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MODELLING THE IMPACT OF EXTREME WEATHER EVENTS ON HOSPITAL FACILITIES MANAGEMENT USING A SYSTEM DYNAMICS APPROACH

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Heatwaves kill more Australians per year than any other type of natural disaster and are predicted to increase in intensity and frequency due to climate change. Effectively designed and managed hospitals are therefore a critical and central part of a community's response to such events. While our understanding of these impacts is increasing, the impacts of potential knock-on effects from other critical infrastructure are not well understood. Using a case study approach, system dynamics is used to investigate the impact of heatwaves on community infrastructure and healthcare facility management outcomes. This provides hospital facility managers with a new way to understand and maximise the resilience of hospitals to the effects of extreme weather events.

Keywords: facility management, heatwaves, system dynamics, hospitals, risk management, health, extreme weather events

INTRODUCTION

The United Nation's Intergovernmental Panel on Climate Change (IPCC 2011) found that in the 21st century "it is *very likely* that the length, frequency and/or intensity of warm spells, or heatwaves, will increase over most land areas" (the italicised phrase "very likely" is one of the IPCC's standard terms, used to denote a probability of over 90%). They predict that these heatwaves will have greatest impact on sectors with close links to climate such as "health" and "infrastructure" (IPCC 2011: 12). In Australia, heatwaves present a particularly high health risk and kill more people than any other natural disaster (PWC 2011). While new Australian hospital buildings are reasonably resilient to climate change, there is considerable scope to improve the resilience of existing building stock through new adaptation strategies (DEWR 2007, Loosemore *et al.* 2011). Not only do heatwaves increase the demand for hospital services by affecting morbidity and co-morbidity, they also have the cumulative effect of disrupting critical hospital and community infrastructure such as electricity supply with subsequent knock-on effects to other critical systems such as water, gas, transport and waste treatment (The Royal Academy of Engineering 2011, DEFRA 2011, PCI 2011). For example, the Victorian heatwave in January 2009 resulted in rolling blackouts, cutting off power to over 500,000 people and disrupted public services such as health and telecommunications (NCCARF 2010). Similar affects have been experienced in many other countries. Both Klein (2005) and Hiete *et al.* (2011) reveal

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how electrical power outages are common around the world and how healthcare facilities are especially vulnerable to failures such as in lighting systems, communications technologies, computer systems, heating and cooling systems, water supply and filtration, food storage, refrigeration, operating theatres and alarm systems. Yet as Hiete (2011) also points out, there has been little research done in this area. Therefore, in this context, the aim of this paper is to report research that investigated the potential impact of extreme weather events including heatwaves on the effective management of healthcare facilities.

USING SYSTEM DYNAMICS TO ASSESS RISK

Loosemore *et al.*'s (2011) assessment of the facility-related risks posed to hospitals during extreme weather events uncovered a wide range of risks and opportunities. During a follow up study, the analysis of interdependencies related to these risks and opportunities demonstrated the limitations of traditional "tick-box" risk management methodologies to understand the problem and develop effective response strategies (McGeorge, *et al.* 2011). These, they argue, produce an artificially linear and static picture of hospital exposure, whereas the impact of an extreme weather event is in fact dependent on a dynamic network of time-related interdependencies within a complex array of human, organisational, technological and physical sub-systems. As Koubatis and Schonberger (2005) point out, traditional approaches to risk management were designed for simple linear systems in relatively stable environments and are inappropriate for complex, dynamic and interdependent systems (such as hospitals) in unpredictable environments.

Given the significant limitations of existing risk management approaches in understanding heatwave risks on hospital infrastructure and the predicted increase in heatwave events, there is an urgent need to employ new methods which can model these subsystem interdependencies in order to develop new evidence-based strategies to mitigate these risks. In this context, system dynamics (SD) holds significant potential. SD is a perspective and set of tools that allow us to better understand and model the structure and dynamics of complex systems (Sterman 2000). SD methods are able to represent and simulate, over time, the complexity, nonlinearity, time dependency and feedback loop structures that are inherent in complex systems such as hospitals.

Simulation models have previously been used to map hospital operations such as patient flows (Lane *et al.* 2000; Yi *et al.* 2010) and the provision of healthcare in a disaster situation (Fawcett and Oliveira 2000). Arboleda *et al.* (2007) used a system dynamics simulation model to assess the impact of an earthquake on the occupancy and patient flow of a health care facility in America, taking into consideration the disruption posed to the water, power and the road network.

