Structured Decision-Making For
Seismic Risk Mitigation in Hospitals

by

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Executive Summary

Purpose and Scope

The purpose of this project was to develop a prototype of a decision support framework that could be used by institutions to assist with formulating and prioritizing options to increase the resilience of their infrastructure. As a prototype, the results of this project are intended to demonstrate how the framework could be structured and to provide a basis for judging the utility of this approach. Seismic mitigation of hospitals was used as a test case for the method, because of existing domain knowledge within the committee. The method could also be applied to other facilities and for other types of extreme events.

This project focused on the non-structural (technical) components of buildings. Historically most efforts to improve the seismic performance of buildings have focused on the structural system; however, risk to safety, damage to property and loss of function of buildings can often result from the failure or malfunction of non-structural assets, even if the building structure performs well.

Background

Resiliency requires that a system have the capacity to absorb disturbance while remaining within the same functional state (Resilience Alliance, 2007). The ability of infrastructure systems to maintain function and deliver services after a major disturbance such as a natural disaster is a significant concern for system designers, planners, customers, and responsible officials. Resilient infrastructure is of paramount importance during and after an extreme event. Hospitals are stretched for resources during normal operations, and extreme events reduce their ability to provide services and often result in increased demand for hospital services. Many hospital emergency planning efforts have focused on responding to the increased demand caused by disasters, rather than on the disasters that may occur within the hospital.

Facility assets can be divided into three broad categories: structural, technical and organizational. Structural resiliency is needed so that the buildings are safe to be in. Technical assets are commonly referred to as "operational and functional components" (OFCs). Types of OFCs include architectural components, building services components and building contents. The very high density of OFCs in hospitals makes them a key part of a resilience strategy. Organizational assets include personnel, inventory, plans and regulations. Organizational assets were not considered in the development of the prototype tool.

Canadian hospitals are covered by the National Building Code (NBC), which sets standards for the structural and non-structural elements to withstand seismic forces. As an appendix to the National Building Code, the Canadian Standards Association has developed a standard for the reduction of seismic risk from OFCs (CSA-S832: *Seismic Risk Reduction of Operational and Functional Components (OFCs) of Buildings*). The standard is not mandatory, but may be fully incorporated into the NBC in the future.

It is estimated that only 50% of OFCs even in new buildings are restrained to the standard outlined in CSA-S832 (Jay Lewis, personal communication). Implementation of seismic risk mitigation measures is constrained by the availability of human and financial resources. The process used to make decisions about which mitigation alternatives to implement varies from hospital to hospital, depending on the resources available. Most hospitals engage in an iterative decision-making process.

The framework presented in this project follows a structured decision-making approach, and provides a means for incorporating multiple objectives directly into the decision process, rather than considering each objective separately, or not at all.

Structured Decision-Marking

Structured decision-making (SDM) is defined by Ralph Keeney as "a formalization of common sense for decision problems which are too complex for informal use of common sense" (Keeney, 1982: 806). The SDM approach usually involves the choice of one alternative based on how well it "performs" against a number of objectives. The objectives can be thought of as criteria, and the performance is a measure of utility. The criteria are weighted to reflect their relative importance to the decision maker(s) and the overall utility of an alternative is the weighted sum of its performance against each criteria.

Hospitals strive to meet many competing objectives, such as savings lives and operating within limited budgets. They also function within a regulatory structure that dictates the standard of care they should be able to provide during both typical and extreme conditions.

SDM is well suited for use in assisting hospitals prioritize seismic mitigation measures, because it facilitates consideration of multiple objectives to be considered, allowing tradeoffs to be made between healthcare service now and better healthcare service in a future emergency.

Application of SDM

The decision chosen for the application of SDM considers whether individual actions should be addressed in order of risk ranking, in order of cost, if a systems approach should be used, or if an area-based approach should be used. There is currently no framework for making this kind of decision, and no guidance for considering how to evaluate these different groupings of actions (or strategies). Within the current decision-making process, the step of moving from technical risk rankings to prioritizing system-wide measures is most in need of strengthening. Therefore, this tool focused on providing a framework for developing and prioritizing alternative strategies when risk index values for individual OFCs have been derived following the CSA-S832 method. The tool was developed in MS Excel, and built on a strategy-generation table tool developed by Compass Resource Management of Vancouver, BC.

The question that this framework seeks to help answer is "What action or set of actions best meets the objectives of seismic mitigation?" "Best" is defined by the overall objective, which is to provide the greatest reduction in risk for the least amount of spending. This objective is further broken down as shown in Table ES1.

Table ES1. Objectives Hierarchy

Fundamental Objectives	Lowest-Level Fundamental Objectives
Minimize total cost	Minimize capital cost
	Minimize operation/maintenance costs
Minimize impact of disaster	Minimize duration of downtime after extreme event
	Minimize impact on hospital capacity after extreme event
	Minimize mortality
	Minimize morbidity
Minimize impact of mitigation implementation	Minimize impact on normal operations during implementation of mitigation initiatives

The alternatives in this decision framework are groups of individual actions (the groupings are known as strategies) that are formed by combining individual actions around common themes. Sample strategy themes include common locations (such as single rooms or functional areas), and common systems (water, mechanical, power etc.). Strategies can also be developed by "default", such as by adding actions in order of cost until a pre-determined budget limit is reached.

Once the strategies are developed, each one must be assessed against the objectives defined earlier. The performance of the strategies depends on the performance of the individual alternatives actions that comprise the strategy. At this point, each strategy has a value for each objective. However, since the objectives are measured in different units, it is necessary to normalize the scores. The simplest method (used in this prototype) is to assign a score of 1 to the best performance and a score of 0 to the worst performance, and to assume a linear relationship between the attribute and the value score. Then the scores across all objectives can be added to generate a total score for each strategy.

The next step was to weight the objectives to account for their varying degrees of importance. Swing weighting is a common method used to determine the relative importance of each of the objectives. For this project, Dr. Stephanie Chang (a committee member and expert on the socio-economic impacts of earthquakes) acted as the decision maker, and performed the weighting exercise. The raw data and normalized weights are shown in Table ES2.

Table ES2. Swing Weighting Data and Results

Attribute	Worst	Best	Rank	Rating	Normalized Weight
Total Cost	$2.3 million	0	2	60	0.353
Risk Index	0	3,011	1	100	0.588
Disruption	156	0	3	10	0.059

These weights were applied to the normalized scores to generate the final score for each strategy. The final results are shown in Figure ES1.

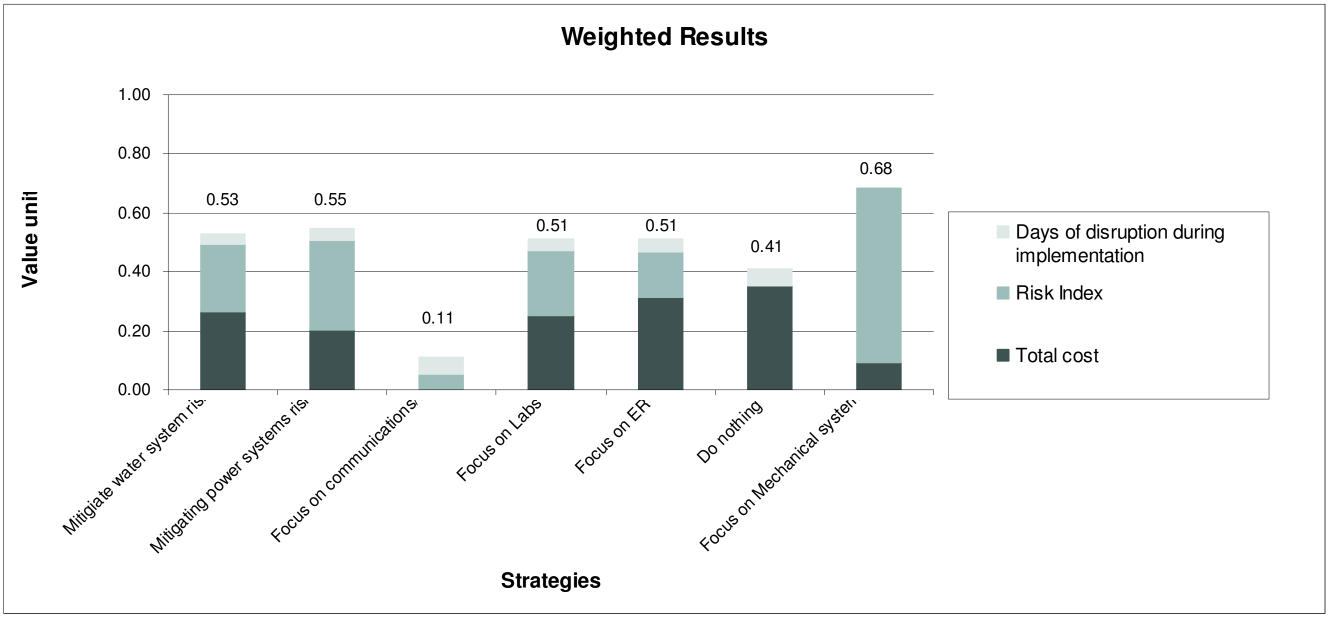


Figure ES1. Final Results

Results/Discussion

To test the effectiveness of this approach, the performance of consciously constructed strategies was compared to the performance two "default" strategies. One default strategy was developed by listing the individual actions in order of their risk rankings (highest to lowest); individual actions were added to the strategy in order of risk ranking, until the total risk reduction potential was no greater than that of the top ranked consciously constructed strategy (i.e. mechanical systems). The second default strategy was developed by listing the individual actions in order of their cost (lowest to highest); individual actions were added to the strategy until the total cost was no greater than the total cost of the top ranked strategy.

The strategy built from the actions with the highest risk index values had a total final score of 0.39, lower than all but the communications/IT strategy. This is because many individual actions with high risk index scores have comparatively high costs. This meant that the cost of this default strategy was $3.7 million, nearly $1.4 million more than the most expensive consciously constructed strategy, and nearly $2 million more than the highest ranked strategy, which had the same risk reduction potential. Therefore, although it scored well on the risk objective, it scored very poorly on the cost objective.

The strategy built from the least expensive individual actions had a total final score of 0.852, which is higher than any of the final scores of the consciously constructed strategy. Using a low-cost approach meant that 50 individual actions could be included for the same budget as the highest ranked consciously constructed strategy. This meant that although the cost was capped at the cost of the highest ranked strategy, the total risk reduction potential was higher.

These results indicate that the practice of consciously constructing strategies to meet a given objective or to service a particular functional area of a hospital may be more effective at meeting the stated objectives than a naïve approach that considers only maximizing risk reduction. However, setting a budget and maximizing the number of actions that can be taken within that budget may generate more effective solutions than the SDM approach.

Further Work

This prototype has some shortcomings that should be resolved before it can be a useful tool. The most major issue that needs to be resolved is the use of the risk index as a proxy attribute for duration and degree of impact, mortality and morbidity. While using the results of the existing CSA protocol will make this tool easier to use, the risk index does not accurately measure the objectives, which means that the final results do not precisely reflect the objectives.

Further refinement of the software tools will also be necessary in order to make this method truly applicable and useful to hospitals. The following changes should be investigated and tested:

- Enable a larger number of individual actions to be considered under each category. A larger number of categories would also be helpful.
- Build in a normalizing function for strategy performance.
- Integrate a swing-weighting function.
- Build a macro that generates the "naïve" strategies, based on cost or other objectives, as defined by the user. The limiting parameter (such as budget) and the parameter used to rank the actions could be entered by the user, and then the ranking and analysis of the strategies could be automatic.

Another feature is required to improve the swing-weighting exercise, particularly if the risk index is still being used as a proxy measure. Since the risk index is a unit-less, abstract number, it is difficult for a decision-maker to know how to trade-off risk index points against the other objectives. This would be easier if meaning were attached to the risk index by providing sample packages that correspond to certain risk index numbers. Since different combinations of individual actions can have the same risk index number, a variety of packages should be provided for the maximum, minimum and middle risk index values.

Conclusion & Recommendations

Structured decision-making is a proven method for approaching complex problems. It is a tool that can be used help to sift through often-conflicting objectives and to define and assess alternatives. It does not generate the "right" answer, but its use helps to define the characteristics of the best answer.

In the context of hospitals making decisions about seismic risk mitigation, SDM can be used to articulate objectives and to combine individual actions together in ways that maximize performance. The difficulty of this application of SDM lies in finding suitable performance measures for risk reduction. Natural attributes such as the impact of an action on the percent of hospital capacity remaining, or on the duration of reduced capacity, are difficult to determine. In this prototype framework, a proxy attribute was introduced that took the place of four natural attributes. Although the proxy attribute is straightforward to calculate for many individual actions, it is not applicable to some actions, and misses some of the nuances of the objectives.

The use of SDM in this context is worth exploring in further detail, and it is recommended that staff at the Disaster Preparedness Research Centre continue with this line of inquiry. Partnership with a hospital would aid this investigation, and help to ensure that the tool met the needs and constraints of real users.

Table of Contents

Figures

Tables

Appendices

1 Introduction

The Disaster Preparedness Research Centre in the School of Community and Regional Planning at the University of British Columbia has been working on the issue of infrastructure failure interdependencies for several years. The research was originally funded by the US National Science Foundation and additional funding was recently received from Infrastructure Canada to continue the investigations. The purpose of the research is to investigate the nature of infrastructure failures, and to determine how these failures impact other infrastructure systems. Work conducted to date has included the creation of a database of infrastructure failure interdependencies resulting from a variety of extreme events and the development of a model of infrastructure residency. In addition, a Master's thesis was completed in 2006 that detailed how hospitals in three countries responded to actual or potential earthquakes and developed a decision-making model for pre-quake mitigation and post-quake adaptation (Cole, 2006). This research indicated a need for study on the topic of prioritizing disaster mitigation activities.

