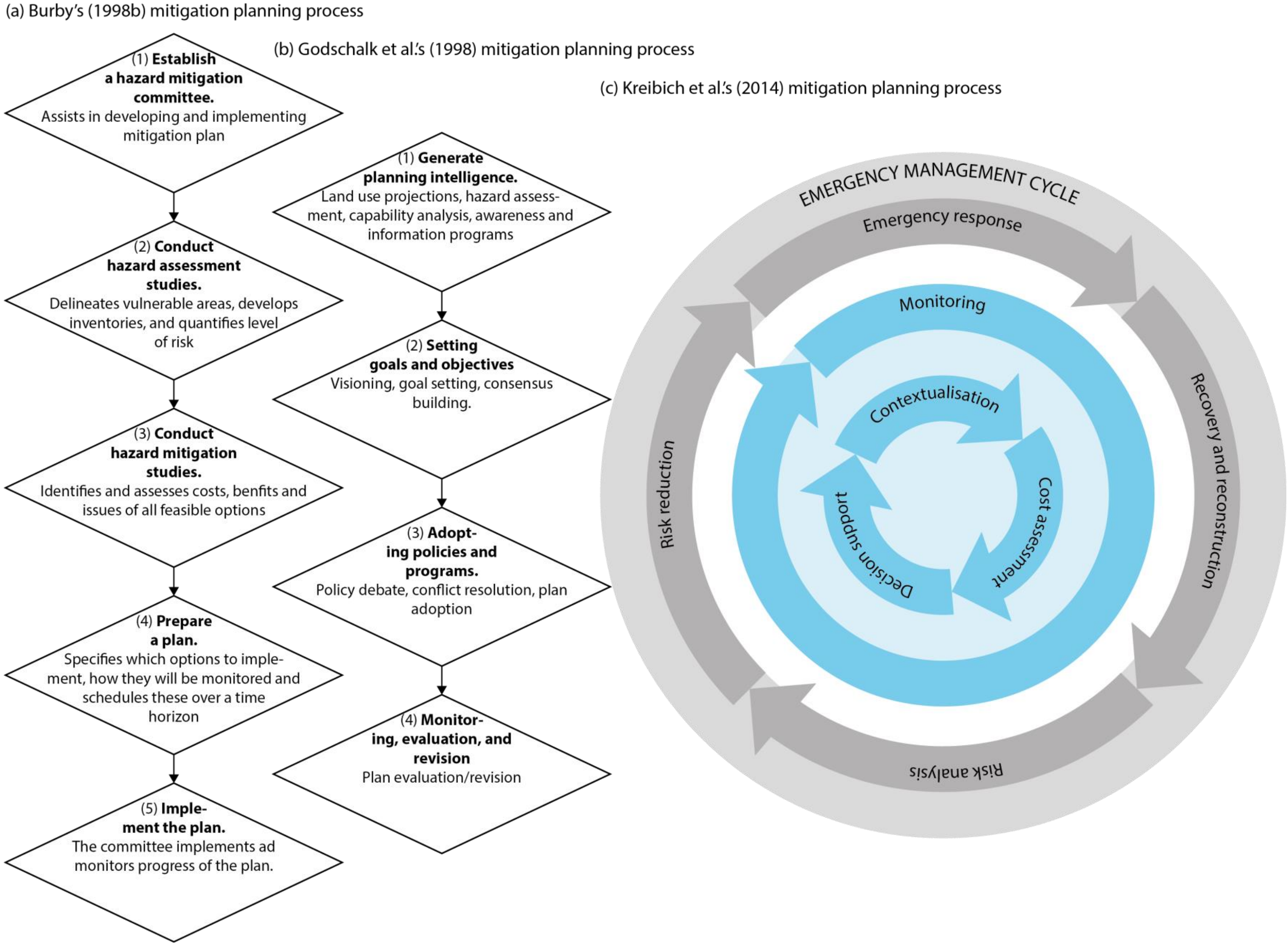
[1] Resilience lacks agreed definition, but the UN/ISDR defines it as the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions (UN/ISDR 2004). See Smith (2013) for a discussion on the diversity of meaning of resilience.

- Educate stakeholders;
- Encourage consensus amongst actors;
- Coordinate and integrate natural hazard policies and projects with other social, environmental and economic objectives, preventing uncoordinated and potentially conflicting actions;
- Create transparency with community members; and
- Provide a reference point for development approvals and to benchmark implementation performance.

Because, as mentioned earlier, the dominant means of mitigation is through land use planning, sustainability is a key concept in mitigation planning, as land use has social and ecological implications, not just economic (Godschalk et al., 1998).

With regard to frameworks that have described a formal process by which a mitigation plan is developed, this report reviews three frameworks developed by Burby (1998b), Godschalk et al. (1998) and Kreibich et al. (2014b).

Both Burby (1998b) and Godschalk et al. (1998)'s frameworks were published in the same book (Burby, 1998a). Although both describe the process of forming and implementing mitigation plans, the focus of their frameworks differ subtly. Flowcharts, depicting the processes in each of these frameworks, are given in Fig. 2 (a) and (b), respectively. As can be seen, Burby (1998b) develops a plan that begins with the formation of a committee that assists in the development and implementation of the plan, while Godschalk et al. (1998) focus more on the activities that would need to be coordinated to develop a plan.



(a) Burby's (1998b) mitigation planning process

(b) Godschalk et al.'s (1998) mitigation planning process

(c) Kreibich et al.'s (2014) mitigation planning process

Figure 2. Overarching frameworks for the formation of mitigation plans. Redrawn from Burby (1998b), Godschalk et al (1998) and Kreibich (2014).

Kreibich et al. (2014b), on the other hand, develop a framework for an integrated continuous cost assessment for natural hazard risk. Although the authors do not claim their framework is for the formulation and implementation of a mitigation plan, it could be considered to be, as the framework includes phases covering contextualisation (which includes the identification of stakeholders and mitigation options), hazard assessment, decision support and the monitoring of implemented mitigation activities. The novelty of Kreibich et al.'s (2014b) framework is that it embeds these phases within the emergency management cycle, as shown in Fig. 2c, and therefore explicitly shows that mitigation planning is a continuous, long term process, and that mitigation planning requires activity in all phases of the emergency management cycle, not just in the periods bounded by recovery and disaster events.

In the following two subsections, two final aspects of mitigation planning are reviewed, which have been frequently discussed in the literature in recent decades. The first of these is the use of multiple objectives when assessing mitigation options and the second is the use of integrated approaches when making mitigation plans.

3.3. Multiple objectives in mitigation planning

As mentioned earlier, the favoured method of mitigating natural hazards in recent decades has been through land use policy. However, risk reduction is not the only criterion that needs to be kept in mind when land use plans are developed. Indeed, risk reduction has only recently been considered as part of land use planning in many jurisdictions (Schmidt-Thomé, 2006). Other objectives in land use planning include the facilitation of economic productivity (e.g. parcels of land may have significant value as they contain important commercial resources, or provide access to efficient transport networks), the maintenance of amenity (e.g. for residential estates), the desire to allow landholders free use of their property, and to increase social capital and environmental benefit (May and Deyle, 1998). Through reviewing numerous US state and local government mitigation plans, Godschalk et al. (1998) found that the following objectives were in common use, being:

- Protecting the safety of the community;
- Reducing private property loss;
- Reducing public property damage;
- Reducing government liability;
- Reducing vulnerability of lifeline facilities (e.g. hospitals, bridges, power plants);
- Minimising fiscal impacts;
- Minimising disruption of the economy and social networks;
- Ensuring equitable distribution of hazard management costs;
- Reducing environmental impact of hazard events;
- Maximising cost effectiveness; and
- Maintaining triple bottom line sustainability.

Clearly, there are many objectives when considering land use plans, many of which will be conflicting. This increases the difficulty of forming and implementing mitigation plans.

3.4. Integrated approaches to mitigation planning

The final aspect of mitigation planning considered in this review is the growing emphasis on integrated approaches. The term "integrated", however, takes on very different meanings depending on the perspective of the scholar, as shown in **Figure 3**.