The advantage of using a SD approach is not only its ability to model health system interdependencies during such events but the production of a simulation tool which will enable health system facility managers to experiment, in a virtual world, with different hospital risk control strategies to optimise health care outcomes. This "collaboration artefact" enables stakeholders to engage in group model building, policy design and testing which can help design more effective policies and organisations (Martinuzzi and Kopp 2011). Given the 24/7 operation of most hospitals and the criticality of services provided to the community, such experiments are extremely problematic if not impossible in the real world.

METHODOLOGY

A multiple case study approach was adopted for this study because case studies represent the best way to study complex, open systems such as healthcare (Yin 2009). Our case studies were chosen in close consultation with partner health services in Australia and New Zealand and are described in Table 1.

Table 1: Case studies

Case study	Description
1.	Coffs Harbour hospital is the largest hospital on the North Coast of NSW and is the area's major referral hospital.
2.	Ceduna hospital provides primary healthcare to the residents of Ceduna and surrounds in South Australia. Ceduna has a population of 3,500 people and 24% of the population are Aboriginal and Torres Strait Islanders.
3.	Whangarei district hospital is located 160km from Auckland, New Zealand, and is the largest urban centre in the Northland region, serving a population of about 75,000.

Case study data were collected using a proprietary system called Risk and Opportunities Management System (ROMS 2012). Using ROMS, focus group sessions were conducted at each case study hospital with key stakeholders such as facility managers, business managers, emergency staff, nurses, clinicians, hospital administrators and community health specialists. Transcripts of the workshops were then cross-referenced and analysed using content analysis to map the interplay of the many interdependent subsystems identified. This process represents the first stage (qualitative reflection) in employing a SD methodology (see Figure 1). The methodology consists of four main stages: Qualitative Reflection; Computer Model Formulation and Simulation; Simulation Testing & Evaluation; and Simulation Policy and Interaction Experiments (Zagonel 2002).

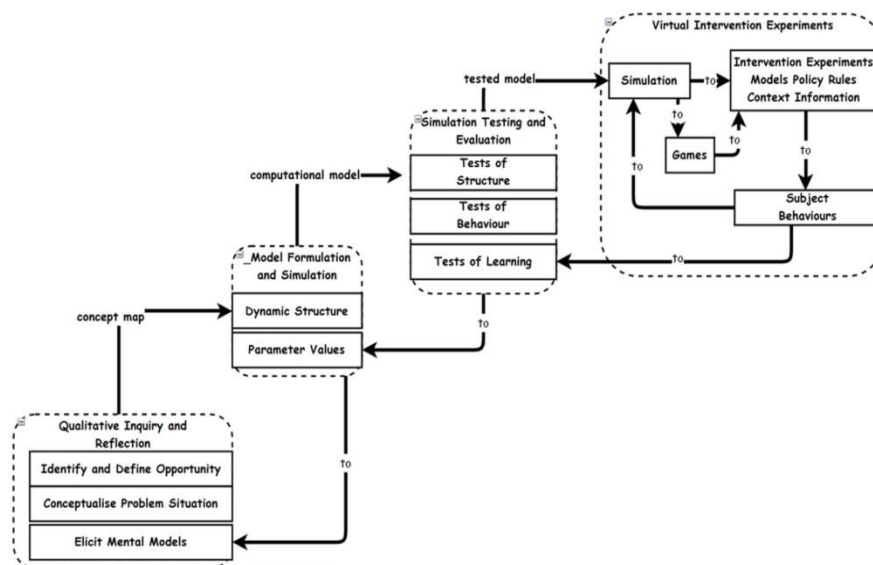


Figure 1 SD methodology (Source: adapted from Zagonel 2002)

Following the “Qualitative Reflection” stage described above, the “Computer Model Formulation and Simulation” stage involved creating an aggregated top down model

by producing rich picture diagrams (RPDs) of the three case studies using a pattern recognition technique developed by Guest and McLennan (2003). In essence, a RPD is a pictorial multi-layered representation of the real world using symbols to represent sub-systems and their relationships within a defined system boundary (Patching 1990). We then aggregated and synthesised the information into a single map of linked concepts, where relationships between main concepts are connected by “linking words” or “linking phrases” (Novak and Cañas 2008). The resulting concept map is presented in Figure 2.