1.1 Project Focus

This project focused on developing a method or approach for prioritizing disaster mitigation alternatives. Seismic mitigation of hospitals was used as a test case for the method, although the method could also be applied to other facilities such as schools water and wastewater treatment plants, and for other types of extreme events.

The purpose of this undertaking was to develop a prototype of a decision support framework that could be used by institutions to assist with formulating and prioritizing options to increase the resilience of their infrastructure. As described above, data for seismic mitigation of hospitals was used to build a test case for the method development, because of the domain knowledge within the research team.

A method to assist with the definition and evaluation of disaster mitigation alternatives could be useful for many different types of infrastructure. Water treatment and distribution facilities, power generation, transmission and distribution facilities, and telecommunications/IT systems all face decisions about which of many mitigation alternatives will be implemented. Although building performance standards often exist for infrastructure systems, it is not uncommon for existing infrastructure to not meet the standards. Applying a systematic means of comparing mitigation alternatives would improve the quality of decisions that are made, and would eventually improve the resiliency of the infrastructure.

1.2 Project Scope

This project focused on the non-structural components of buildings (also referred to as operational and functional components, or OFCs); structural elements were not included in the analysis. Historically most efforts to improve the seismic performance of buildings have focused on the structural system; however, risk to safety, damage to property and loss of function of buildings can often result from the failure or malfunction of OFCs, even if the building structure performs well.

As a prototype, the results of this project were intended to demonstrate how the framework could be structured and to provide a basis for judging the utility of this approach. The framework was based on existing software, such as the software for creating decision trees supplied with *Making Hard Decisions* (Clemen & Reilly, 2001), and proprietary macros developed in MS Excel by Compass Resource Management. The prototype was not intended to be a fully functional stand-alone program; rather the results will be used to examine the utility of the concept; if successful, it will provide a basis for developing a more refined product in the future.

The client for this project is the researchers at the Disaster Preparedness Research Centre, who will assess the usefulness of the prototype. If the prototype is found to be useful, it may be applied in a series of workshops that will be conducted in the fall of 2007 with a range of infrastructure institutions. The workshops will be used to prioritize seismic mitigation alternatives for each type of infrastructure.

2 Background

2.1 Resiliency

The concept of resiliency (the ability to maintain system function after a shock) has long been associated with ecological systems. More recently, resiliency has become a concern for infrastructure systems and their managers. Resiliency can be considered to be the result of two factors: robustness (relating to the degree of impact) and rapidity of recovery (the length of time the system needs to recover). These concepts are discussed in detail in McDaniels, Chang, Cole, Mikawoz & Longstaff (forthcoming), and are summarized below to inform the approach taken in this project.

Resiliency requires that a system have the capacity to absorb disturbance while remaining within the same functional state (Resilience Alliance, 2007). The ability of infrastructure systems to maintain function and deliver services after a major disturbance such as a natural disaster is a significant concern for system designers, planners, customers, and responsible officials. Resiliency in infrastructure systems is important because of the role they play during extreme events (such as earthquakes, storms, floods or terrorism)[1]. Systems such as electric power, water, and health care, are often referred to as "lifeline systems"; resilience of these systems is crucial for minimizing the societal impact of extreme events. In addition to keeping individual infrastructure systems operating, it is important to avoid system interactions, in which one infrastructure system failure leads to failures in other systems (McDaniels, Chang, *et al.*, 2006). An example of this kind of interaction is the failure of a water treatment plant due to an electric power outage, or the inability of a hospital to provide care due to outages of electric power and/or potable water.

The Multidisciplinary Center for Earthquake Engineering Research (MCEER) provides the following definition of resiliency (2005, p.18):

> [C]ommunity resilience to hazards is defined as the ability of social units (e.g., organizations, communities) to mitigate hazards, contain the effects of hazard-related disasters when they occur, and carry out recovery activities in ways that minimize social disruption and mitigate the effects of future hazards. The objectives of enhancing disaster resilience are to minimize loss of life, injuries, and economic impacts – in short, to minimize any reduction in quality of life due to these hazards. Resilience can be achieved by enhancing the ability of a community's infrastructure, e.g., lifelines and structures, to perform during and after a hazard, as well as through emergency response and strategies that effectively cope with and contain losses and recovery strategies that enable communities to return to levels of predisaster functioning (or other acceptable levels) as rapidly as possible.

Put more simply, disaster resilience is characterized by: reduced failure probabilities, reduced consequences from failures, and reduced time to recovery. As compared to a system that is

[1] As defined by the National Science Foundation, extreme events are characterized by nonlinear responses, low-probabilities, high consequences, and the potential for systems interaction that leads to catastrophic losses (Stewart and Bostrom, 2002).

not resilient, a resilient system will be less likely to sustain damage or failure, will suffer fewer consequences from any failures (consequences can be measured by a range of variables, including injuries, lives lost, economic, environmental and social impacts), and will need less time to return to its normal (pre-disaster) functionality (MCEER, 2006).

Resilience involves technical, organizational, social, and economic dimensions. While technical resilience refers to the performance of physical systems in disasters, organizational resilience indicates the capacity of organizations to make appropriate decisions and take effective actions. Social resilience consists of measures designed to reduce the impact of losing critical services on communities, and economic resilience is the capacity to reduce direct and indirect economic losses resulting from disasters (MCEER, 2006). This project is primarily concerned with the technical and organizational resilience of institutions, although local governments could use the same techniques to prioritize actions related to social and economic resilience.

Given the importance of resiliency, a framework is needed to measure it. MCEER uses a four-pronged approach: robustness, rapidity, redundancy and resourcefulness. Robustness refers to "the ability… to withstand a given level of stress… without suffering degradation or loss of function". Redundancy refers to the "extent to which elements… are substitutable", while resourcefulness is "the capacity to identify problems, establish priorities and mobilize resources when conditions exist that threaten to disrupt some element". Rapidity indicates "the capacity to meet priorities and achieve goals in a timely manner in order to contain losses and avoid future disruption." (MCEER, 2005, p.19)

Two of these axes of resilience are particularly important to infrastructure systems: robustness and rapidity. Figure 1 provides a general illustration of these properties of resilience. Resilience is measured with reference to some level of system performance; in the case of a hospital, this might refer to the number of patients treated or operations performed. The occurrence of a disaster such as an earthquake leads to a rapid decrease in performance or capacity. The extent of this decrease reflects the system's *robustness*. Over time following the disaster, the system regains some level of stability or equilibrium.[2] The

[2] This may be the same as performance levels had the disaster not occurred, or may be an alternate stable state. In extreme events, it is possible for the system to achieve a stable state that is either higher or lower than the pre-disaster or "without"-disaster level.

speed with which this is achieved reflects the system's *rapidity*. The diagram illustrates that robustness and rapidity can be improved by both ex-ante and ex-post decision-making. That is, resilience can be enhanced by both risk mitigation activities undertaken before the disaster and response activities following the event.

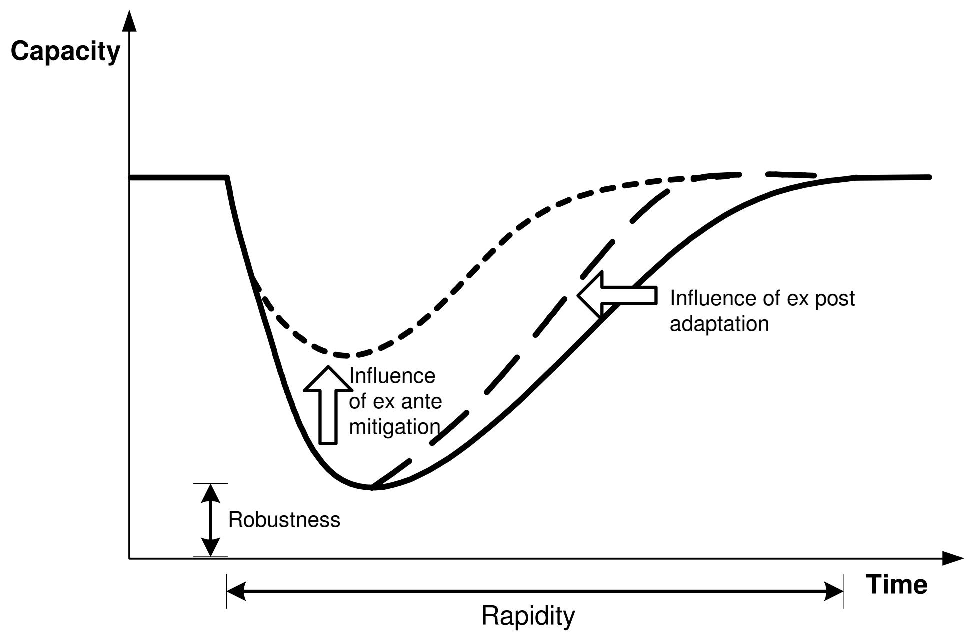


Figure 1. Effects of decision-making on resilience (McDaniels et al. (forthcoming))

2.2 Infrastructure Mitigation Standards

The National Building Code of Canada (NBCC) sets the level of service various categories of buildings must be able to provide after an earthquake. This level of service is expressed as an "importance factor". These factors are used in force calculations to determine the performance standard for both structural systems and OFCs. These mandated performance standards represent the minimum level that should be met. An importance factor of 1.0 corresponds to a "life safety" standard, which should allow all people in the building to leave safely, with no loss of life. An importance factor of 1.5 corresponds to a "post disaster serviceability" standard, which means that base systems should still be in reasonable shape and the facility should be up and running within a reasonable length of time (6-24hr). Importance factors beyond 1.5 are not defined, but extend towards a "business continuity" standard, which means that the facility would experience no or only minimal interruptions before returning to operation.

Most commercial or institutional buildings are assigned an importance factor of 1.0. Schools have an importance factor of 1.3, and hospitals use an importance factor of 1.5.

Although the NBCC defines the importance factors, these can be considered the minimum level of effort required. Facility-owners may choose to maintain their buildings at a higher standard. The possible consequences of meeting each standard are examined below.

2.2.1 Life safety

The life safety standard represents minimal hazard mitigation. Facilities that have been mitigated to this standard should survive the earthquake without causing injury to occupants either through building failure or falling equipment. After a serious earthquake, a facility that meets only the life safety standard would not likely be able to operate. While the National Building Code (2005) mandates that hospitals exceed this standard, the reality is that many hospitals do not even meet this standard (Jay Lewis, personal communication). The decision about whether to mitigate to reach the life safety standard was modeled by Cole (2006), and the resulting diagram is provided as Figure 2.

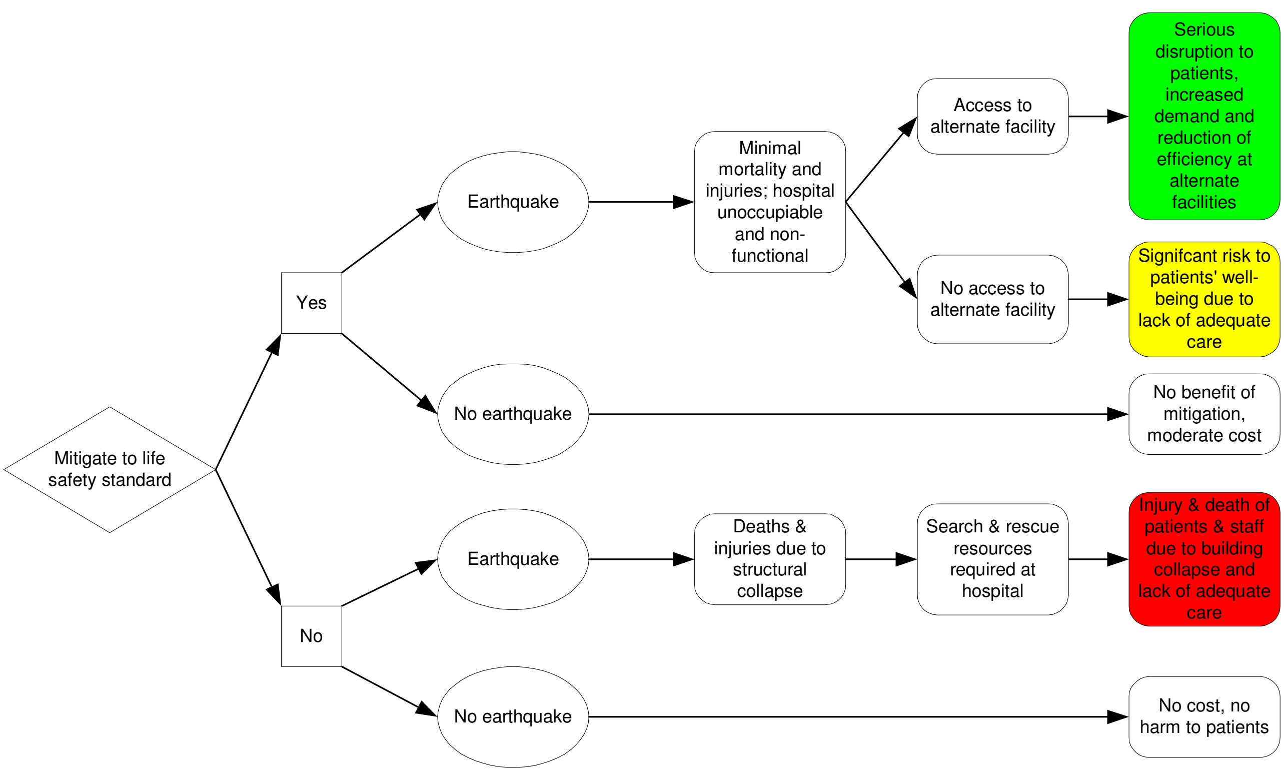


Figure 2. Decision tree for mitigation to life safety standard (adapted from Cole, 2006)

Figure 2 is a simplified decision tree that does not include probabilities, costs or the resulting expected utilities for each possible outcome. The outcomes are characterized by the expected ability of the hospital to function in each outcome. Green represents the most desirable outcome, yellow indicates an unsatisfactory outcome, and red indicates severe negative impacts; white is used for outcomes without an earthquake.