For May and Deyle (1998), an integrated approach is one whereby policy and projects to mitigate a particular hazard are coordinated across a number of government institutions, private landholders and businesses. In this way, May and Deyle (1998) make an analogy between US natural hazard policy and a house that has been subjected to a number of changes/redesigns across several owners without a grand design:

"The various choices made by the federal and state governments in attempting to influence land use and development in hazardous areas are reflected in a diverse set of policies and programs. Most of these are aimed at influencing the ways in which local governments regulate land use or development. The various policies and programs resemble a house that has been subjected to numerous cosmetic fixes and redesigns over the years. Different owners and architects have added their perspectives on what would make it more liveable. New additions have been appended to the old structure to accommodate changing demands or preferences and different ideas about what constitutes good design. As a consequence, the system is awkward and inconsistent in design, and many of its parts do not function well. The house is better thought of as a set of overlapping structures than the product of any grand design."

The downside of non-integrated approaches for May and Deyle (1998) is that they create inefficiencies.

For Godschalk et al. (1998), integration refers to designing mitigation plans such that they fit with other community plans (such as for land use and infrastructure, for instance). Again, the reason for integrating community plans across a number of objectives is that it creates efficiencies and prevents contradictory policies/programs. Although there is some danger in this approach, as hazard mitigation can become lost in the range of other community issues (Godschalk et al., 1998).

Kreibich et al. (2014b) speak of integrated approaches in the sense that costings consider the entire natural hazard cycle, including direct, business interruption, indirect, intangible, and risk mitigation costs (see also Kreibich et al., 2014a). This approach is also integrated across time, in that it includes the monitoring of disaster response/recovery and mitigation costs, so that cost data quality can be improved.

Finally, Tate et al. (2010) and Tate et al. (2011) promote a multihazard integrated approach, whereby all hazards are considered simultaneously when assessing the potential losses in a particular region. Usually, different hazards are considered in isolation, with mitigation efforts largely based on the rank order of individual hazards. However, mitigation efforts should be concentrated in areas with the highest combined hazard vulnerability. In addition, this approach is favoured because some mitigation measures may reduce risk across multiple hazards, while some measures may reduce risk for one hazard while increasing vulnerability in another. This issue will be considered further in section 5.

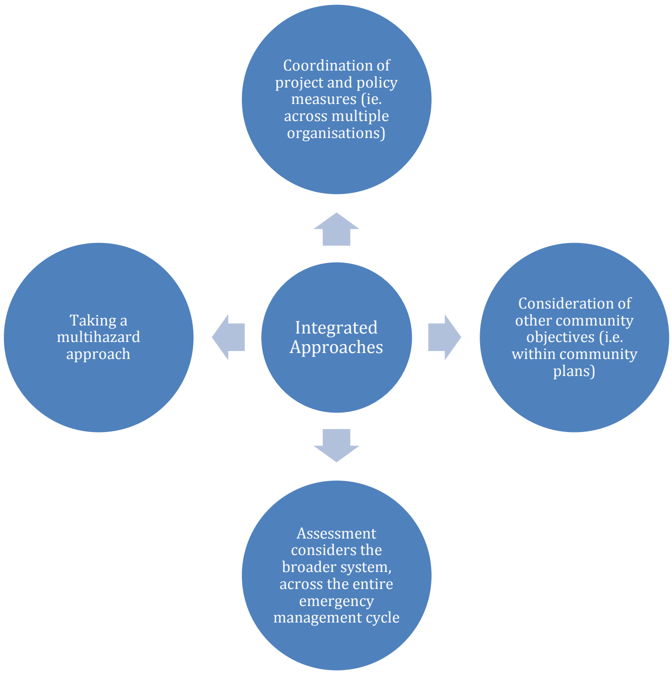


Figure 3. The various ways in which 'integrated approach' is referred to in emergency management

4. DECISION SUPPORT SYSTEMS

The focus in this section changes to decision support systems. First, a definition of "decision support system" is given. Based on this definition, a number of classification systems found in the literature for decision support systems are surveyed. Finally, important research directions for decision support systems, in general, are identified. The purpose of this section is to build a foundation from which to review individual research efforts at developing components needed for natural hazard decision support systems, which will be the focus of Section 5 of this report. The classification systems developed here will be crucial for organising the literature that has specifically focussed on natural hazard decision support.

4.1. What is a Decision Support System?

The term 'Decision Support System' (DSS) was first coined by Gory and Scott Morton (Gory and Scott Morton, 1971 cited in Keen and Morton, 1978). A DSS is an interactive software system that provides information from data and models in such a way to support decision makers to more effectively solve decision problems. Given this definition, a DSS does not replace a decision maker or necessarily make her/him more efficient. In addition, the purpose for which a DSS is used is not specifically defined, and may include unstructured, semi structured and, according to some scholars, structured tasks (Eom and Lee, 1990), as defined in Section 4.2. They are generally designed to allow the decision maker to consider more aspects of a decision (preventing tunnel vision), may generate better alternatives and analyse more alternatives (preventing suboptimal choices), allow the consideration of multiple scenario analysis and uncertainty (testing choices for their robustness, minimising regret, and making complex decision analysis more efficient), and might help explore the perceptions and values of the decision maker and/or stakeholders (Eom and Lee, 1990). Decision support systems differ from other computer-based information systems through the incorporation of management science and/or operations research tools.

4.2. Frameworks for Classifying Decision Support Systems

Given the definition developed in the previous section, DSSs can take on many different forms, and can be used in many different ways (Power, 2004). Therefore, systems to organise different forms of decision support systems are useful when analysing the decision support literature.

A number of scholars have sought to categorise DSSs. This was first attempted by Alter in his Phd dissertation (Alter, 1978), whose classification is based on the generic operations that a DSS is designed to perform, as shown in **Figure 4**. At one end of this classification are DSSs that predominantly retrieve information elements, while at the other end of this classification are DSSs that attempt to suggest (and sometimes, to automatically implement) an option (otherwise known as expert systems or knowledge-based DSSs). Across this classification is a progression from data-oriented to model-oriented DSSs.

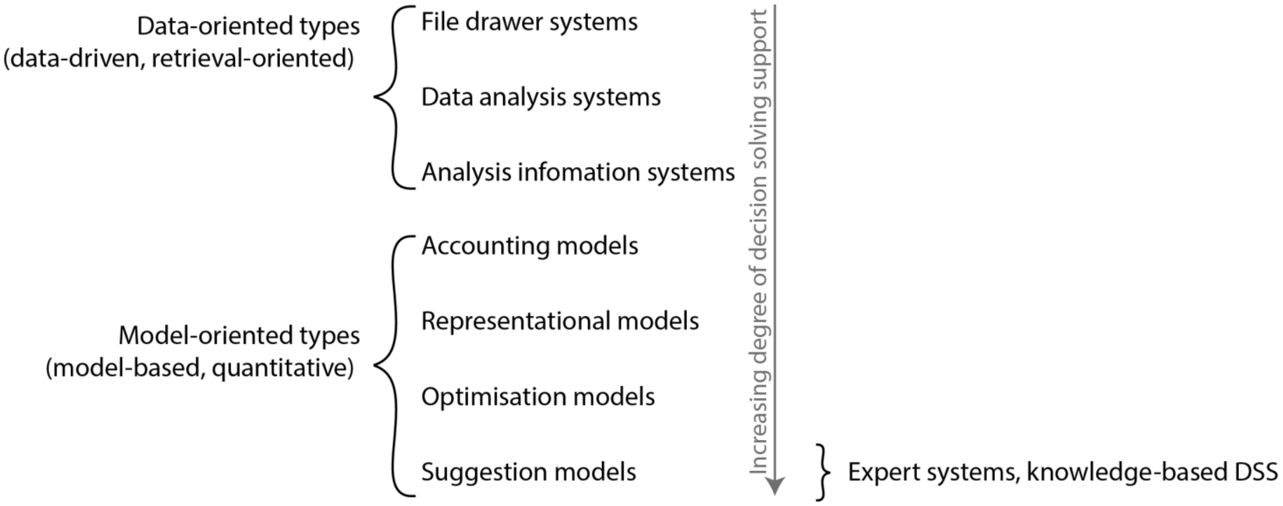


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Figure 4. Alter's classification for decision support systems.