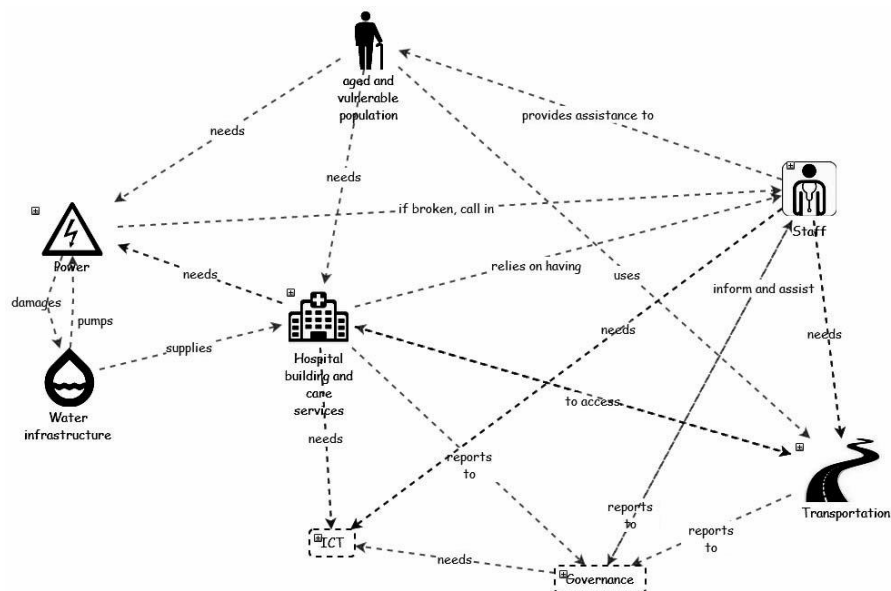


Figure 2 Aggregated map of linked concepts

The aggregated linked concept map shown in Figure 2 represents a generic model of the various components of the system which can be affected by an extreme weather event such as a heatwave. The effectiveness of the whole system in responding is therefore determined by how well these interdependencies are recognised and enabled through the various interacting management systems and through the informal actions of human actors who might be forced to move outside those systems (the invisible organisation). This concept map was then converted into a dynamic map of stocks, flows and interactions of key items of interest in the system using a process view, together with the relevant connecting information feedbacks and delays. While the RPD emphasised the interactions of the system, stock and flow diagrams represent their underlying physical and feedback control structure (Sterman 2000). In simple terms, stocks represent accumulations of money, materials and information in the system and flows represent the rate of increase or decrease in those stocks over time as the system operates. For example, as patients are admitted, treated and cured through health care services being delivered, the number of patients staying in the hospital rises and falls. In creating a stock and flow diagram, it is important to define an appropriate level of aggregation and a boundary for the stock and flow maps. The stock and flow diagram for our aggregate linked concept map is illustrated in Figure 3 and was produced using a program called Insight Maker (<http://insightmaker.com/>).