While a decision to not mitigate to the life safety standard could result in an outcome of no cost and no harm to patients or the facility, this outcome depends on no earthquake occurring. Since geologists know that an earthquake will occur in southern British Columbia, choosing not to mitigate to this standard is clearly a poor decision for facilities in that area. However, facility managers are faced with mismatched timeframes, which complicate the decision: while an earthquake is likely to occur some time in the next 100 years, the manager is concerned with budgets over the next 3-5 years. In order to resolve this discrepancy, planners must accept the that an earthquake will happen, and that the only acceptable response is to mitigate facilities to at least a life safety standard. Mitigating to this level still does not meet the minimum level mandated by the National Building Code.

2.2.2 Serviceability

The post-disaster serviceability performance standard means that a facility, including its base systems (water, power, etc) and its equipment, can function immediately after an earthquake. This is the performance standard mandated for hospitals in the National Building Code, and is applicable to both the structural systems and OFCs of a hospital. Although this performance standard is required, the simplified decision tree in Figure 3 includes a node for deciding whether or not to mitigate to this standard, since many hospitals are not yet in compliance with the code.

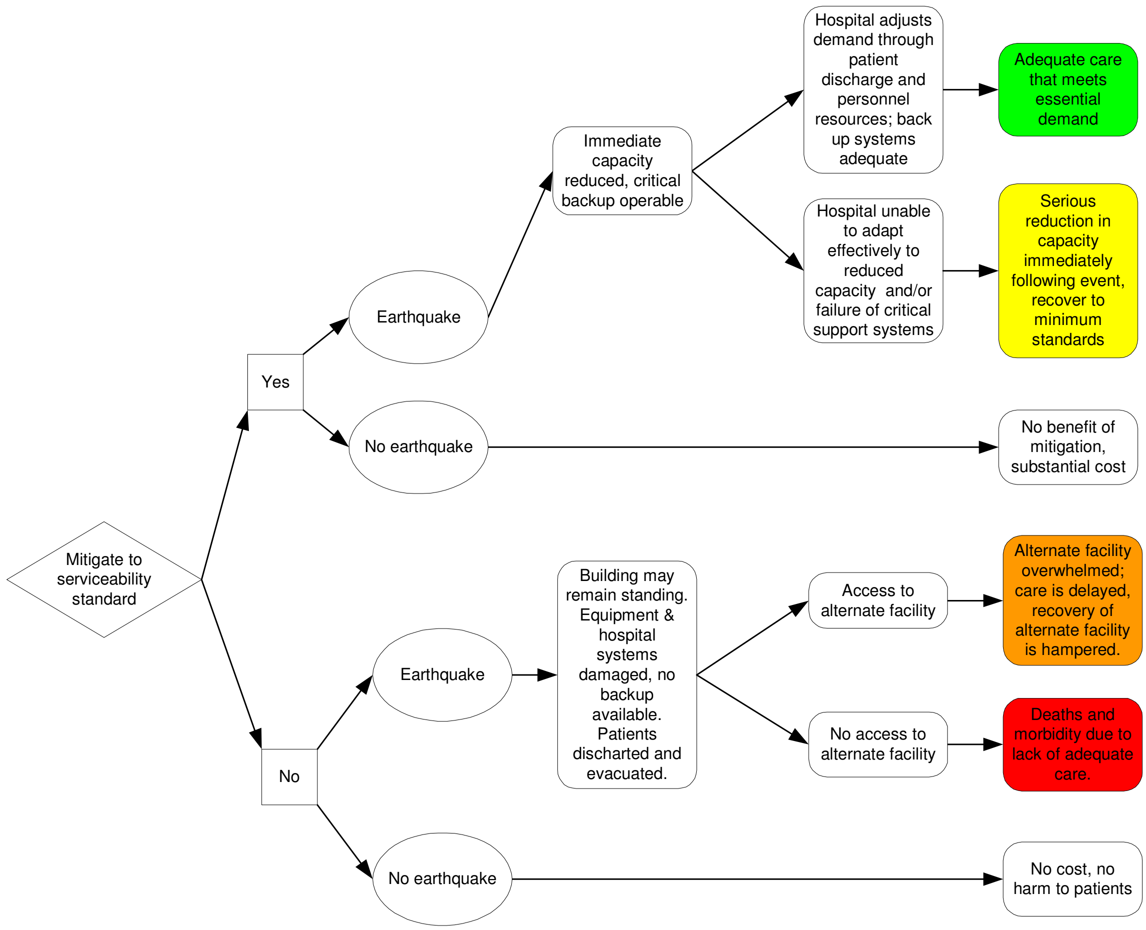


Figure 3. Decision tree for mitigation to serviceability standard (adapted from Cole, 2006)

Figure 3 is also a simplified decision tree that does not include probabilities, costs or the resulting expected utilities for each possible outcome. The outcomes are characterized by the expected ability of the hospital to function in each outcome. Green represents the most desirable outcome, yellow indicates an unsatisfactory outcome, orange indicates significant negative impacts, and red indicates severe negative impacts; white is used for outcomes without an earthquake.

Only one` of the four outcomes involving an earthquake is positive, and it requires that the hospital have mitigation measures in place before the disaster occurs and also be able to adapt post-disaster. This illustrates the need for both ex-ante and ex-post planning.

2.2.3 Continuity

The business continuity mitigation standard is less well defined than the life safety or serviceability standards. The ideal business continuity strategy would allow a facility to continue operating at its usual capacity with no down time after an extreme event. This standard is currently applied very rarely, and only for extremely critical infrastructure such as nuclear power plants, emergency operations centres, and critical government command and control centres. While few hospitals are mitigated to this performance standard, past disasters indicate the need for key medical facilities to maintain operational capacity. Figure 4 illustrates the decision process involved with this standard of mitigation.

As with Figures 2 & 3, Figure 4 is a simplified decision tree that does not include probabilities, costs or the resulting expected utilities for each possible outcome. The outcomes are characterized by the expected ability of the hospital to function in each outcome. Green represents the most desirable outcome, yellow indicates an unsatisfactory outcome, and grey is used to indicate multiple possible outcomes, as shown in the previous figures; white is used for outcomes without an earthquake.

Figure 4 illustrates that deciding to mitigate to the continuity performance standard avoids any of the highly undesirable outcomes seen in Figures 2 and 3. However, there are still risks to making the decision to mitigate to this level. First, if an earthquake does not occur within the timeframe used for planning, critics may claim that the resources spent on mitigation would have been better spent directly on improving heath care. Second, an earthquake could occur that exceeds the design of the mitigation measures, so absolute continuity will not be achieved, and there would still be some degree of negative outcomes. Once again, critics may argue that since the mitigation was "ineffective" the resources spent on it would have been better spent directly on health care. The critics' arguments highlight the need to consider broad, long term objectives within a decision context that includes improved health care at all times, not only during normal operations.

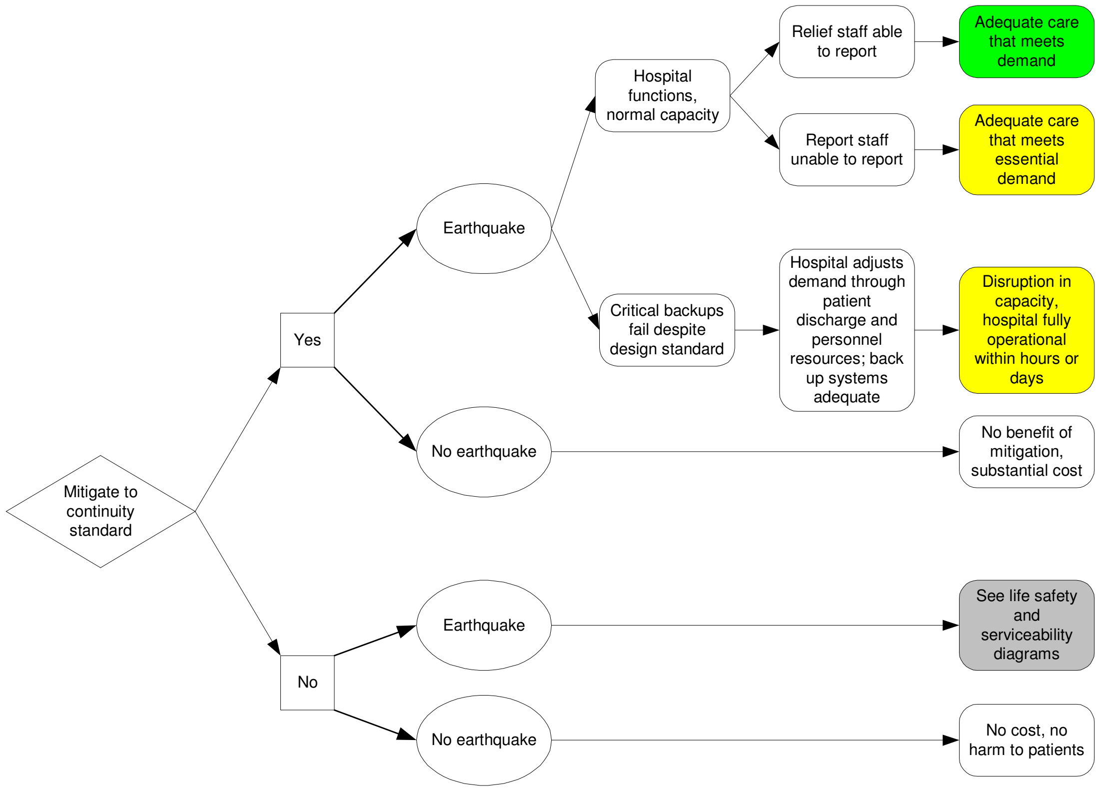


Figure 4. Decision tree for mitigation to continuity standard (adapted from Cole, 2006)

2.2.4 Deciding on a Performance Standard

As well as considering the consequences of each performance standard, the decision about which standard to achieve is influenced by a variety of factors. Some of these factors are internal to the hospital (such as its budget), while others are external (such as a hospital's role in a regional health care system). Figure 5 illustrates the factors that influence the decision of which performance standard to choose. These factors were derived from research conducted by Cole (2006).

Figure 5 is in the form of an influence diagram. Influence diagrams are used to illustrate the connections (influence) between decision elements such as uncertain events and outcomes, decisions and alternatives (Clemen & Reilly, 2001). Influence diagrams are particularly useful in depicting decisions with multiple objectives and for determining the range of elements that must be considered. By understanding the decisions that need to be made and the uncertainly involved, decision-makers can improve their understanding of the problem, and the potential impacts of the alternatives available.

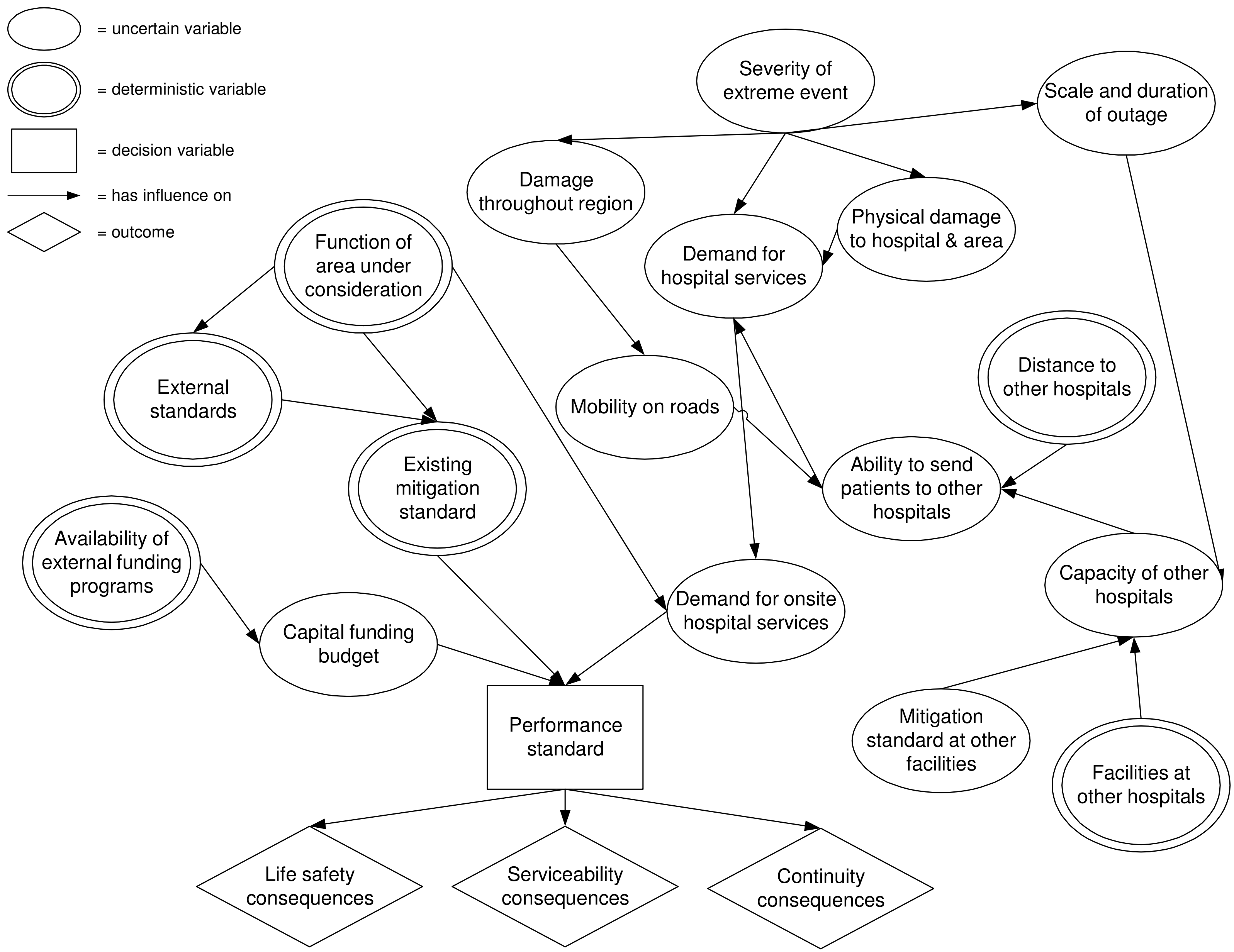


Figure 5. Influence diagram for performance standard decision

3 Hospital Resiliency

As described above, the National Building Code of Canada has assigned an importance factor of 1.5 to hospitals, which recognizes the importance of hospitals in a post-disaster situation. Hospitals may also plan for faster serviceability or even continuity. The level to which mitigation is implemented often varies across different functional areas of the hospital, depending on the services needed after a disaster.