Other classifications focus on management level, in relation to which DSSs may be categorised as predominantly supporting operational, tactical or strategic activities, as shown in Figure 4 (Eom and Lee, 1990).

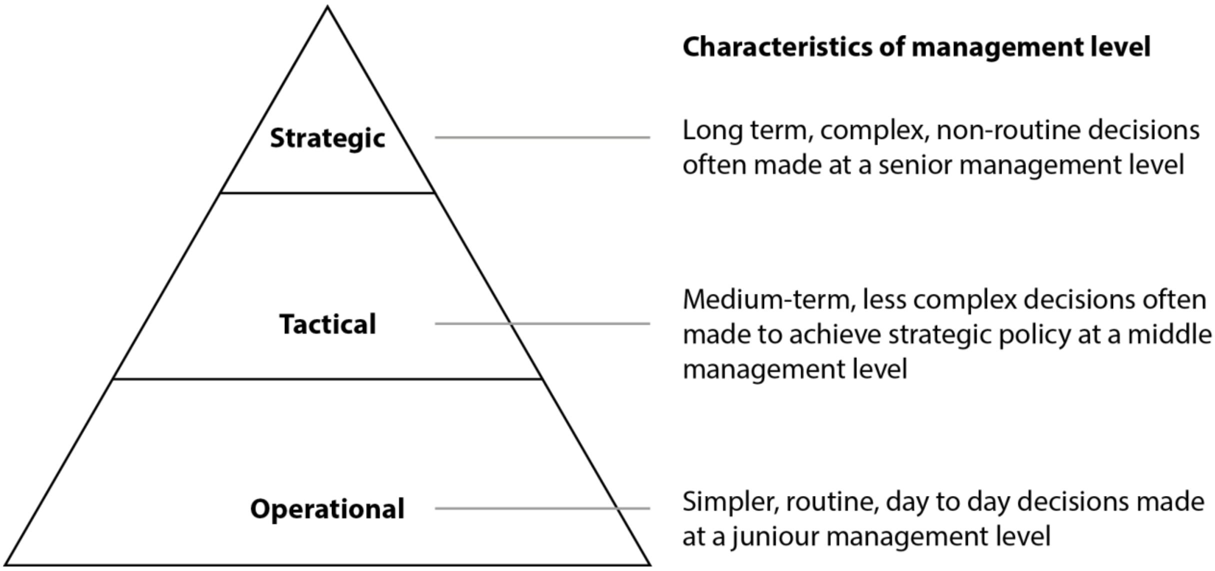

Figure 5. Classification of decisions by management level (adapted from Eom & Lee, 1990)

In addition to management levels, DSSs may also be classified according to decision maker interdependence and the level of structure in the decision making task. For example, Hackathorn and Keen (1981) classify DSSs based on whether the system supports individual decisions makers working on independent tasks, groups of individuals who are working on separate, but interrelated tasks (sequential), and organisation tasks involving a number of actors (pooled). The characteristics of DSSs supporting each of these three levels of interdependence will generally be different. For example, in sequential task dependency, DSSs may need to share information from task predecessors and pass on decision outcomes to task dependencies. In pooled tasks, multi criteria decision analysis will be relatively more important.

Decisions may be classified as either structured, semistructured, or unstructured (Gory and Scott Morton, 1971). Structured decisions are those that are routine, typically repetitive, with clearly defined objectives where standard solution methods may exist. These decision process can be explicitly described beforehand, and are often routine decisions such as maintaining emergency response appliances, or the securing of budgetary and legislative support for programs (Wallace and Debalogh, 1985). Unstructured decisions are those that are associated with fuzzy (more than one right answer), complex problems, where there is no “cut-and-dried” solutions, and none of the decision making phases (such as obtaining intelligence, design-inventing, developing and analysing possible courses of action, and making a choice from these possible courses of action) are structured. Examples include the decision to relocate populations, major recovery expenditure allocation, and actions to be considered in light of unexpected findings (such as geological faults under hospital facilities). The decision processes for semi-structured tasks include some phases that are structured, but also include phases that are unstructured, and include tasks such as the enforcement of zoning and similar standards (although determining the severity of penalties for zoning non-conformance may be structured, the gathering of data and assessment of zoning infringement in properties post development is not) and determination of priorities and needs (determining what goals/objectives should be considered is a structured task, but ranking them in priority order, is not; see Wallace and Debalogh, 1985).

Based on characterising DSSs by these three elements (management level, task structuredness, and task interdependency), Hackathorn and Keen (1981) introduced a three dimensional DSS space as a framework for classifying DSSs, as shown in Figure 6.

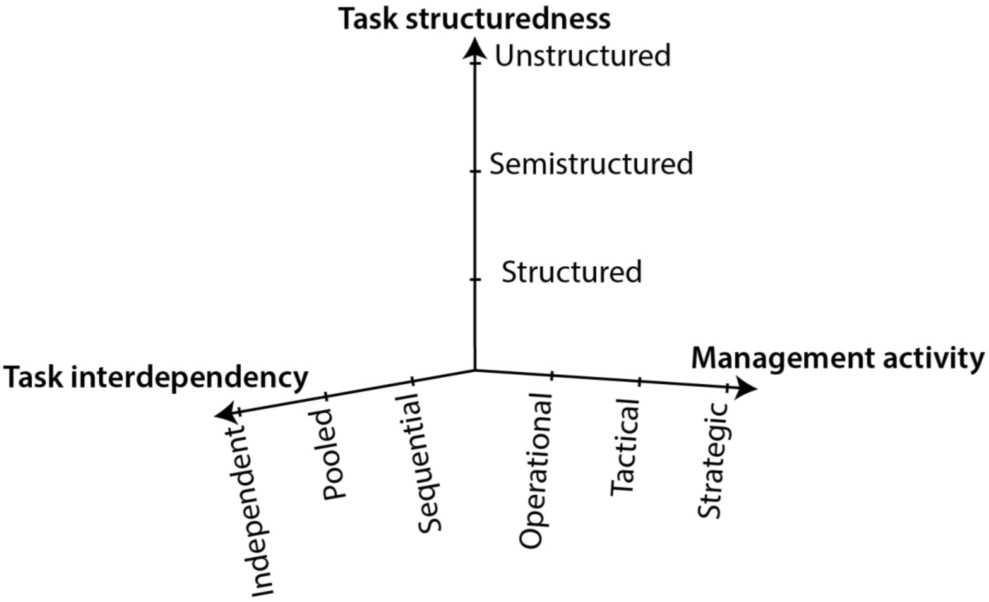

Figure 6. DSS classification framework with three dimensions — task, management activity and task interdependency. Adapted from Hackathorn and Keen (1981)

Although the classification frameworks presented here are dated, their use has continued to recent times (see, for example, Eom and Lee, 1990; Eom and Kim, 2006; Eom et al., 1998; Power, 2004). More recently, Power (2004) expanded on these frameworks to include document oriented and communication oriented DSSs as additional categories in Alter's classification, and added more dimensions to Hackathorn's DSS space concept. The two additional dimensions to the DSS space are DSS purpose and the technologies used to deploy and enable DSSs. DSS purposes may be function specific, task specific or general purpose, while Power (2004) notes that online DSSs deployed over the internet have become increasingly common. Although deployment may be largely a practical issue, rather than a research topic, a number of papers have been published in this area (for example, see Tate et al., 2011).

4.3. Overview of Research Directions and Focus in the Decision Support System Literature

Decision support systems have been developed since the early 1970s (Eom and Lee, 1990), and were originally focussed on corporate management functions for marketing, transportation and logistics, as well as production and operations management (Eom and Lee, 1990). Since then, decision support systems have been implemented across a diverse range of fields for a wide range of tasks, including those encountered in government agencies (e.g. allocating resources, assessing flood risk, cost-benefit analysis, developing policy, environmental planning, hurricane mitigation planning), and for natural resources and urban planning.