In the 2003 Canadian Health Accreditation Report, the Canadian Council on Health Services Accreditation (CCHSA) reported that 37% of the patient-safety related recommendations it made were related to emergency preparedness, and 30% were related to risk management. These statistics indicate the need for hospitals to improve their resiliency (CCHSA, 2003).

3.1 The role of hospitals in disasters

As described above, resilient infrastructure is of paramount importance during and after an extreme event. Hospitals are stretched for resources during normal operations, but extreme events further reduce hospitals' ability to provide services and create a higher demand for services. Buildings may be damaged and need to be evacuated, water and power may be limited, staff may be in short supply, and deliveries of consumable supplies may not be possible. The tension between increased demand and reduced supply of medical services highlights the necessity of hospital resilience. Many hospital emergency planning efforts have focused on responding to the increased demand caused by disasters, rather than on the disasters that may occur within the hospital (Cole, 2006). Assistance from outside the area impacted by the disaster is not likely to arrive sooner than 24 hours after the disaster, and often takes longer. For at least the first 72 hours after a disaster, the responsibility for treating current patients and disaster victims rests almost entirely with local authorities. Hospitals also serve as community focal points after a disaster, providing a venue for public communication. Mitigating risks within hospitals so that they can continue to offer services is therefore critical to minimizing the impacts of disasters. Without suitable mitigation, hospitals will be unable to treat existing patients and disaster victims, and will also be unable to maintain sanitary conditions, which may results in the spread of disease, creating further demand.

3.2 Types of Hospital Assets

Hospital assets can be divided into three broad categories: structural, non-structural technical, and organizational. Structural resiliency is needed so that the buildings are safe to be in. Non-structural technical assets are also referred to as "operational and functional components" (OFCs), and include architectural components, building services components and building contents (CSA, 2006). Organizational assets include personnel, inventory, plans and regulations. Organizational assets were not considered in the development of the prototype tool.

In a hospital context, OFCs include the water and power systems, mechanical systems, communications/IT, and equipment, as well as general architectural OFCs. The very high density of OFCs in hospitals makes them a key part of a resilience strategy. Hospitals are "brittle" systems, containing sophisticated diagnostic and operating equipment that is highly sensitive to disturbance and that is dependent on centralized computer controls; access to hospital records relies heavily on telecommunication systems that are also susceptible to failure in a disaster. Hundreds of kilometers of piping carry water, medical gases, and wastes throughout the hospital; if these pipes burst, the resulting fire, floods, contamination and loss of life-support systems could require that the hospital be evacuated, and at the very least reduce the level of service that can be provided. Evacuation is very risky, as it ends the support current patients are receiving, and means that no new patients can be accepted.

OFCs typically represent 92% of the total investment in a hospital, compared to only 8% for the building structure (Lewis & Wang, 2004). Since hospitals rely heavily on their OFCs and organizational assets, and since the National Building Code has set the performance standard for hospitals at a "serviceability" level, this project is focused on risk mitigation alternatives for OFCs.

4 General Description of Hospital Decision-Making

The MCEER group of researchers has characterized a generic model of hospital decision-making about seismic mitigation. More detail on decision-making processes in specific hospitals is available in Cole (2006) and Connell (2003). Jay Lewis of TerraFirm Inc provided further insight (personal communication).

MCEER researchers Petak and Alesch (2004) have refined the "garbage can model" of organizational decision-making, (developed by March and Olsen in 1973) to more accurately reflect the process used in hospitals. The garbage can model requires that four streams converge simultaneously: a problem must be recognized and agreed upon by a critical number of individuals; credible solutions must exist; there must be space on the organization's agenda to address the problem, and finally, there must be an advocate who maintains the profile of the issue. The refined model preserves many of these features, but builds on it to reflect the specific details related to hospitals making decisions about mitigating seismic risk. The refined model identifies five pre-requisites for decision-making. These pre-requisites are listed in chronological order: awareness of the issue (both problems and opportunities are included); belief that the problem can be addressed internally; belief that it is in the organization's best interests to address the problem (both absolutely and at the current time); ability to find a means to address the problem that is consistent with the organization's other goals, mandates, and constraints, and a belief that the organization has the capacity to take action (sufficient resources). While the model reads as being linear in nature, most hospitals engage in an iterative decision-making process, searching out and incorporating new information. Many hospitals (particularly in the United States) also do not function as autonomous units, capable of making their own decisions about seismic mitigation; rather, they are part of larger health care organizations (corporations) that must balance and prioritize the problems and opportunities faced by number of facilities. The model does not yet incorporate a description of how this prioritization takes place.

Connell (2003) notes that many different levels of management and specialized units within the hospital each contribute to the decision-making process. A framework of official and operative goals (as described by Perrow, 1961) is used to describe the bureaucratic process of decision-making. Official goals are the widely understood, generally accepted purposes of an organization. For a hospital, the official goal is to provide medical care for patients. In general, official goals are vague and do not indicate the how decisions should be made among alternative ways of achieving them, or the relative priority of multiple goals. Operative goals are often the means to achieving the official goals. While an operative goal may lead towards the achievement of one official goal, it may undermine progress towards another official goal. Operative goals may provide more insight regarding what an organization is trying to do than the official goals do. Operative goals are often expressed at lower levels (sub-groups) within the organization. While official goals apply to the entire hospitals, operative goals can vary across departments. Although seismic risk mitigation activities do not directly support the official goals of hospitals or the operative goals of most departments (with the notable exception of the emergency planning department), the implementation of mitigation measures contributes to maintaining functionality in the case of a disaster, allowing the official and operative goals to be achieved. Bureaucratic decisions must reflect both types of organizational goals.

5 Decision-Making in British Columbian Hospitals

5.1.1 Regulatory and Funding Context

As described in Section 2, Canadian hospitals are covered by the National Building Code, and have been assigned a relative importance weighting of 1.5, which applies to both structural and non-structural (OFC) elements. As an appendix to the National Building Code, the Canadian Standards Association has developed a standard for the reduction of seismic risk from OFCs (*CSA-S832: Seismic Risk Reduction of Operational and Functional Components (OFCs) of Buildings*). This standard provides information and methodologies to identify and evaluate seismic hazards associated with OFCs and to undertake appropriate mitigation strategies and techniques (CSA, 2006). While application of the standard is not mandatory, experts in the area of hospital seismic risk mitigation are hopeful that it will be incorporated into the NBC in the future. The standard provides a logical, engineering-based approach to rating the risk associated with each OFC. The soil, building and component characteristics are assessed to produce an OFC vulnerability risk score. Life safety and performance requirements are then considered to generate a consequence risk score. The CSA risk index of an OFC is the product of the vulnerability index score and the consequence index score.

Although OFCs have been included in the NBC since 1953, little attention has been paid to them by the construction industry, with the result that few OFCs are restrained to the levels set out in the NBC. It is estimated that only 50% of OFCs even in new buildings are restrained (Lewis and Wang, 2004). Lewis and Wang (2004) cite six reasons for the lack of OFC restraint:

1. Inadequate regulatory standards: A rather nebulous definition in the NBCC as to exactly which components require restraint;

2. Poor directives for implementation: A performance code rather than a prescriptive one; no visual guidelines;

3. Inadequately written seismic specifications: The construction industry is forced to exploit omissions in order to deliver competitive bids;

4. Lack of industry expertise: Poor understanding of seismic restraint design and installation practice until recently;

5. Inadequate Code enforcement: Lack of training and awareness of building code officials concerning requirements and installation of nonstructural seismic mitigation systems;

6. Fiscal constraints: Reluctance on the part of building owners to add cost to buildings when the requirement is not clearly defined and enforced.

In 1999, the government of British Columbia launched a pilot Seismic Mitigation Program that provided funding for seismic risk mitigation for schools, hospitals and other critical provincial buildings. $133 million was available for disbursement over five years. For the first year, the emphasis was on OFC restraint; later the emphasis shifted to structural mitigation. The program ran for only four years, and achieved approximately 10-15% of the work that needed to be done. At that time, the Seismic Mitigation Branch was closed and the remaining upgrade funds were distributed to the schools, hospitals and other facilities (Lewis and Wang, 2004).

5.1.2 Decision processes

Seismic risk mitigation is constrained by limited human and financial resources. The process used to make decisions about which mitigation alternatives to implement varies from hospital to hospital, depending on the resources available. The following section describes the typical decision making process, which will vary with the availability of funds and of dedicated emergency planning staff.

Funding decisions about emergency preparedness are made at various levels of the organization. Individual department managers identify mitigation needs and make recommendations to individuals responsible for emergency management at the facility (this may take the form of an advisory committee, comprised of representatives of various departments and disciplines). The emergency planner (or facilities manager, if there is no emergency planner) collects the recommendations from various departments, organizes the information, and attempts to set priorities. These priorities are in turn reviewed by senior hospital management, who then submit the recommendations to management at the health authority. Health authority managers review the information and make decisions about which options to pursue. Funding is then sought for these options from provincial and federal sources.

The step of identifying mitigation needs may be carried out in accordance with CSA-S832. This standard sets out a method for setting priorities based on a risk index that is calculated using measures of vulnerability and consequence. The standard also recognizes that additional factors may be taken into account, such as cost, schedule of building renovations, and the value of the OFCs under consideration, but does not integrate these additional factors. The framework presented in this project provides a means for incorporating these objectives directly into the decision process, rather than considering them separately.

The CSA S832 method is summarized in the following steps:

1. Complete an inventory of OFCs (by reviewing plans and/or site inspection).
2. Preliminary assessment of OFCs to group them into three categories: OFCs that pose no life safety hazard, OFCs that pose a life safety hazard but are not critical to post-quake operation, and OFCs that need to remain operation during and after the earthquake. OFCs that pose an insignificant seismic hazard will also be identified at this stage and removed from further analysis.
3. Confirm performance objectives for each OFC (life safety, immediate/continued occupancy, functionality, or property protection).

4. Determine risk index for each OFC. This requires a site inspection and the collection of data necessary to calculate the vulnerability[3] and consequence[4] index scores. The values for the vulnerability index range from 0.024 to 15, and the values for the consequence index range from 1 to 20. The risk index is the product of the vulnerability and consequence scores (R = V x C). The range of risk index values for a single OFC is therefore 0.024 to 300.
5. Rank OFCs according to their risk indices. OFCs with identical risk indices will be ranked according to their consequence indices (i.e. for two OFCs with R = 40, and with VxC = 8x5 and VxC = 4x10, the second OFC would rank higher). Mitigation is considered necessary for OFCs with a risk index greater than 16; mitigation is optional for OFCs with a risk index less than 16.

While this method deals effectively with quantifying the technical aspects of risk, it falls short at the final step, by failing to provide guidance on how to choose which mitigation measures to implement. A OFCs with the same risk index are prioritized according to their consequences index scores, but no support is given on comparing different approaches to mitigation. Given a shortage of funds, it is unlikely that all of the OFCs with a risk index greater than 16 will be able to be mitigated, and hospital administrators will need to chose which items will receive attention. OFCs could be addressed strictly in order of risk rank, but this approach could miss out on additional benefits that could be realized from combining OFCs in various ways. For example, OFCs could be combined according to the building system they support, or according to which room or functional area they are in. These systems-based and room based approaches present an opportunity to combine OFCs into packages that better meet the mitigation objectives.

The following section outlines the basic principles of structured decision-making (SDM) and then examines how SDM techniques could be applied to the issue of prioritizing seismic mitigation alternatives in hospitals.

[3] The vulnerability index is a function of the following parameters: current restraint; sensitivity of OFC to impact, pounding and/or displacement; the likelihood of the OFC overturning; the flexibility of the OFC, characteristics of the ground on which the facility in built, and characteristics of the building. Ground characteristics are defined as the product of the 5% damped spectral response acceleration value for a period of 0.2s, and the acceleration-based site coefficient, as defined in the National Building Code.
[4] The consequence index is a function of the number of people threatened by OFC malfunction or failure (which in turn is a function of area, occupancy density and a duration factor (average weekly hours of human occupancy/100) and the required level of functionality post disaster.

6 Structured Decision Making Method

6.1 Overview

SDM is defined by Ralph Keeney as "a formalization of common sense for decision problems which are too complex for informal use of common sense" (Keeney, 1982: 806). He further describes this approach as providing "a sound basis and general approach for including judgments and values in an analysis of decision alternatives" (Keeney, 1982: 807). Morgan and Henrion (1990) have gone on to outline a wide range of criteria that are used in making decisions. These include utility-based criteria, rights-based criteria and technology-based criteria. The SDM approach discussed in this paper fits best into the utility-based criteria category, and can be more specifically described as way of maximizing the multi-attribute utility function, since it involves choosing between options that have a number of attributes which cannot all be expressed in monetary terms.

A multi-criteria decision problem usually involves the choice of one alternative based on how well it "performs" against a number of objectives. The objectives can be thought of as criteria, and the performance is a measure of utility. The criteria are weighted to reflect their relative importance to the decision maker(s) and the overall utility of an alternative is the weighted sum of its performance against each criteria.

6.1.1 Defining the Problem

The first step in undertaking an SDM process is to define the question or problem. This requires setting the right decision context. Clemen & Reilly (2001) suggest asking three types of questions to assist with this step:

1. Are you addressing the right problem? Does the chosen context accurately capture the issues you are debating?

2. Do you have the authority to make decisions in that context? (If not, you may need a narrower context.)

3. Do you have the resources to do the necessary analysis? (If not, you may need a narrower context.)

6.1.2 Eliciting Values and Determining Objectives

Once the problem and decision context are set, it is time to answer the question "what is important?" The answers to this question will form the basis of the objectives.

In setting the objectives, it is necessary to distinguish between means and ends objectives. Clemen & Reilly provide a simple rule of thumb for distinguishing between them: ask the question "why is this objective important". If the answer relates to the importance of that objective in achieving something else, then it is a means objective. If the answer is "because it is important", then the objective is a fundamental objective. (Clemen & Reilly, 2001: 48).

Fundamental objectives can be organized into a hierarchy. Broad fundamental objective can be considered "motherhood" objectives, and might represent the categories usually associated with sustainability (e.g. minimize harm to the environment, maximize social benefits, minimize cost). Sub-objectives describe what is meant by the upper level objectives. In the case of minimizing harm to the environment, sub-objectives could include specific risks to flora and fauna, air, water, or specific species. The question to ask to identify sub-objectives is "what do you mean by that?" (Clemen & Reilly, 2001:49)

Clemen & Reilly also set out a number of criteria to consider when developing the objectives to be used in a decision. The criteria are summarized as follows (Clemen & Reilly, 2001:601-602)

1. The set of objectives needs to account for all the relevant considerations that will play a role in the decision-making.

2. The set of objectives should be kept concise to avoid the analysis becoming awkward. Any objectives that do not differentiate between the alternatives (i.e. if all the alternatives perform the same way for an objective) should be eliminated because that objective does not help in making the decision.

3. Redundant objectives should be eliminated.

4. Objectives should be independent. If it is not possible to think about each objective without thinking of others then further refinement is needed.

5. The set must distinguish between means and fundamental objectives. While means objectives may be used as a proxy for fundamental objectives, they must be identified.

6. The performance of alternatives against the objectives must be operational. If the attribute scale is not straightforward to measure, a different scale is needed. This may require the use of a proxy objective.

6.1.3 Setting Attributes

Once the objectives are set, it is necessary determine how the performance of each alternative will be measured against the objectives. This performance is assessed by comparing specified attributes of the alternatives. The choice of attributes introduces a level of judgment and subjectivity into the decision analysis.

Von Winterfeldt (1992) describes two broad groupings of attributes: natural attributes (costs, deaths, jobs) and constructed attributes (often a verbal scale of the degree to which an objective may be achieved). In addition, proxy attributes may be used if an objective is not easily operationalized (Keeney 1992; Keeney & Gregory 2005). In general, natural or constructed attributes are preferable to proxy attributes; however, there are cases in which it is very difficult to directly measure how well the alternatives meet a given objective. In these cases, it may be necessary to use an indirect, or proxy, attribute. Proxy attributes may be natural measures for means objectives that are related to the fundamental objective in question. The attribute is valued only for its relationship to the fundamental objective.

As long as there is a direct, one to one relationship between a lowest level fundamental objective and a proxy attribute, the analysis can be straightforward. However, if several means objectives interact to affect the achievement of several lowest level fundamental objectives, the use of proxy attributes becomes more complicated, because there are interdependencies among the proxy attributes (Keeney, 1992). If natural or constructed attributes can be use for some of the lowest level fundamental objectives that are also described in part by the proxy attributes, then the situation becomes even more complex. Since proxy attributes may measure more than one objective, the use of proxy attributes can lead to double counting (i.e. the evaluation becomes redundant). This situation is equivalent to having some means objectives in the fundamental objectives hierarchy.

Fischer et al (1987) conducted an empirical study on the impact of using proxy attributes on the weighting assigned to objectives. The results of the experiment indicated an additional complication that can result from using proxy attributes: objectives that were measured by proxy attributes were given greater weight than objectives measured by natural attributes (test subjects were asked to weight the same set of objectives, once with natural attributes and once with a mix of natural and proxy attributes).

A major advantage of using proxy attributes is that their use typically reduces the number of attributes needed. This simplifies the description of the alternatives and their consequences and reduces the effort needed to gather information. However, it does increase the effort necessary to specify the value model (i.e. the relationship between the proxy attribute and the measure of attainment of the objective).

Regardless of the type of attribute used, the scale of the attributes needs to be normalized, so that the total utility (or score) for each alternative can be determined across objectives. Normalization allows the analyst to compare performance across scales and units.

6.1.4 Developing and assessing alternatives

Alternatives may be identified either before or after the objectives are determined. If alternatives are identified beforehand (or set externally), then the objectives that are subsequently developed are used to assess the alternatives in a linear process. If the objectives are set first, then they may be used to identify alternatives, and then again to assess the alternatives (Keeney, 1992). This is a more iterative process, but may lead to the development of more creative alternatives.

Once the alternatives are set, they must be assessed against each of the objectives. The most convenient form for this evaluation is a consequences table. These tables list objectives down the left hand side, with alternatives (in this case, alternate strategies) across the top. The performance of each alternative against each objective is then filled in to create a matrix.

6.1.5 Weighting

Weights can be applied to the objectives using a variety of methods, two of which will be discussed here. The first method is the direct weighting technique, in which the decision maker directly assigns a weight to each objective, so that the sum of all the weights is equal to one. Using this method, it is important to keep in mind the range of performance (i.e. the scale) of each objective, since an objective with a very narrow range will have less impact on the final outcome.

The second weighting method is swing weighting. The following description of this method is adapted from Clemen & Reilly (2001). Swing weighting involves a thought experiment, in which pairs of hypothetical outcomes are considered that vary on only one attribute. One outcome will have the worst value for one attribute, and the other outcome will have the best value for that attribute. Consecutive pairs of outcomes are compared, which allows the decision maker to discover how much each attribute contributes to the over all decision.

A "benchmark" outcome is set that has the worst attribute values from all of the "real" alternatives. Then subsequent outcomes are developed that hold all but one attribute the same; the one that is varied is "swung" from worst to best value.

Once these hypothetical outcomes are developed, the decision maker ranks them. The outcome with all the worst attribute will rank last, but the ranking of the other outcomes depends on the values of the decision maker.

After completing the ranking, a rating is assigned to each outcome. The rating for the lowest ranked outcome will be 0, and the rating for the highest ranked outcome will be 100. The ratings for the other outcomes will reflect the degree of preference between the different rankings. When the ratings are done, they can be normalized, based on the sum of the ratings.

Once the weights are calculated, the overall utility of each real outcome or alternative can be calculated by multiplying the weight by the normalized attribute value for each objective, and then summing up the weighted values.

Swing weights are sensitive to the range of values that each attribute has in a given decision. For example, if the cost does not vary much between alternatives, then the rating for the alternative with the lowest cost would not vary much from the rating for the alternative with the highest cost.

6.2 Suitability of SDM for hospitals

Hospitals strive to meet many competing objectives, such as savings lives and operating within limited budgets. They also function within a regulatory structure that dictates the standard of care they should be able to provide during both typical and extreme conditions. SDM is well suited for application in this type of situation, because it allows multiple objectives to be considered, resulting in a more holistic consideration of the alternatives. Whether implicitly or explicitly, SDM allows tradeoffs to be made between healthcare service now and better healthcare service in a future emergency.

As noted in Cole (2006), hospitals have historically had a difficult time developing metrics to measure the performance of mitigation alternatives. In the 2003 Canadian Health Accreditation Report, the Canadian Council on Health Services Accreditation criticized hospitals for a lack of metrics to analyze their emergency preparedness. The 2004 report notes that hospitals have made improvement in this area since 2002.

SDM is also often used iteratively, which is a major benefit given the complexity of disaster mitigation. It is essential that disaster mitigation decisions be reviewed periodically through an iterative process that is flexible enough to adapt to changing technology and attitudes towards risk. The process should also support organizational learning and development by reviewing past decisions and looking for lessons that can be applied in the future. In addition to learning from internal experiences, if a common framework (such as that proposed here) is adopted by many hospitals, the opportunity exists for hospitals to learn from each other's experiences.

Finally, SDM is effective at engaging a wide range of stakeholders in the decision making process. Representatives of different departments and from both the administrative and operating sides of a hospital can contribute to defining the objectives and the alternatives. This can result in more creative solutions and also helps to ensure that the mitigation measures meet the needs of the people who will be keeping the hospital functioning during a disaster.

Hospitals face many challenges in implementing seismic mitigation including a shortage of funding and a shortage of personnel. While decision analysis does not provide the solution to all of these challenges, it can provide a framework for approaching the difficult decision.

The framework allows facility manager to move beyond using judgment, and to clearly articulate values, define objectives and performance measures, and then assess the tradeoffs that the alternatives require.

7 Application of SDM to seismic mitigation decisions in hospitals

The following sections describe how SDM was used to develop a prototype tool.

The tool under development built upon a strategy generation table tool that runs in MS Excel, created by Compass Resource Management (CRM). The CRM tool allows users to input individual actions, to create strategies and add actions to them, to define objectives, to input the performance of individual actions against the objectives, and to roll up the performance of individual actions to generate strategy performance. Prior to this project, the tool did not have functions for normalizing or weighting the results.

7.1 Decision context

Deciding which seismic risk mitigation activities to undertake occurs at three scales. First, hospitals must decide on the overall performance standard they wish to achieve. This decision is made in part by the National Building Code, which mandates a minimum standard for hospitals (serviceability). The decision to meet or exceed that standard is described in Section 2.2.4 and illustrated in Figure 5. Since most hospitals do not currently meet the mandated NBC standard, their primary goal will likely be to meet the standard. Since that decision is externally influenced, that context was not used for the SDM analysis.

At the other end of the spectrum, the method in CSA-S832 provides a means for ranking the risk associated with individual OFCs. The decisions that arise from the CSA-S832 method include very technical decisions based on engineering considerations, such as choosing specific mitigation actions for a given OFC (e.g. what type of restraint to use). This is considered to be too narrow a context for this project.

The current decision making mechanism lacks a framework for thinking about whether individual actions should be addressed in order of risk ranking, if a systems approach should be used, or if a room-based approach should be used. There is also no guidance for considering how to evaluate these different potential groupings of actions. These decisions are left to the discretion of the facility manager. While these managers usually have excellent knowledge of their facilities and are well equipped with the information needed to make this decision, they lack a systematic method for building and then considering the alternatives. Within the current decision-making process, the step of moving from technical risk rankings to holistically derived priorities is most in need of strengthening. Therefore, this tool focused on providing a framework for developing and prioritizing alternative strategies when risk index values for individual OFCs have been derived following the CSA-S832 method. The decision context lies between the choosing an overall performance level and the technical decision about individual OFCs, and addresses the problem of prioritizing packages of mitigation options. This is illustrated in Figure 6.

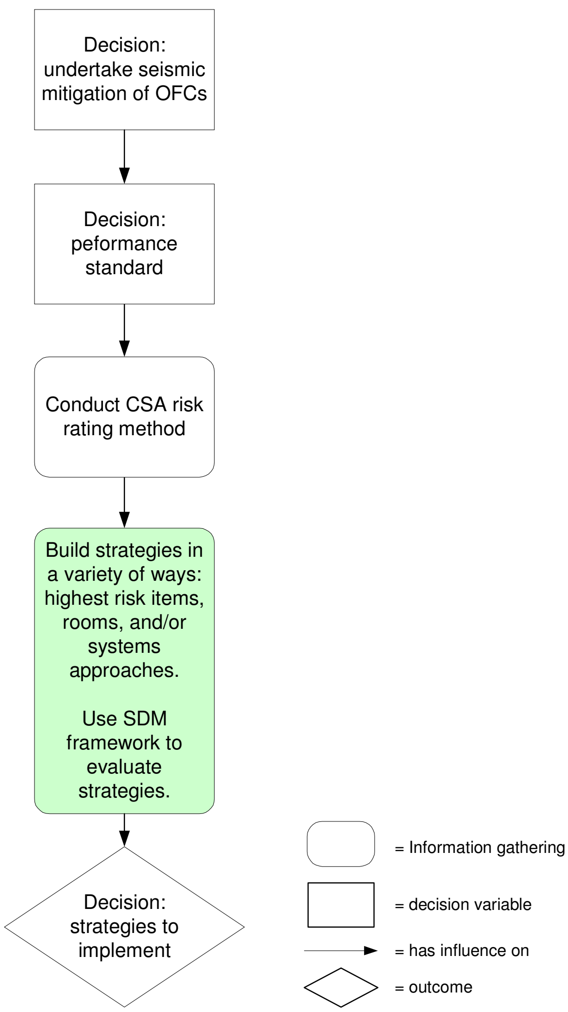


Figure 6. Decision context

7.2 Problem Statement

The question that this framework seeks to help answer is "What action or set of actions best meets the objectives of seismic mitigation?" "Best" is defined by the objectives, as detailed in the next section. Sets of actions will be defined using a strategy table, a method that is described below under "Alternatives".

7.3 Objectives & Attributes

The overall objective for seismic mitigation is to provide the greatest reduction in risk for the least amount of spending. However, this objective needs to be broken down into sub-objectives that are more easily measured. Table 1 provides a list of the objectives developed for this project, along with their associated attributes, units and preferred direction.

Table 1. Objectives and Associated Attributes

Fundamental Objectives	Lowest-Level Fundamental Objectives	Attributes	Units	Preferred Direction
Minimize total cost	Minimize capital cost	Capital expenditure	$	Low
	Minimize operation/maintenance costs	Present value of annual expenditures over 20 years	$	L
Minimize impact of disaster	Minimize duration of downtime after extreme event	Reduction in time until hospital regains normal capacity	# of days	L
	Minimize impact on hospital capacity after extreme event	Increase in capacity remaining immediately post-disaster	%	H
	Minimize mortality	Deaths averted	# of people	H
	Minimize morbidity	Incidence of disease avoided	# of incidences	H
Minimize impact of mitigation implementation	Minimize impact on normal operations during implementation of mitigation initiatives	Days of disruption during implementation	# of days	L

In a study of compliance with a seismic mitigation regulation in California, Petak & Alesch (2004) discovered that decision makers considered multiple objectives and that an acceptable solution had to meet all of them. The objectives varied by organization, but generally included: immediate affordability, long-term financial viability, serving the organizational mission, and complying with regulations and fundamental corporate strategy. The objectives above are in line with these findings, but also expand on them to include objectives related to the efficacy of the mitigation.