With regard to the use of operations research/management science tools, the earliest DSSs relied heavily on statistical analysis and model based scenario analysis. Over time, the incorporation of more complex and computationally demanding tools has become more frequent, including the use of integer programming techniques, network models, multicriteria decision analysis, nonlinear programming models, Markov process models and queuing models. During the last two decades, optimisation, rather than simulation based systems, have become more frequent, and the adoption of graphics, artificial intelligence and visual interactive modelling has emerged (Eom and Kim, 2006; Eom et al., 1998). More recently, web based interfaces have been developed, GIS data management and visualisation tools have been incorporated and negotiation support systems have emerged (Eom and Kim, 2006).

User interaction, through the graphical user interface (GUI) is a standard component of decision support systems. The interface should be designed to help decision makers engage with the problem and prevent the blind acceptance of DSS outputs. Research has shown that the ability to create, manipulate and use visual images within a DSS that are designed in line with the decision making process increase a user's ability to structure their decision problem, and ability to problem solve (Loy, 1991).

The evaluation of decision support systems after their release is also important. Too often, DSS uptake has been low, and this may be related to the quality of systems that have been developed (Diez and McIntosh, 2009; McIntosh et al., 2011). Therefore, evaluating the value of decision support systems to endusers is useful to gauge how well a system achieves its purposes, and what changes are required in order to meet user needs. Sojda (2007) states that it is irresponsible not to do so for new DSSs. Toward this end, including endusers throughout the DSS development process is also beneficial, as demonstrated by Lautenbach et al. (2009), and Oxley et al. (2004).

There have been a number of studies that have developed metrics to evaluate DSS quality. For example, Sun and Kantor (2006) introduce the cross-valuation technique, which makes use of statistics to determine system quality based on end user opinion regarding the system's utility in helping them achieve task goals. Sojda (2007) develops an evaluation framework that takes into account the verification and validation of underlying DSS models. These two studies reflect the two areas that need evaluating when reviewing DSSs — (1) the effectiveness of the DSS in providing information that is helpful for decision makers, and (2) the ability of DSS processes to provide information that is sufficiently accurate and precise for the decision to be made. Therefore, DSS evaluation should use multi criteria techniques, as has been done by Phillips-Wren et al. (2004), Phillips-Wren et al. (2009), Wang and Forgionne (2006), and Wang and Forgionne (2008) using analytic hierarchy processes. All of these evaluation processes should involve evidence from end-users, such as that emphasised in Inman et al. (2011).

To ensure that a DSS is effective in aiding decisions, and therefore to increase the likelihood of its adoption amongst decision makers, it is important that the DSS development procedure is geared toward end-user acceptability. van Delden et al. (2011) offers a development framework that can guide in this matter, as will be discussed in the next section. In addition to these frameworks, McIntosh et al. (2011) identifies the following recommendations to ensure DSS adoption:

- Use champions to promote the DSS in their respective organisations;
- Create a plan for end user adoption and continuing DSS support;
- Actively build capacity to use the system within end user organisations;
- Be open and honest to end users regarding system capability;
- Minimise costs by making clear what objectives and functionalities the DSS will fulfil, therefore preventing scope creep;
- Reduce requirements for expensive training or software licenses; and
- Design intuitive user interfaces which, for example, are consistent, provide permanent and instructive feedback, minimise opportunity for input and parameter error, and minimise the mental load of endusers (Shneiderman et al. (2009) cited in McIntosh et al., 2011).

4.4. DSS development frameworks and recommendations

The following discussion focuses on guidelines for the development of decision support systems, as taken from the literature. These guidelines are primarily relevant to the development of DSSs that are integrated modelling systems for planning and policy support. Integrated modelling systems for planning and policy support should (van Delden et al., 2011):

- Support policy relevant questions;
- Focus on long term and strategic issues;
- Facilitate group interaction;
- Facilitate effective decision outcomes in complex, poorly-structured or wicked decision problems, which have a large number of actors, factors and relations, and are characterised by high uncertainty, and conflicting interests amongst actors;
- Incorporate intuitive interfaces between endusers and software;
- Integrate interdisciplinary data and process knowledge;
- Operate on different temporal and spatial scales and resolutions as appropriate;

- Adequately capture system dynamics, including feedback loops, including those that occur between individual models; and
- Be built using flexible and modular software systems that can be efficiently maintained, extended and adapted to similar case studies.

The framework van Delden et al. (2011) presents for the design, development and implementation of such DSSs is given in **Figure 7**. This framework consists of three aspects. **Figure 7**a describes the relationship between the main parties involved in DSS development, and is used to describe the responsibilities of each party and identify communication blocks that could hinder the development process. **Figure 7**b describes the development process as being iterative (or in other words, evolutionary) instead of a waterfall. **Figure 7**c orders the tasks that are required in DSS development, but incorporates the iterative nature of these tasks, which arises through the iterative development paradigm.

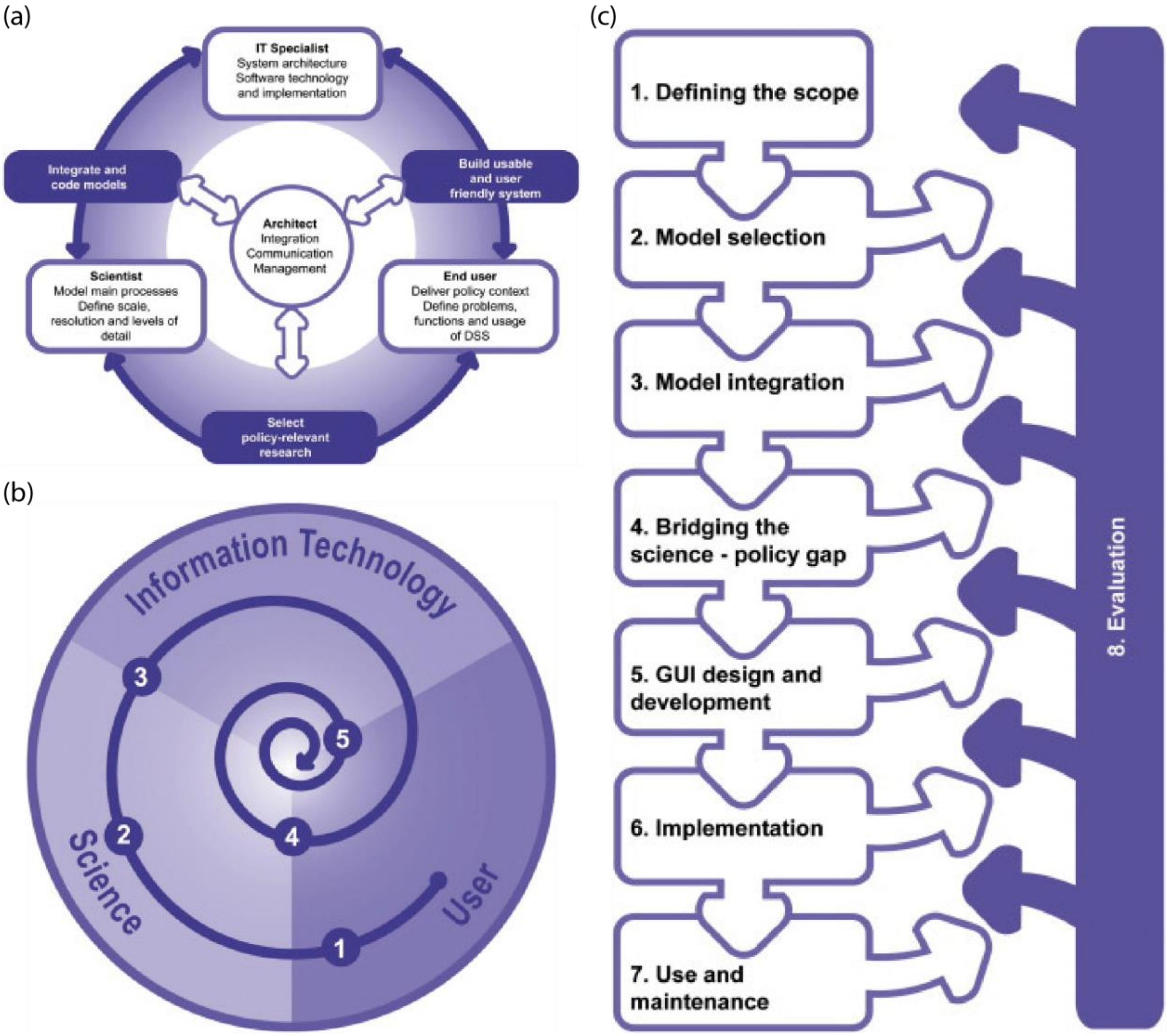

Figure 7. Decision Support System Development Framework developed by van Delden (2011).