7.3.1 Integration with CSA-S832 and Proxy Attributes

In order to facilitate the integration of this framework with CSA-S832, the risk index can be used as a proxy attribute. While the use of proxy attributes does have some drawbacks (as described in Section 6.1.3), the advantage of minimizing data collection outweighs the drawbacks in this case. Utilizing data that has already been collected will enable administrators to apply this framework without extensive additional data collection. This will allow the decision-making process to be improved without significant extra effort.

The risk index can be used as a proxy attribute for the fundamental objective of "minimize impact of disaster". The risk index applies to all four of the sub-objectives:

- Minimize duration of downtime after extreme event
- Minimize impact on hospital capacity after extreme event
- Minimize mortality
- Minimize morbidity

The risk index is the product of the vulnerability index and consequences index. The vulnerability index is based on characteristics of the OFC (current restraint status; sensitivity to impact, pounding and/or displacement; likelihood of overturning, and flexibility), characteristics of the ground (based on ground motion and soil characteristics), and building characteristics (number of stories and lateral-force resisting system in place). A lower vulnerability index is associated with increased resilience. OFCs with lower vulnerability scores will be more robust and recovery will be faster. Vulnerability relates directly to the first two objectives listed above.

The consequences index is the sum of a life safety measure and a functionality measure. The life safety measure considers the area, the occupancy density and the duration factor (hours of occupation per week). The functionality measure considers how soon the OFC is needed following an earthquake (in more than a week; between 24 hours and 1 week; functional according to the NBC's "post-disaster facility" criteria; or fully functional immediately after an earthquake). Consequences relate directly to the final two objectives listed above.

The following influence diagram is an adaptation of Figure 5 that illustrates how proxy measures fit into the decision context, and how the proxy attributes relate to the objectives/natural attributes.

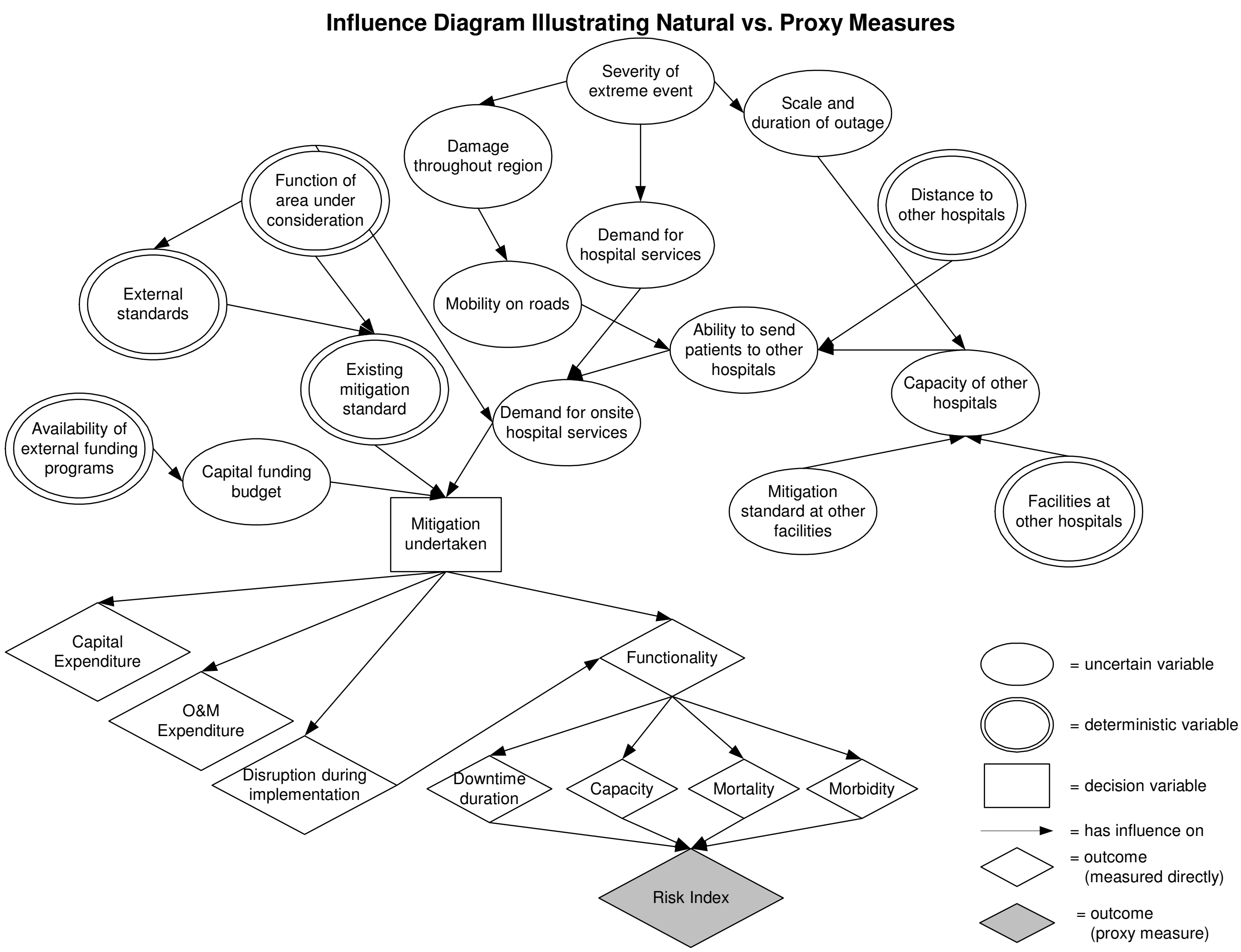


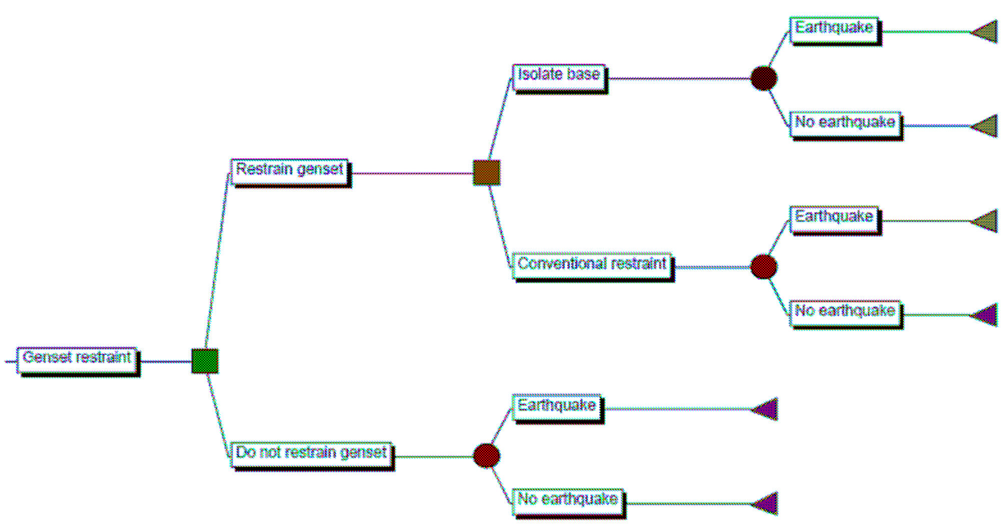
Figure 7. Illustration of Proxy measures Alternatives

Under this framework, alternatives could be considered individually (alternate means of achieving a given degree of risk reduction on a single OFC) or broader alternatives may be constructed out of multiple individual actions. The broader, constructed alternatives are referred to as strategies. The actions included in single strategy are generally tied together by a common theme, but need not be related in physical space.

7.3.2 Single Alternatives

This section briefly illustrates how the framework could be applied to consider single alternatives, although the prototype addresses the issues using strategies. A decision about a single alternative can easily be represented by a decision tree. Decision trees are used when the potential outcomes of a decision are exhaustive and mutually exclusive, and are useful for illustrating the time element and sequential nature of decisions (Clemen & Reilly, 2001). When used formally, decision trees include the probability and cost associated with each outcome, allowing the analyst to calculate the expected utility of each decision. In the case of seismic risk mitigation in hospitals, there are additional objectives beyond maximizing expected utility, as calculated by cost and probability. The desire to minimize risk may force the decision maker to make difficult tradeoffs between cost and lowered risk. Figure 8 below is a sample decision tree for the decision of whether or not to restrain a single OFC. In a real situation, there may be more than two restraint alternatives, in which case the decision tree would be modified to reflect the actual number of alternatives.

Figure 8. Decision tree for a single OFC



7.3.3 Strategies

As described above, strategies are formed by combining individual alternatives around some common theme. Different strategies are formed by focusing on different themes (or objectives). Sample strategy themes include grouping OFCs with the highest CSA risk index from throughout the hospital, grouping actions according to their location (such as in a single room or functional area), and grouping actions that are related to a single system (water, medical gas, power etc.). Once the strategies are formed, they are assessed in much the same way as individual alternatives.

While there are theoretically a staggering number of combinations of alternatives, it is important to remember, "…not all combinations make sense, that a certain decision in one area implies or at least indicates particular decisions in other areas." (Howard, 1998). As Clemen & Reilly (2001, pg 235) note, "the value… is not so much to find all possible combinations as much as to provide a framework within which all imaginable combinations can be screened easily to determine the most appropriate candidates."

Strategies are often built by using a "strategy generation table" to organize the individual alternatives and the underlying themes. A sample strategy table is illustrated in Figure 9. Should this approach be applied in an actual hospital that has undergone an assessment of its OFCs following CSA-S832, the individual actions listed would be based on the results of the assessment. In this case, no actual assessment data was available. Therefore, where realistic, general actions are known (based on mitigation actions documented in Cole (2006) and from personal communication with Jay Lewis, an expert on seismic risk mitigation) a sample of alternatives has been used; where very facility-specific actions would be generated by the CSA process, placeholder actions have been used. While many potential themes are listed down the left hand column, only one theme has been completed for strategy generation the diagram, in order to maintain the legibility of the table.

The actions circled in red are all actions that could be taken in the ER to improve its resilience in the event of an earthquake. Actions that are not directly applicable to the ER are not included, nor are actions that are applicable to the entire hospital (such as installing an EPSS). These actions would be captured by other strategies, and the multiple strategies would be compared against the mitigation objectives in the next step. The actions included in each of the strategies developed for testing the tool are listed in Appendix A.

Strategy Themes	Categories of Alternatives				
	Power	Water	Communications	Mechanical	Equipment
Focus on water system	Install UPS on equipment A	Secure water pipes from source to lab	Supply staff with walky-talkies or similar for on-site communication (12 units)	Secure boilers (4)	Secure medical equipment A
Focus on power system	Install UPS on equipment B	Secure water pipes from source to ER	Secure server racks	Secure vents, suspended ceilings and lights in Labs	Secure medical equipment B
Focus on communications/IT	Install UPS on equipment C	Secure water pipes from source to ORs	Maintain a "hot site"	Secure vents suspended ceilings and lights in ER	Secure medical equipment C
Focus on labs	Install UPS on equipment D	Secure water pipes from source to patient rooms	Purchase computers with own power supply like laptops (12 units)	Secure vents suspended ceilings and lights in ORs	Secure non-medical equipment A
Focus on ER	Install UPS on equipment E	Secure waste water pipes from labs		Secure vents suspended ceilings and lights in patient rooms	Secure non-medical equipment B
Focus on mechanical systems	Install EPSS with sufficient capacity	Secure waste water pipes from ER		Secure medical gas pipes from source to Labs	Secure non-medical equipment C
	Install portable generators that can provide limited power if the EPSS fails.	Secure waste water pipes from ORs		Secure medical gas pipes from source to ER	
	Restrain transformers (16-20 large + 50 small)	Secure waste water pipes from patient rooms		Secure medical gas pipes from source to OR	
	Restrain switch gears (8-9)	Have tanker trucks available to provide water (contract)		Secure medical gas pipes from source to patient rooms	
	Secure motor control centres (20)	Maintain inventory of alcohol-based sanitation supplies and water purification tablets		Secure medical gas canisters (400)	
	Secure conduits from electrical vault to lab, ER, OR, patient rooms (400 braces)	Secure existing water tanks		Fire suppression system (sprinklers) for labs	
		Install a seismically reinforced water storage tank		Fire suppression system (sprinklers) for ER	
		Access groundwater on the site		Fire suppression system (sprinklers) for OR	
		Install an on-site purification system for water		Fire suppression system (sprinklers) for patient rooms	
		Secure existing water treatment facilities (2-3 rooms, 20 OFCs in each)		Secure gas lines into boilers (30 braces)	
				Secure water lines into boilers (150 braces)	
				Secure pumps & motors (mech room & elsewhere) (200-300)	
				Securechillers (20)	

Figure 9. Sample strategy generation table

This approach could also be applied to non-technical (i.e. organizational) mitigation measures. Organizational mitigation measures may apply to OFCs (such as identifying which equipment needs to be on UPS or EPSS, determining the capacity of UPS and EPSS systems, and committing resources to maintaining EPSS and checking that restraints remain on equipment), or may deal entirely with organizational resources (such as having a communication strategy, creating and practicing an evacuation plan, and setting up agreements with nearby hospitals). Themes for grouping organizational measures into strategies are not as easy to define as themes for OFC measures. Most organizational measures can be implemented individually (i.e. there are fewer synergies) or can be intuitively grouped without need for a strategy generation table. Intuitive groups include: focusing on evacuation, focusing on partnering with other organizations, and focusing on community education. Organizational measures were not examined in the development of the prototype.

7.4 Consequences Table

Once a range of strategies is developed, each one must be assessed against the objectives defined earlier. A sample consequences table for OFC mitigation strategies is show in Table 2. Note that data is reported for the highest level fundamental objectives.

The performance for strategies depends on the performance of the individual alternatives actions that comprise the strategy. The performance of individual alternatives is measured against the objectives using the natural and proxy attributes defined in Section 7.3. Then the total performance of each strategy for each objective can be determined by summing up the performance for the individual alternatives that contributes to the strategy.

Data used in the prototype was supplied by Jay Lewis, based on his experience providing mitigation services to hospitals in British Columbia. All of the values are considered to be ballpark estimates based on typical conditions.

Table 2. Strategy Consequences table

Fundamental Objective	Attributes	Direction of preference	Units	Strategies: Mitigate water system risks	Mitigate power systems risks	Focus on communications/ IT	Focus on Labs	Focus on ER	Mitigate mechanical system risks
Minimize total cost	Total cost	L	$	$571,000	$975,400	$2,305,100	$663,600	$252,800	$1,697,300
Minimize impact of disaster	Risk Index	H	Reduction in risk index	1,170	1,543	277	1,125	771	3,011
Minimize impact of mitigation implementation	Days of disruption during implementation	L	# of days of dis-ruption	63	50	12	54	33	156

Note: The range of values for the risk index for individual actions is 0.024-300 (see Section 5.1.2 for an explanation). At the strategy level, the range of values for the risk index depends on the number of individual actions included in the strategies.

At this point, each strategy has an attribute value for every objective. However, since the objectives are measured in different units (cost, risk index, time), it is necessary to transform the attributes into unit-less scores that can then be added to determine the overall performance of each strategy. The performance is converted into "value units" using a value function. This involves assigning a score of 1 to the best performance and a score of 0 to the worst performance. Performances between the best and worst are assigned a value between 1 and 0. The simplest method (used in this prototype) is to assume a linear relationship between the attribute and the value. More accurate results may be obtained by using expert judgment to elicit the corresponding value for intermediate performance levels (i.e. a cost that is 10% higher than the lowest cost may not result in a corresponding reduction in value of 10%). For some objectives, the highest score is considered the best performance (such as the risk index); for other objectives, the lowest scores are considered the best performance (such as cost).

Once the value functions are established, the value units can be assigned to the strategies for each objective, and the total value units can be calculated for each strategy. At this stage, it is possible to calculate the strategy with the highest cumulative value across all objectives. A chart showing this is shown in Figure 10 (the total value for each strategy is indicated on the chart). However, this analysis has not yet taken into account that the objectives are not necessarily of equal importance to the decision-maker. Weighting the objectives provides a means of accounting for these varying degrees of importance, and is the next step.

7.5 Weighting the Objectives

As described in Section 6.1.5, swing weighting is a common method used to determine the relative importance of each of the objectives. The method outlined in Section 6.1.5 was followed to determine weights for capital cost, operating cost, addressing vulnerability, addressing consequences, and the disruption of implementation. Dr. Stephanie Chang, committee member and expert on the socio-economic impacts of earthquakes, acted as the decision maker, and performed the ranking and rating steps described above.

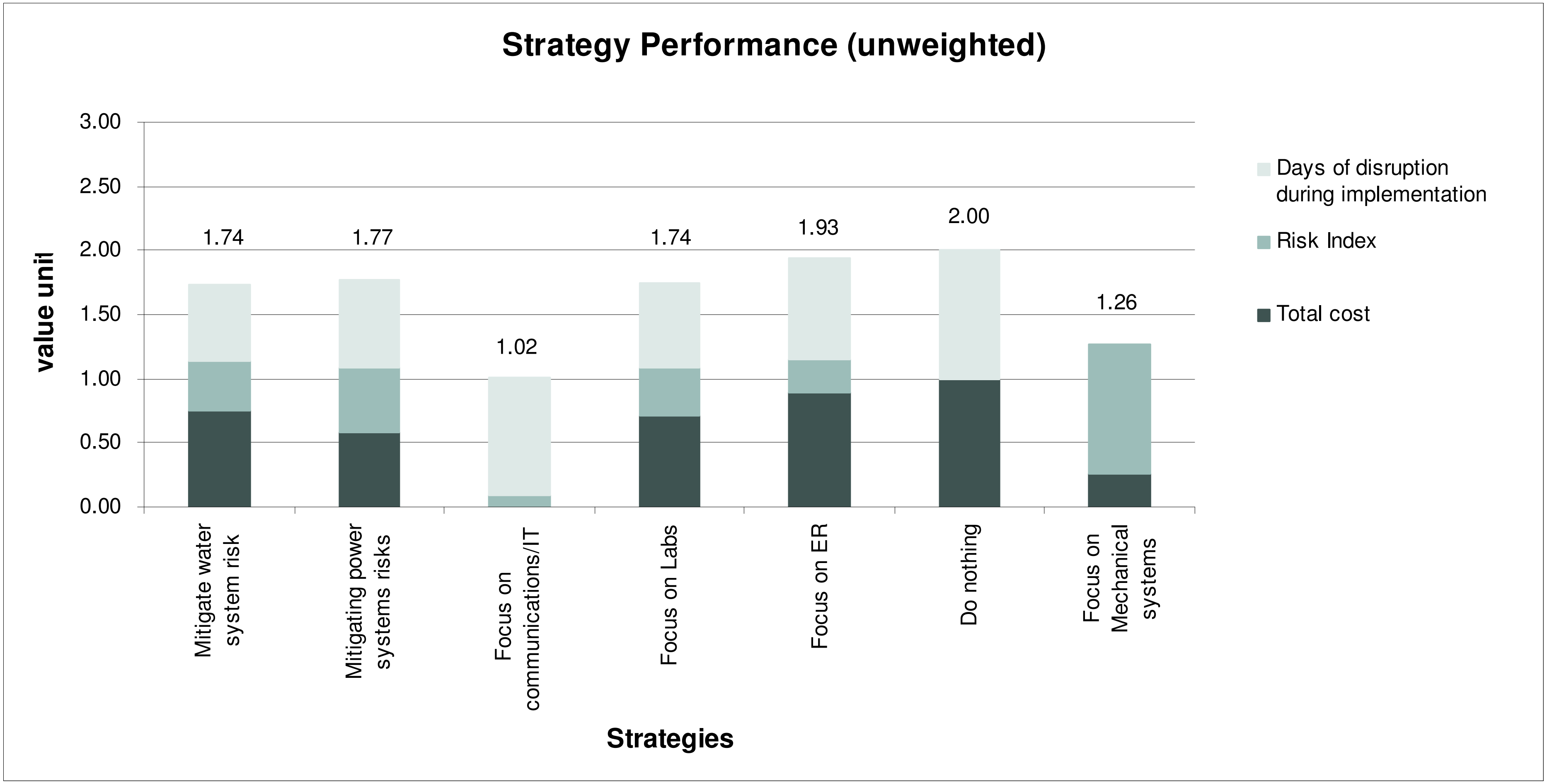


Figure 10. Normalized, unweighted scores for each strategy

Dr. Chang was presented with a table that showed the worst and best performance for each attribute. A "do-nothing" alternative was added to the strategies for comparison, although this strategy would not help hospitals meet the NBC standard. This affected the range for each attribute, since doing nothing has no direct costs, mitigates no degree of risk, and has no days of disruption. The revised ranges for each attribute, based on these decisions, are shown in Table 3.

Table 3. Data for Swing Weighting Exercise

Attribute	Worst	Best
Total Cost	$2.3 million	0
Risk Index	0	3,011
Disruption	156	0

Dr. Chang considered swinging the risk index from worst to best to be the most important change, so it was assigned a ranking of 1. Reducing the cost from $2.3 million to $0 was considered next most important and received a ranking of 2. Reducing the disruption to the hospital system, assuming that the disruption did not increase the length of the waiting list, was considered the least important change.

In the next step, Dr. Chang indicated the degree of difference between the various rankings. The top ranked attribute was given a score of 100, and Dr. Chang was asked to assign a score to the other two attributes that reflected their relative importance. This data was then used to weight the objectives that correspond to the attributes. The raw data and normalized weights are shown in Table 4.

Table 4. Swing Weighting Results

Attribute	Worst	Best	Rank	Rating	Normalized Weight
Total Cost	$2.3 million	0	2	60	0.353
Risk Index	0	3,011	1	100	0.588
Disruption	156	0	3	10	0.059

The normalized weights were then multiplied by the normalized attributes for each objective (the unweighted normalized attributes are shown in Figure 10). The final results are shown in Figure 11 (the total weighted value for each strategy indicated on the chart).

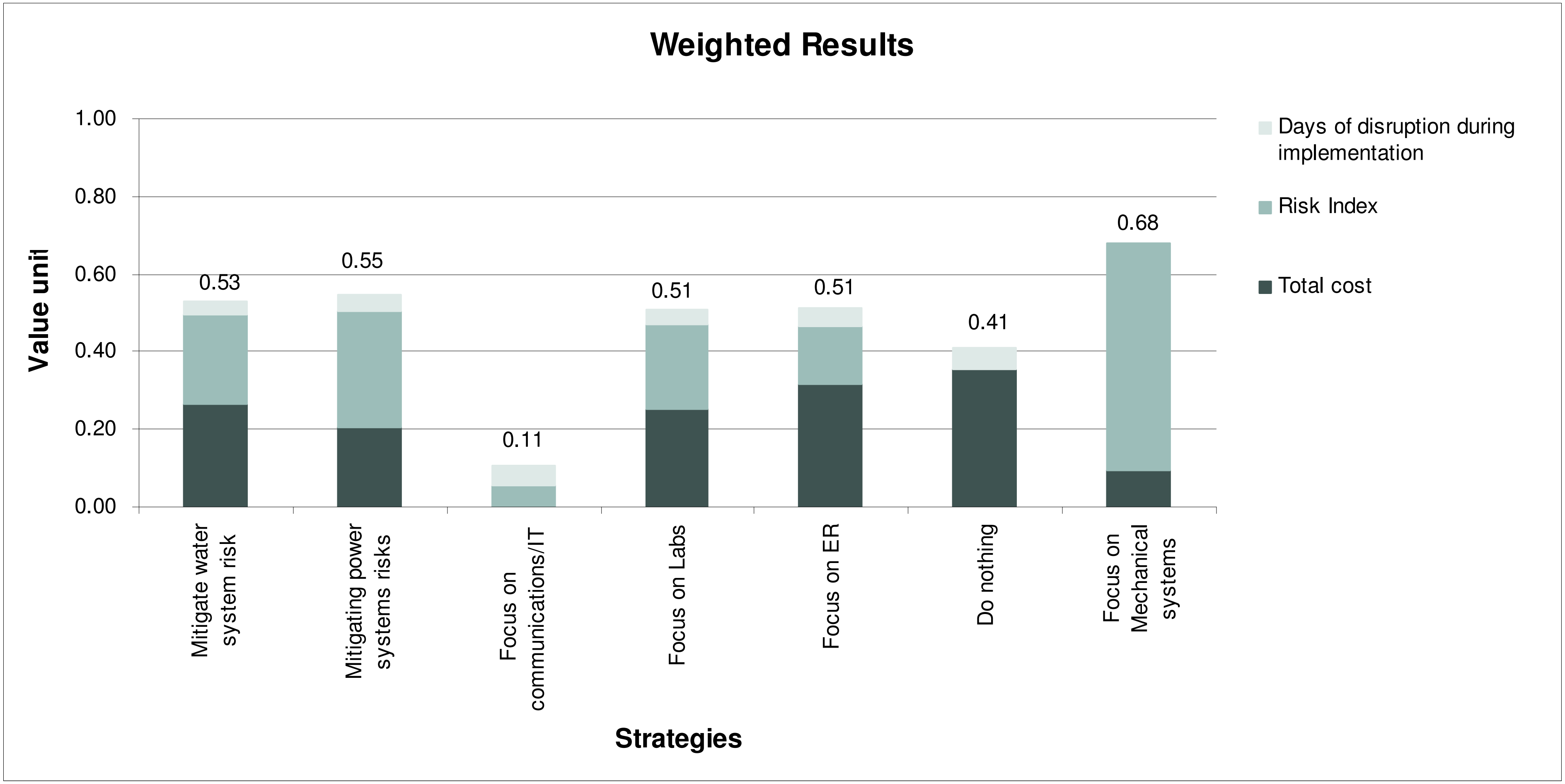


Figure 11. Normalized, weighted scores for each strategy

8 Discussion

Table 5 allows a direct comparison of the weighted and unweighted results. The weighting significantly affected the ranking of the do nothing strategy and the mechanical systems strategy. The zero cost and zero days of disruption for the do-nothing strategy give the strategy the highest unweighted value. However, the emphasis on risk reduction and the lack of emphasis on days of disruption, means that the weighted value is ranked sixth out of seven strategies. The weighting had the opposite effect on the mechanical system strategy, increasing its rank from sixth to first. The high degree of risk associated with the mechanical system outweighs its high cost and the days of disruption. .

For the remaining five strategies, the weighting did not significantly affect the relative ranking. The power and water system strategies improved their rankings slightly with the weightings, and the ER and lab strategies performed less well with the weightings. The communications/IT strategy maintained its position as the poorest performing strategy.