As shown in **Figure 7**a, there are three main parties in the development of DSSs, including end users, scientists and IT specialists. In an ideal development environment these three parties are involved in an iterative process of communication and social learning. Interaction between these three parties is just as important as communication within each party. Together, end-users and scientists select policy relevant research and models that are capable of informing the decision making process, identify model inputs required for these models, and link model outputs to policy-relevant indicators. Scientists and IT specialists work together to implement new models, integrate models into a single modelling system, and ensure consistency throughout the system, and IT-specialists work with end users to set up an interface that enables users to select and understand model inputs, parameters, and outputs at the appropriate level of detail.

Given the differences in responsibilities, language, and background between the three parties, van Delden et al. (2011) stresses the importance of a fourth role, the DSS architect(s), for successful development. The architect is a generalist who facilitates communication between the parties, manages the process, and therefore ensures integration of the three parties by bridging the methodological and knowledge gaps between end users, IT specialists and scientists.

The interaction between these three parties allows each group to gain a better understanding of the needs of the end-users, the process issues and limitations identified by the scientists, and the software design difficulties faced by the IT specialists. An understanding of these issues allows each party to better offer their expertise to solve these difficulties. For this understanding to have full effect, an iterative approach, as represented in **Figure 7**b is suggested. First, the process ideally starts with the end users who have a need for a DSS. With the initial goals and requirements of the system established, relevant knowledge from the scientists is used to develop a first prototype by the IT specialists (see also Belardo and Karwan, 1986). Feedback is then obtained on this prototype by end users, thus completing the first iteration of development. This process continues, even after the release of the first production version, for extensions of the system or refinement of constituent parts may prove desirable, thus beginning new development cycles. The ultimate aim of this development approach is to produce a system that is useful for policy makers and planners, which incorporates robust scientific knowledge, and is approachable through a user-friendly software package.

This approach is participatory, which is important, as a growing body of research indicates that system adoption is correlated with end user involvement. Concerning this, McIntosh et al. (2011) makes the following recommendations for involving end users:

- Identify end users, stakeholders, clients, etc., and the responsibilities of each party, to avoid misunderstandings and disagreements in the future;
- Invest time and resources into understanding the requirements and organisational context of end users, using methods such as Contextual Development (McIntosh cites Beyer and Holtzblatt, 1997) and usability assessment (McIntosh cites Tullis and Albert, 2008);
- Evaluate the cost effectiveness of the DSS compared to other means of achieving the aims of the parties involved in DSS development, and make exit strategies, accordingly to ensure that the development process can be considered a success;
- Include stakeholders in the report writing process, by providing opportunities to contribute to, and challenge model assumptions;
- Include and effectively communicate uncertainties in the modelling process through the DSS interface;
- Provide feedback to parties regarding how their input has been incorporated into the DSS design;

- Recognise that end user interaction is an active, not a passive process, and the crux of effective DSS design. In this regard, consider including social scientists and other relevant personnel to provide better understanding of the human factors involved in DSS design.

Figure 7c distinguishes tasks that are involved in DSS development, and the relationship between tasks.

The first step in this procedure is defining the scope of the DSS. This should not only consider the problems of today, but also envisage future needs. Scoping documents, such as strategy papers, help in communicating issues raised and decisions made to involved parties. These documents are best kept updated during the development processes to give structure to the workflow. In scoping, overarching themes should be identified, and the DSS should be designed around these, resulting in a more flexible DSS that is able to serve over the long term. In addition, external factors, which policy makers cannot influence, and policy measures they can implement should be identified, in addition to indicators that provide some quantitative/qualitative measures of change in outcomes.

In the next phase, scientists generally take charge of model selection. This selection can be made with the aid of a conceptual diagram that demonstrates the main components and their linkages. Important criteria and information for choosing models include:

- The inputs and outputs of each model component;
- The level of model complexity;
- The spatial and temporal scales;
- Data availability for inputs and parameterisation of models;
- Availability of models; and
- Time and cost required to set up, calibrate, and validate models.

Jakeman et al. (2006) list additional factors for consideration when choosing models, including :

- The accuracy expected or hoped for; and
- The flexibility to be reconfigured to explore new scenarios.

The third phase is model integration, which often involves scientific and technical challenges related to models that represent processes operating on different time and spatial scales and resolution, and models developed using different modelling paradigms. However, integrating models is important, so that feedback loops can be adequately represented. These feedback loops are involved in reinforcing effects and understanding the side effects of different policy and project alternatives.

Bridging the science-policy interface is one of the crucial elements of DSSs, as it creates the link between the objectives and usefulness of the DSS, as scoped in phase 1, with model selection and integration in phases 2 and 3. This involves users and developers working together as co-producers in a social process that aims to bring understanding of the policy practise and process in which decisions are made, and the potential and limitations of DSSs in aiding these practices and processes. In regard to DSS interface, this phase will bring clarity regarding indicators, which evaluate policy effectiveness from model outputs, how users will use these indicators to assess the sensitivity of policy/project alternatives under different scenarios, and how scenarios will be specified by users.

The fifth, sixth and seventh phase of DSS development are the creation of a graphical user interface (GUI), implementing the DSS, and the use and maintenance of the DSS, respectively. The GUI should be easy to use and provide access to an appropriate level of detail, to the policy options, external factors, model parameters, and scenarios that define a model simulation. Implementation issues surround where to best place the DSS, whether within the organisation of policy making institutions themselves, or within consultant organisations. This often needs to be at a rather high level, as many organisations are organised in a very sectorial way where integration occurs at a rather high political level. Use and maintenance involves keeping the system up to date with recent data, and modifications to support new policy directions.

In regard to improving this development process, as just described, McIntosh et al. (2011) offer the following additional recommendations:

- Creating a business plan to outline costs and outcomes;
- Developing DSS tools incrementally using known technology;
- Developing a systematic way of ensuring raw data accuracy; and
- Developing efficient ways of extracting and combining data or using models to provide necessary data that do not exist.

5. DECISION SUPPORT SYSTEMS FOR NATURAL HAZARD MANAGEMENT

The goal of this section is to survey the literature that has contributed to the development of natural hazard decision support systems. This section is structured as follows: First the development of natural hazard decision support system research in the literature is set out. From this, two research themes are identified which are subsequently reviewed in detail, being: (1) the integration of multiple hazards within mitigation assessment, and (2) the use of optimisation to identify efficient mitigation options.

5.1. Development of Natural Hazard Mitigation DSSs in the Literature

The adoption of decision support systems for aiding natural hazard management was first reported in the literature in the early 1980s. Salvatore Belardo and William Wallace, academics from the United States, were amongst the first implementers of such DSSs for natural hazards (e.g. Belardo et al., 1984a; Belardo et al., 1984b; Wallace and Debalogh, 1985).

At this time, Belardo made a number of important contributions to the development of decision support systems for natural hazard management. In 1984, Belardo et al. (1984b) realised that the flexibility of software development, and efficiency of computation on personal computers could provide decision support for disaster management. In the same year Belardo et al. (1984a) also investigated the unique challenges of building decision support systems for natural hazard management. Finding that natural hazards are characteristically low-frequency events but with potentially high consequences, he recommended that support systems for natural hazard response should allow simulation of disaster events, as this not only allows for training and research (important given their characteristic low-frequency and therefore lack of experience that decision makers have in responding to events), but also helps further develop and refine prototype systems. In 1986, Belardo and Karwan (1986) were the first to demonstrate the validity of using a prototyping based development strategy for decision support systems for disaster management. However, it should be noted that Belardo's research predominantly focused on supporting emergency response, rather than mitigation decisions. This emphasis on response over mitigation has continued to the present in the decision support system literature.

It was Wallace and Debalogh (1985) who first considered decision support systems across all the preparedness, mitigation, response and recovery phases of disaster management, and introduced a framework for building decision support systems across these phases, which included (1) the identification of components that make up disaster management DSSs, consisting of databases, data analysis tools, models and a user interface, and (2) a delineation of data, modelling, and software requirements for DSSs supporting each phase of the disaster management cycle. In this paper, Wallace and Debalogh (1985) identify that mitigation DSSs address the following questions:

- What is the nature of the hazard?
- What is the probability of occurrence with various magnitudes of adverse effects?
- What are the area and population-at-risk and their vulnerability?
- What are the cost implications of the risk?
- What are the time constraints?
- "How safe is safe enough?"
- "What if" we follow such a policy?

- What alternatives do we have and what are their consequences?

In addition, this paper introduced the first mitigation DSS that is published in the literature (an earthquake DSS for Los Angeles that assesses different policy options relating to the improvement in earthquake resilience of present and future buildings).

A literature search using the Thomson Reuters Web of Science database for paper titles including "disaster" and either "decision support" or "DSS" returned 79 papers which were published after Wallace and Debalogh's (1986) article, of which 56 concerned the use of DSSs for natural hazards. Of these 56 papers, only 19 concerned disaster planning (refer to Figure 8), which highlights that more research effort continues to be spent on operational aspects, as opposed to strategic planning for hazard reduction, a similar result to that found by Eom and Kim (2006) when reviewing DSSs more generally.

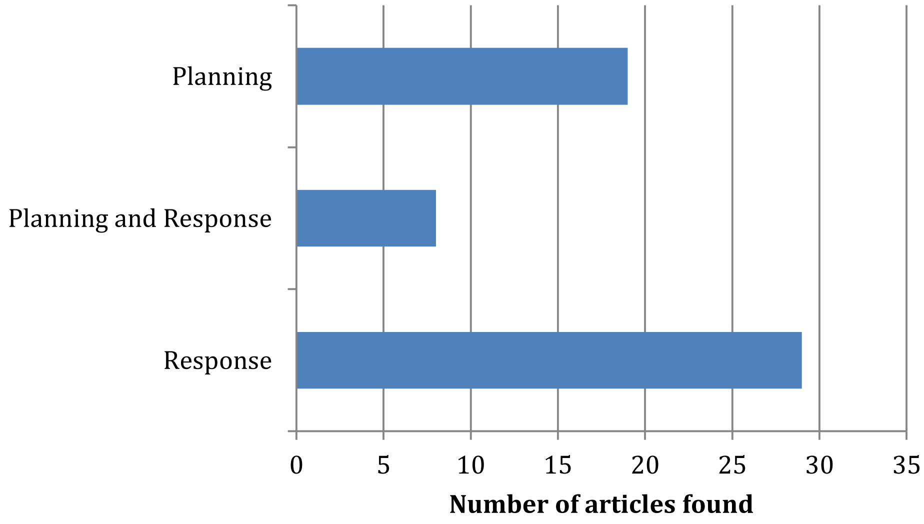

Figure 8. Number of articles that considered natural disaster planning or response that had titles including "disaster" and either "decision support" or "DSS", within the Thomson Reuters Web of Science database.

Table 1 provides summaries of the articles that considered planning aspects of natural hazards. A number of research directions can be observed in these papers. For example, a number of authors have developed ways in which to increase knowledge and understanding from data and information, so that better decisions can be made (Cui et al., 2009; Iliadis and Spartalis, 2005; Lee and Torpelund-Bruin, 2008; Min-Yuan and Chien-Ho, 2000; Othman and Beydoun, 2010; Pham and Kamei, 2012; Tinguaro Rodriguez et al., 2011; Wei et al., 2003), while others have focussed on how new information technologies can make better DSSs (Buraga et al., 2007; Cioca et al., 2007; Levy et al., 2005; Lin et al., 2004). In addition, some authors have presented DSSs for predisaster planning with the objective of improving response and relief (Dobson, 1986; Kumar and Havey, 2013; Levy et al., 2005; Zheng et al., 2010; Zhi-Hua, 2010). Furthermore, a number of authors have presented DSSs for the assessment of vulnerability through the use of models (Buzolic et al., 2002; Feng et al., 2004; Jena and Sahoo, 2007; Li et al., 2003; Li et al., 2005; Min-Yuan and Chien-Ho, 2000; Qing and Qiang, 2007; Tong et al., 2008; Yang and Zhang, 2007). However, of these, only Buzolic et al. (2002), Kumar and Havey (2013), Li et al. (2003), Tong et al. (2008) and Zheng et al. (2010) explicitly considered mitigation measures, although Tong et al. (2008) only considered short-term management options. Tellingly, only Zheng et al. (2010) and Li et al. (2003) have made use of formal optimisation techniques and therefore there has been little research into mitigation decision support systems that provide the greatest levels of decision support according to Alter's classification, as shown in Figure 4. In addition, only Buzolic et al. (2002) and Feng et al. (2004) have taken a multihazard approach, and no author has explicitly considered long-term changes in climate, demographics, the economy or landuse in their DSSs. These are significant limitations, as this literature review has already shown. Therefore, the final two sections of this chapter will consider work relating to the development of multihazard approaches and the use of optimisation to help identify and select mitigation options.

Table 1. Summaries of papers in the literature that considered decision support systems for planning aspects related to natural hazards

Kumar and Havey (2013)	Plans communication networks between organisations in the supply chain, before a disaster event, to improve efficiency during response/recovery.
Pham and Kamei (2012)	Aggregates multiple expert decisions to better reduce risk pre and post disasters.
Tinguaro Rodriguez et al. (2011)	Assesses the consequences of disaster scenarios in data scarce situations. Although focussed on disaster response, the SEDD DSS enables the study of "what if…?" disaster scenarios to draw vulnerability maps to support the design of mitigation policies.
Zheng et al. (2010)	Uses hydrodynamic models and GIS to assess flooding risk, and uses formal optimisation techniques to plan evacuation routes to reduce losses before a disaster event occurs (Shanghai case study).
Zhi-Hua (2010)	Models the monitoring network, simulates contingency events, and keeps stock of emergency resources for oil spill disasters.
Othman and Beydoun (2010)	Develops metamodels that capture decision maker expertise. Could be used for all phases of the emergency management cycle.
Cioca and Cioca (2010)	Reviews and introduces the topic.
Cui et al. (2009)	Generates hyetographs from rainfall station data for flooding mitigation decisions.
Tong et al. (2008)	Models risk and losses from grassland fires, and includes a management DSS module.
Lee and Torpelund-Bruin (2008)	Develops a robust framework/technique for geospatial enquiries, with usefulness both in planning and response.
Buraga et al. (2007)	Uses grid based architecture for assisting the prevention of natural disasters using information and communication technology.
Jena and Sahoo (2007)	Delivers data on hazards in the Orissa region in India (e.g. regarding buildings, life lines, and critical facilities) and evaluates hazard risk.