Table 5. Comparison of Weighted and Unweighted Results

Strategy	Unweighted Total Score (Max = 3)	Unweighted Rank	Weighted Total Score (Max = 1)	Weighted Rank
Mitigate water system risks	1.74	5	0.53	3
Mitigate power system risks	1.77	3	0.55	2
Focus on communications/IT	1.02	7	0.11	7
Focus on labs	1.74	4	0.51	5
Focus on ER	1.93	2	0.51	4
Do nothing	2.00	1	0.41	6
Mitigate mechanical system risks	1.26	6	0.68	1

To test the effectiveness of this approach, the performance of consciously constructed strategies was compared to the performance two "default" strategies. One default strategy was developed by listing the individual actions in order of their risk rankings (highest to lowest); individual actions were added to the strategy in order of risk ranking, until the risk reduction potential was no greater than that of the top ranked consciously constructed strategy (i.e. mechanical systems). The second default strategy was developed by listing the individual actions in order of their cost (lowest to highest); individual actions were added to the strategy until the total cost was no greater than the total cost of the top ranked strategy.

The strategy built from the actions with the highest risk index values had a total final score of 0.39, lower than all but the communications/IT strategy. This is because many individual actions with high risk index scores have comparatively high costs. This meant that the cost of this default strategy was $3.7 million, nearly $1.4 million more than the most expensive consciously constructed strategy, and nearly $2 million more than the highest ranked strategy, which had the same risk reduction potential.

The strategy built from the least expensive individual actions had a total final score of 0.852, which is higher than any of the final scores of the consciously constructed strategy. Using a low-cost approach meant that 50 individual actions could be included for the same budget as the highest ranked consciously constructed strategy. This meant that although the cost was capped at the cost of the highest ranked strategy, the total risk reduction potential was higher than that of the highest ranked strategy.

These results indicate that the practice of consciously constructing strategies to meet a given objective or to service a particular functional area of a hospital may be more effective at meeting the stated objectives than a naïve approach that considers only maximizing risk reduction. Although the strategy formed by setting a budget and maximizing the number of actions that can be taken within that budget resulted in the highest total risk reduction potential, it is important to note that the "consciously constructed" strategies may have not accounted for some of the benefits associated with taking a theme or area-based approach. For example, undertaking many retrofit activities in a single area may cost less than the sum of the cost of the individual actions, because of efficiencies in implementation. Similarly, addressing a single system may result in synergistically improved functionality.

9 Further Work

9.1 Conceptual Refinement

The exercise of creating this prototype has revealed that the current decision-making process about seismic risk mitigation in hospitals could benefit from the application of structured decision-making principles. Defining objectives and then measuring the performance of alternatives against those objectives will bring a greater degree of transparency and accountability to the decision-making process. Furthermore, the results from this trial run indicate that the SDM process may produce results that would not necessarily be generated otherwise.

This prototype does, however, have some shortcomings that need to be resolved before it can be launched as a useful tool. The most serious issue that needs to be resolved is the use of the risk index as a proxy attribute for duration and degree of impact, mortality and morbidity. While using the results of an existing protocol will make this tool easier to use, the risk index does not accurately measure these objectives, which means that the final results do not precisely reflect the objectives.

The risk index proxy attribute deals poorly with alternatives that consider actions other than securing and restraining OFCs. The CSA method only measures the vulnerability of existing infrastructure, and the primary consequences of infrastructure failure. Infrastructure that is not yet in place or off-site services would not be included in a CSA assessment, and would therefore not be assigned risk index values that could be use in this tool. However, these types of decisions are important (and arguably more difficult to make), and should be included in the tool. Another shortcoming of the risk index is that the consequences index, which is used to calculate the risk index, is concerned with primary consequences, such as people being trapped or crushed by equipment. The consequences index does not consider secondary consequences, such as "how many people might die if this piece of equipment is not available", or "how many illnesses may result if clean water is not available". This is a major shortcoming when applied to hospitals, since the purpose of hospitals is to provide health care. For schools or other institutional buildings, simply avoiding deaths or injuries is a sufficient consideration, but for hospitals the secondary or tertiary consequences must be considered.

The risk index also does not reflect whether or not equipment will continue to work even if it is restrained. Pieces of equipment are treated as black boxes, so although restraining the equipment may keep it from moving, it does not guarantee that it will not be broken inside. 95% of hospital equipment has not been tested on a shake table (Jay Lewis, personal communication), so its response to an earthquake is unknown.

The concepts of synergy and economies of scale resulting from a strategic approach are not yet formally integrated into the tool. As discussed above, consciously created strategies that focus on a system or functional area may have a higher risk reduction potential or reduced costs compared to the sum of the individual actions. The tool currently does not yet have a mechanism to account for these benefits, and future versions should include this if possible. The simplest approach may be to add an extra step for expert input, to allow costs and risk reduction potential to be manually adjusted.

9.2 Tool Refinement

While the concept has merit, further refinement of the tools will be necessary in order to make it truly applicable and useful to hospitals. The following changes should be investigated and tested, either within the research group, or using real data from a single hospital as a test case.

The most useful feature of the workbook supplied by CRM is the strategy generation table, and the function that builds a consequence table for the strategies out of the performance of individual actions. Without the macros in this workbook, this would be a time-consuming and error prone exercise. If there is interest in refining the tool, the following capabilities should be added by someone experienced with Excel macros. These modifications would allow the entire analysis to be completed in a single workbook and without the need to add worksheets and to create formulas.

- Enable a larger number of individual actions to be considered under each category. A larger number of categories would also be helpful.
- Build in a normalizing function for strategy performance.
- Integrate a swing-weighting function.
- Build a macro that generates the "naïve" strategies, based on cost or other objectives, as defined by the user. The limiting parameter (such as budget) and the parameter used to rank the actions could be entered by the user, and then the ranking and analysis of the strategies could be automatic.

Another feature is required to improve the swing-weighting exercise, particularly if the risk index is still being used as a proxy measure. Since the risk index is a unit-less, abstract number, it is difficult for a decision-maker to know how to trade-off risk index points against dollars or days of disruption. This would be made easier if meaning were attached to the risk index by providing sample packages that correspond to certain risk index numbers. Since the same risk index number can be achieved by a number of combinations of individual actions, a variety of packages should be provided for the maximum, minimum and middle risk index values.

Finally, the tool could be modified to incorporate an analysis of the sensitivity of the results to the weights assigned to the objective. This would reveal how much the weights would have to change for the rankings of the alternatives to change. These results could be taken back to the decision-makers who generated the weights; the decision-makers could then evaluate whether or not the uncertainty associated with the weights (stemming from the range of acceptable values for the weights) had any impact on the final results.

10 Conclusion & Recommendations

Structured decision-making is a proven method for approaching complex problems. It is a tool that can be used help to sift through the often-conflicting objectives and to define and assess alternatives. It does not generate the "right" answer, but its use helps to define the characteristics of the best answer.

In the context of hospitals making decisions about seismic risk mitigation, SDM can be used to articulate objectives and to combine individual actions together in ways that maximize performance. The difficulty of this application of SDM lies in finding suitable performance measures for risk reduction. Natural attributes such as the impact of an action on the percent of hospital capacity remaining, or on the duration of reduced capacity, are difficult to determine. In this prototype framework, a proxy attribute was introduced that took the place of four natural attributes. Although the proxy attribute is straightforward to calculate for many individual actions, it is not applicable to some actions, and misses some of the nuances of the objectives.

The use of SDM in this context is worth exploring in further detail, and it is recommended that staff at the Disaster Preparedness Research Centre continue with this line of inquiry. Partnership with a hospital would aid this investigation, and help to ensure that the tool met the needs and constraints of real users.

Table A1. Actions included in Strategies

Mitigate water system risk	Mitigating power systems risks	Focus on commun-ications/ IT	Focus on Labs	Focus on ER	Focus on Mechanical systems	Highest risk	11 Lowest cost
Secure water pipes from source to lab	Install UPS on equipment A	Supply staff with walky-talkies or similar for on-site communication (12 units)	Install UPS on equipment A	Install UPS on equipment C	Restrain transformers (16-20 large + 50 small)	Install EPSS with sufficient capacity	Secure medical gas canisters
Secure water pipes from source to ER	Install UPS on equipment B	Secure server racks	Install UPS on equipment B	Install UPS on equipment D	Restrain switch gears (8-9)	Maintain an adequate reserve fuel supply (>24 hrs)	Supply fire extinguisher in room A
Secure water pipes from source to ORs	Install UPS on equipment C	Maintain a "hot site"	Secure conduits from electical vault to lab, ER, OR, patient rooms (400 braces)	Secure water pipes from source to ER	Secure motor control centres (20)	Maintain an adequate reserve fuel supply (>72 hrs)	Supply fire extinguisher in room B
Secure water pipes from source to patient rooms	Install UPS on equipment D	Purchase computers with own power supply like laptops (12 units)	Secure water pipes from source to lab	Secure waste water pipes from ER	Secure conduits from electical vault to lab, ER, OR, patient rooms (400 braces)	Perform scheduled maintenance, testing and operation check on EPSS.	Secure non-medical equipment B
Secure waste water pipes from labs	Install UPS on equipment E		Secure waste water pipes from labs	Have tanker trucks available to provide water (contract)	Secure water pipes from source to lab	Install a means of cooling the EPSS if water is not working	Secure non-medical equipment C
Secure waste water pipes from ER	Install EPSS with sufficient capacity		Secure existing water tanks	Supply staff with walky-talkies or similar for on-site communication (12 units)	Secure water pipes from source to ER	Install portable generators that can provide limited power if the EPSS fails.	Secure medical equipment A
Secure waste water pipes from ORs	Install portable generators that can provide limited power if the EPSS fails.		Secure existing water treatment facilities (2-3 rooms, 20 OFCs in each)	Purchase computers with own power supply like laptops (12 units)	Secure water pipes from source to ORs	Secure water pipes from source to lab	Secure medical equipment B

Mitigate water system risk	Mitigating power systems risks	Focus on commun-ications/ IT	Focus on Labs	Focus on ER	Focus on Mechanical systems	Highest risk	12 Lowest cost
Secure waste water pipes from patient rooms	Restrain transformers (16-20 large + 50 small)		Supply staff with walky-talkies or similar for on-site communicatio n (12 units)	Secure vents suspended ceilings and lights in ER	Secure water pipes from source to patient rooms	Secure drop ceilings in ER	Secure medical equipment C
Have tanker trucks available to provide water (contract)	Restrain switch gears (8-9)		Purchase computers with own power supply like laptops (12 units)	Secure medical gas pipes from source to ER	Secure waste water pipes from labs	Secure water pipes from source to ER	Secure non-medical equipment A
Secure existing water tanks	Secure motor control centres (20)		Secure vents, suspended ceilings and lights in Labs	Fire supression system (sprinklers) for ER	Secure waste water pipes from ER	Secure vents in ER	Install UPS on equipment E
Install a seismically reinforced water storage tank	Secure conduits from electical vault to lab, ER, OR, patient rooms (400 braces)		Secure medical gas pipes from source to Labs	Secure medical equipment B	Secure waste water pipes from ORs	Secure water pipes from source to ORs	Maintain inventory of sanitation supplies such as alcohol-based cleansers that can be used in case of low potable water levels
Access groundwater on the site			Secure medical gas canisters (400)	Secure non-medical equipment B	Secure waste water pipes from patient rooms		Perform scheduled maintenance, testing and operation check on EPSS.
Install an on-site purification system for water			Fire supression system (sprinklers) for labs		Secure existing water tanks		Install UPS on equipment D
Secure boilers (4)			Secure medical equipment A		Secure existing water treatment facilities (2-3 rooms, 20 OFCs in each)		Install UPS on equipment B
Secure water lines into boilers (150 braces)			Secure non-medical equipment A		Secure boilers (4)		Install UPS on equipment A

Mitigate water system risk	Mitigating power systems risks	Focus on commun-ications/ IT	Focus on Labs	Focus on ER	Focus on Mechanical systems	Highest risk	13 Lowest cost
					Secure vents, suspended ceilings and lights in Labs		Secure drop ceilings in ER
					Secure vents suspended ceilings and lights in ER		Secure vents in ER
					Secure vents suspended ceilings and lights in ORs		Secure drop ceilings in Labs
					Secure vents suspended ceilings and lights in patient rooms		Secure drop ceilings in OR
					Secure medical gas pipes from source to Labs		Secure vents in Labs
					Secure medical gas pipes from source to ER		Secure vents in ORs
					Secure medical gas pipes from source to OR		Secure drop ceilings in patient rooms
					Secure medical gas pipes from source to patient rooms		Secure vents in patient rooms
					Secure medical gas canisters (400)		Secure boilers
					Fire supression system (sprinklers) for labs		Supply staff with walky-talkies or similar for on-site communication
					Fire supression system (sprinklers) for ER		Install UPS on equipment C

Mitigate water system risk	Mitigating power systems risks	Focus on commun-ications/ IT	Focus on Labs	Focus on ER	Focus on Mechanical systems	Highest risk	14 Lowest cost
					Fire supression system (sprinklers) for OR		Secure medical gas pipes from source to OR
					Fire supression system (sprinklers) for patient rooms		Secure medical gas pipes from source to ER
					Secure gas lines into boilers (30 braces)		Secure medical gas pipes from source to Labs
					Secure water lines into boilers (150 braces)		Secure medical gas pipes from source to patient rooms
					Secure pumps & motors (mech room & elsewhere) (200-300)		Maintain an adequate reserve fuel supply (>24 hrs)
					Secure chillers (20)		Secure water pipes from source to patient rooms
					Secure air handling units (40)		Secure existing water tanks
							Have tanker trucks available to provide water
							Provide an alternate way to access the server
							Maintain an adequate reserve fuel supply (>72 hrs)
							Secure water pipes from source to lab

Mitigate water system risk	Mitigating power systems risks	Focus on commun-ications/ IT	Focus on Labs	Focus on ER	Focus on Mechanical systems	Highest risk	15	Lowest cost
							Secure waste water pipes from labs Secure water pipes from source to ER Secure water pipes from source to ORs Secure waste water pipes from ORs Secure waste water pipes from ER Secuure waste water pipes from patient rooms Install a seismically reinforced water storage tank Put measures in place for retrieving medical records Install a means of cooling the EPSS if water is not working Implement a network that provides real-time data about Emergency Department status, ICU beds available, and hospital beds available over the Internet.	

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