Yang and Zhang (2007)	Presents a system design for a DSS that assesses flood risk and supports decisions throughout the emergency management cycle.
Cioca et al. (2007)	Presents the need for a disaster loss prevention DSS, and discusses IT technologies to achieve this, including models and GIS to support information retrieval and risk assessment for decisions such as locating public infrastructure.
Levy et al. (2005)	Discusses the components of flood DSSs (databases, hydrological and hydrodynamic models and user interface), and the various technical options available for these. Surveys the use of such DSSs in China, with a focus on forecasting flood disasters such that protection measures can be deployed.
Iliadis and Spartalis (2005)	Forecasts and assesses bushfire risk and the spatial extent of burning for planning short-term risk reduction measures.
Li et al. (2005)	Estimates earthquake losses using GIS technology for disaster prevention planning.
Lin et al. (2004)	Assesses flood risk to enable more efficient operation of insurance firms, through integration of GIS, remote sensing and GPS technology.
Feng et al. (2004)	Develops a multihazard assessment system incorporating fire, earthquake and flood assessment and a database of infrastructure properties, that uses GIS technology to enhance impact reduction activities.
Li et al. (2003)	Optimises highway renovation schemes for reducing debris flow risk in mountainous regions.
Wei et al. (2003)	Estimates slope stability and slump risk for land use planning using triangular irregular network mesh of terrain.
Min-Yuan and Chien-Ho (2000)	Uses fuzzy set theory to enable residents to assess hillside collapse risk, so that appropriate measures can be taken to prevent slumping events.
Dobson (1986)	Enhances decision processes for disaster early warning for the reduction of vulnerability.
Buzolic et al. (2002)	Evaluates vulnerability of a telecommunication system to earthquake, floods, weather, and bushfires, and considers interventions to reduce vulnerability through the use of optic fibre rings and SDH equipment, positioning of GSM towers and other telecommunication infrastructure, and prioritisation of users.

Before we consider the development of multihazard and optimisation approaches, additional literature pertinent to decision support systems for natural hazard mitigation, which was not covered in Table 1, is now reviewed.

The Land Use Portfolio Model is the most similar DSS to what this project will deliver, and was designed to help understand and reduce vulnerability and risk of natural hazards (Bernknopf et al., 2006). This software tool has been developed by the US Geological Survey, and is used for modelling (using HAZUS-MH), mapping (using ArcGIS) and communicating risk. Using an evaluation methodology based on financial-portfolio theory, the system estimates a number of economic and loss metrics for a user selected portfolio of mitigation options.

In recent times, a number of Australian researchers have also been developing DSSs for natural hazard applications. For example, the Bushfire Cooperative Research Centre (Bushfire CRC) has developed the Fire Impact and Risk Evaluation Decision Support Tool (FireDST) and Melbourne University in partnership with NICTA have been developing an intelligent disaster decision support system.

FireDST was developed under the Bushfire CRC in collaboration with Geoscience Australia, CSIRO, the Bureau of Meteorology, and Melbourne University, and integrates weather, bushfire, smoke plume and building damage models to understand the likely spread and damages caused by fire events (Cechet et al., 2014). It is primarily intended as an operational tool to help decision makers allocate firefighting resources and make evacuation plans. As with many models for operational support, the system support mitigation planning by using it to answer a number of what-if questions/scenarios.

The University of Melbourne and NICTA have been developing a number of decision support platforms for natural disasters, including the Holistic decision-support Platform for Emergency Services in Australia (NICTA HOPES) , Watch-out (which is a realtime risk information system build around social media observations), the Hazard Prediction and Vulnerability Assessment Tool for First Responders (HPVAT), and the Australia Disaster Management Platform (ADMP) (Ngo et al., 2012). Under the Bushfire and Natural Hazards CRC, Melbourne University in collaboration with Deakin University are developing a predisaster multihazard damage and economic loss estimation DSS.

5.2. Multihazard Integrated Approaches to mitigation

Taking a multihazard approach to mitigation is important, as it is widely recognised that there is interaction between different hazards types and mitigation measures. For example:

1. Some mitigation options may reduce losses across multiple hazard types. For example, a mitigation effort, such as strengthening a building for earthquake mitigation, may also improve wind resistance.

2. A mitigation option for one hazard may lead to heightened risk for another. For example, policy to discourage development in periurban fringes adjacent to natural vegetation to reduce bushfire risk may result in development within areas more susceptible to flooding.

3. A mitigation option may reduce risk resulting from small natural disaster events, but may increase risk from larger natural disaster events, or transfer the risk spatially. For example, structural measures, such as levees, reduce the risk of flooding for events below their design specification. However, for larger floods, levees can cause greater losses should failure occur. In addition, levees reduce flood plain storage and therefore often increase flooding risk downstream.

4. Natural disaster events of different hazard types are often causally linked (Marzocchi et al., 2012b). For example, there is increased tsunami, urban fire and landslide risk after an earthquake (Bommer and Rodríguez, 2002; Chang et al., 2007; Keefer, 2002), and increased flooding risk after a bushfire. In addition, flooding and storm hazard are often correlated, as they often have the same climatic drivers (e.g. cyclones). The

importance of taking a multihazard approach is recognised in many government emergency planning reports (e.g., FEMA, 2008; Government of South Australia, 2014), and in software packages such as HAZUS-MH (Scawthorn et al., 2006a; Scawthorn et al., 2006b; Schneider and Schauer, 2006; Vickery et al., 2006a; Vickery et al., 2006b) and RiskScape (Schmidt et al., 2011). However, it would seem this approach is infrequently adopted in practise or in the literature. This may be due to the difficulties related to the ability to conduct multihazard assessments, which have been identified by Kappes et al. (2012a) as:

- The calculation of a single 'risk' index based on multiple hazards that have very different natural processes, scales, units and measures;
- Hazards are interacting processes within geosystems, and cannot be considered as independent of one another. Models are required to deal with hazard interactions that result in amplified risk or differing patterns, in addition to hazard chains and cascades;
- The vulnerability of elements in the built environment, institutions and communities is assessed in very different ways according to the hazard type and the particular element at risk; and
- The difficulty of visualising multidimensional results to enable effective communication.

Most multihazard studies have focussed on the mapping of a number of natural hazards, but have not extended to the assessment and selection of mitigation options, as summarised below:

- Granger et al. (1999) mapped earthquake, landslide, flood, cyclonic wind, coastal surge risk for Cairns. However, no synthesis of the risk across hazards was conducted.
- Grünthal et al. (2006) calculated the loss due to windstorm, flooding and earthquake for the city of Cologne using a common economic assessment which estimated the costs of damage to buildings and contents, across a number of average return intervals ranging from the 1:10 year to 1:100,000 year events.
- El Morjani et al. (2007) mapped the spatial distribution of flood, landslide, wind speed, heat and seismic hazard over the Eastern Mediterranean and Northern Africa region, and aggregated this information into a single, spatially explicit index of overall risk, to aid decision making, using a weighted average approach.
- Thierry et al. (2008) mapped a number of geologic risks in the region surrounding Mount Cameroon (volcanic, seismic and landslide). Based on the frequency and intensity of these hazard types, five hazard classes were developed as a standardised way of comparing the risk of different hazard types. For each location in the region, the hazard level was mapped according to this classification. The net hazard at each location was taken as the maximum hazard class over all the hazards considered. Rather than using a classification system to standardise risk across multiple hazards, indicator based methodologies have also been developed, such as that used in Kappes et al. (2012b), Ferrier and Haque (2003), and Blong (2003), who developed a damage index for buildings in Australia for a number of different natural hazards, including tropical cyclones, tornados, hail, earthquake, bushfire, flood and tsunami.

As identified by Kappes et al. (2012a), one of the difficulties of implementing multihazard studies was capturing the interactions between different hazard types and mitigation options. Marzocchi et al. (2012a) developed a methodology for conducting multihazard studies that took into account the interaction between hazards. Because it becomes mathematically and computationally unwieldy to consider all hazards and their interactions in risk assessment studies, the authors propose that a number scenarios be developed that adequately capture this interaction using a Bayesian event tree approach. Another approach to including hazard interactions uses tables or matrices that describe or classify the nature of interactions between each hazard, such as that developed in Tarvainen et al. (2006) and De Pippo et al. (2008).

Multihazard analysis necessarily extends beyond understanding the interactions between hazards, for the vulnerability of elements at risk is also modified when hazards occur simultaneously. For example, if a building is simultaneously subjected to flood and wind hazard, then the loss will likely be more than if only the flood or wind hazard occurred by themselves, and less than the sum of both losses. Hazards that occur sequentially in a small time period also modify the vulnerability of buildings. For example, when a landslide follows shortly after an earthquake, the damages can be greater than the sum of the two hazards if they occurred a longer time apart, as the earthquake left the building in a more fragile state when the landslide occurred. Studies focussing on the effects of overlapping and sequential hazards on vulnerability are scarce in the literature (Kappes et al., 2012a), and methodologies for their assessment have not been extensively tested, although dual factor vulnerability functions have been implemented in the HAZUS model.

Only one paper was found that incorporated mitigation within a multihazard approach that was tailored toward decision support. In this paper, Li and Ellingwood (2009) developed a multihazard assessment framework for wood-frame residential buildings which considered both wind loading from hurricanes and shaking from earthquakes. The framework is designed to aid the development of building standards.

5.3. Optimisation of Mitigation Measures

In the literature, two main approaches to employing optimisation for the selection of mitigation options are evident. The first attempts to simplify the problem formulation so that conventional optimisation techniques can be used that are guaranteed to find the global optima of the simplified problem. The second approach maintains a realistic formulation of the problem, which normally requires the use of complex simulation models, and utilises artificial intelligence techniques as the optimiser. While the use of these AI techniques has been shown to find solutions that are close to the global optima of the more realistic formulation, they cannot be proven to be the global optima. Most of the research effort has focused on the former approach, with works published in the last fifteen years surveyed below.

Researchers at the International Institute for Applied Systems Analysis (IIASA) have combined the use of models, optimisation and decision support systems to help develop mitigation strategies. In Amendola et al. (2000) and Ermoliev et al. (2000c), an optimisation approach that took the space-time dynamics of natural hazards, policy mechanisms, and dependency between different disaster events and mitigation measures into account was presented. In Ermoliev et al. (2000a) and Ermoliev et al. (2000b) this approach was illustrated using a case study that considered insurance premiums and risk spreading through reinsurance and catastrophe bonds in relation to earthquake hazard in Irkutsk, Russia. The research at the IIASA was later extended to earthquake risk in Italy and flood risk in the Upper Tisza River region in Hungary (Ermoliev et al., 2013).

The methodology developed by the IIASA used the second approach to optimisation, where a realistic formulation was maintained. In these case studies, a spatially explicit model was used, that incorporated Bayesian nets to characterise the dependency between disaster events. This model was coupled with a Monte Carlo approach to optimisation, whereby decision variables were adaptively adjusted to obtain better outcomes with respect to objective functions.

Although related to mitigation, the approach undertaken at the IIASA focussed on financial instruments, particularly insurance. In contrast, over the last decade, Rachel Davidson and her collaborators have developed optimisation approaches that focus on mitigation decisions from a public policy perspective. Also in contrast to the approach at the IIASA, Rachel Davidson has tended to take the first approach to optimisation, whereby the problem formulation is simplified so as to use conventional optimisation techniques that are guaranteed to find globally optimal solutions, as listed below:

- Dodo et al. (2005) presented a linear programming model that optimised the level to which buildings of particular structural and occupancy types, in each census tract within a study region, were retrofitted in order to minimise the sum of the present value of retrofit and post-disaster reconstruction expenses. There were 125,000 decision variables in the formulation of this linear programming model.
- Due to the large size of the optimisation problem presented in Dodo et al. (2005), Dodo et al. (2007) compared two efficient optimisation algorithms for solving this problem — a Dantzig-Wolfe decomposition approach and a greedy heuristic approach. The greedy heuristic was shown to provide comparable solution quality to the Dantzig-Wolfe decomposition approach, but at much less computational expense.
- In Xu et al. (2007), the problem formulation was extended, such that future reconstruction costs were estimated using a stochastic model that estimated the variability in annual earthquake loss across a number of scenarios, which enabled the use of an objective function that considered the likelihood of an unacceptably high economic loss resulting from any one earthquake within the planning period, in addition to the expected cost of mitigation and future earthquake losses. These two objectives were combined using a weighted average method and solved using a Dantzig-Wolfe decomposition approach.
- Vaziri et al. (2010) modified the approach of Xu et al. (2007) such that damaged buildings are not necessarily reconstructed immediately after an earthquake (thus making it more suitable for weaker economies or in situations where earthquakes cause such widespread damage that reconstruction within the one year time step of the model is not feasible). Vaziri et al. (2010) also introduced an additional constraint that prevented mitigation solutions with extremely high death tolls resulting from any one earthquake within the planning period[2].
- Apivatanagul et al. (2012) and Li et al. (2012) adapted the approaches outlined above for hurricane evacuation studies. To do this, they developed an integrated hurricane evacuation model consisting of a traffic assignment submodel and an optimisation submodel, for the formulation of evacuation plans. The models were demonstrated using case studies in North Carolina, where risk and evacuation

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[2] Compare this with the approach in Xu et al, 2007, where an objective very similar to this constraint was used, which minimised the likelihood of extremely high economic loss from any one earthquake event.

travel time were minimised. Decision variables in these case studies were spatially explicit and included who should evacuate and who should remain (shelter-in-place), when evacuation should commence, and where evacuees should go.

- Although there has been much work on developing simulation and optimisation models for evacuation (e.g. Cova and Johnson, 2003), these have tended to focus on emergency response. In contrast, the work of Apivatanagul et al. (2012) and Li et al. (2012) contribute to the mitigation literature, because making plans for evacuation before a disaster strikes can make evacuation more efficient when these plans are implemented, and also because the models are used to more strategically locate hurricane shelters. These studies build on the work of Ng et al. (2010) who developed similar approaches for optimally locating shelters, but extend them by using a stochastic approach that considers a set of hazard scenarios, rather than a deterministic approach, which only considers a single hazard scenario.
- Legg et al. (2012) developed a linear programming model for optimising the selection of hurricane mitigation options that included buy-back of property, in addition to the level in which buildings of each structural and occupancy type, in each census tract within a study region were retrofitted. A physically based model of hurricane damage was coupled with a component-based damage assessment tool (that is, buildings are considered as comprising a roof cover, roof sheathing, roof-to-wall connections, windows and door openings, and a flood susceptibility which respond differently to hurricane events), and this coupled model was used to assess mitigation options that treat different building components in isolation.
- In Peng et al. (2014), rather than finding the system optimal strategy as in previous studies, the objectives, mitigation options, and constraints of different stakeholders (insurer, reinsurer, government and homeowner) were considered separately using a stochastic model for hurricane hazard. In this study, insurance was also considered as a mitigation option in addition to retrofit. Due to the nonlinear formulation of the optimisation problem, genetic algorithms were used as the solution technique to maximise the profit of the insurer, in order to understand how insurers and homeowners would respond to different government policies regarding hurricane insurance and retrofit incentives. Solving a similar optimisation problem using simulated annealing rather than genetic algorithms was reported by Kesete et al. (2014). Due to the problem formulation in these studies, the approach taken is classified within the second approach to optimisation.

An issue with the use of optimisation in all of the studies outlined above is the computational demand of loss models, which need to be run over a large number of hazard scenarios to calculate the probability distribution of different magnitudes of losses in any year. In order to reduce computational demand, Han and Davidson (2012), Vaziri et al. (2012), Apivatanagul et al. (2011), and Legg et al. (2010) have developed optimisation based approaches that select a smaller subset of scenarios and weight factors that result in similar hazard-probability curves to that developed using the full set of scenarios.

To summarise, in recent times, some research effort has been directed toward the development of optimisation approaches to help develop mitigation plans. However, it is important to note that none of these studies have considered an extensive number of mitigation options, have always focussed on a single hazard type, and have not considered climate, population demographics and landuse change. In addition, most studies have sought to simplify the problem formulation to ensure mathematical properties that allows the identification of globally optimal solutions. However, it is arguably better to maintain a more realistic problem formulation when applying optimisation to these types of real-world applications.

5.4. Research gap

This chapter has identified that the use of optimisation and taking a multihazard approach is important when assessing mitigation options. However, no previous research has taken both of these aspects, and incorporated them into DSSs. In addition, as identified in section three of this report, land use is a critical component of risk, and land use planning measures are the predominant means of minimising this risk. However, research to date has not considered how land use will change into the future, even though mitigation measures tend to be long-term in implementation and effect. Furthermore, research to date has also not considered the impact of climate change, which is important, as identified in Chapter 2.

Consequently, the development of decision support systems, using the state of the art methodology, as surveyed in chapter 4, including the use of optimisation within a multihazard approach, is both important and novel, and is the objectives of the research project being conducted by the authors of this report.

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