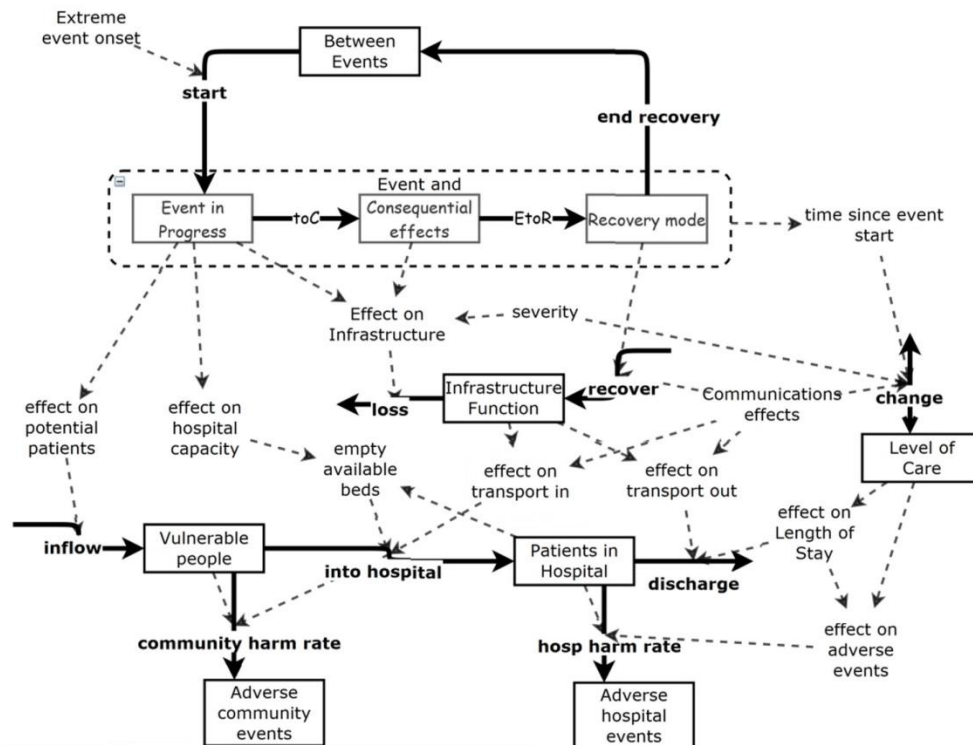


Figure 3 Stock and flow diagram created using Insight Maker

An extreme weather event directly affects the flow of patients and the level of care available from within the hospital. The top of the diagram shows the timing of the event and its consequences, the loss and recovery of community infrastructure, and the change in the level of care inside the hospital. The bottom of the diagram shows the flow of patients from the community to the hospital and the accumulation of adverse events suffered by the patients as a result of not receiving care in time.

During the third “Simulation and Testing” phase of Zagonel’s SD method the stock and flow model was progressively refined over multiple iterations with experts and differences between the real world event patterns and the model outputs were detected and reconciled. Sterman (2000:852) describes modelling as “... a process of communication and persuasion among modellers, clients and other affected parties. The real test is whether the model helps make better decisions. Therefore it is important to test the overall suitability of the model for its purpose, its conformance to fundamental formulation principles, the sensitivity of results to uncertainty in assumptions, and the integrity of the modelling process.”

The final stage of the SD method was to simulate the model which involved experimenting with parameter values to test the resilience of the system in the face of different scenarios. In our case this was a heatwave with and without an induced electrical outage scenario. These scenarios were constructed around the impact of the heatwave followed by an induced electrical outage on the model’s key performance measures. The scenario fed into the model was generated out of our second ROMS workshop at Ceduna District Health Services. The hospital is located in a very isolated arid zone with hot dry summers and very high temperatures. Although extreme heat has been common historically in Ceduna, periods of prolonged temperatures in the mid 40 degrees Celsius range has increased in frequency and intensity in recent years. One of the scenarios envisaged in this workshop was that a heatwave could potentially stress or even knock-out electrical supply due to electrical grid and generator

overload. This would in turn reduce the capacity of the hospital to deliver appropriate levels of care to their area. Also, some supporting care agencies' occupational health and safety policies prevent their staff from road travel during heatwaves due to extreme heat and fire risks, which further limits the level of care that is delivered at the hospital and in the local community.

RESULTS

A proof-of-concept model was set up to first examine various parameters of the hospital healthcare system as identified in Figure 3. Key performance indicators which best represented the successful functionality of a hospital were selected. Some of these indicators and their descriptions are given in Table 2 below.

Table 2: Selected hospital key performance indicators

Key performance indicators	Description
1. Access functionality index	The extent to which the road infrastructure providing hospital access retains their functionality.
2. Index of care	The ability for care to be provided to patients.
3. Adverse non-admit events	Number of patients who will likely suffer an adverse impact due to the inability to access hospital treatment in time.
4. Adverse hospital events	Number of patients who will likely suffer some sort of adverse impact while inside the hospital.
5. Time under care	The total amount of time it takes for a patient to be treated, measured from when they fall ill/are injured, to when they are discharged from the hospital after receiving the treatment required.

Our base case scenario assumes a heatwave event that starts on day 5, lasts 14 days, and then takes a further 2 days to ease. A behaviour-over-time graph of this base scenario is generated to explore likely short to medium term effects the heatwave event may have on the hospital system. Figure 4 shows that the road access remains 100% functional during the first 6 days, before starting to decline to 75% between days 6 and 18.5. It recovers rapidly and is again fully functional by day 21. This takes into account the cumulative effect of a proportion of healthcare staff being prohibited from travelling by road, which abates abruptly once the event has past. The index of care, which is directly influenced by how well staff and patients can access the hospital, follows a similar pattern to road access functionality but then takes significantly longer to recover. The recovery rate depends on how severely care has been disrupted; how long the consequential effects of an event last; and how quickly the hospital is able to progress from "response" mode to "recovery" mode.

The two key performance indicators discussed above have a knock-on effect on the number of "adverse non-admit events" and "adverse hospital events" in the healthcare system. Both are influenced by the prevalence of vulnerable people in the hospital's catchment area, which increases during and immediately after a heatwave event. However, "adverse non-admit events" is also caused by the inability of patients to access the hospital due to unsafe road conditions; whereas "adverse hospital events" is exacerbated by prolonged waiting times at the hospital due to a reduced "index of care". Both will contribute to the total number of adverse events, but as they have different causes it is important to monitor them independently.

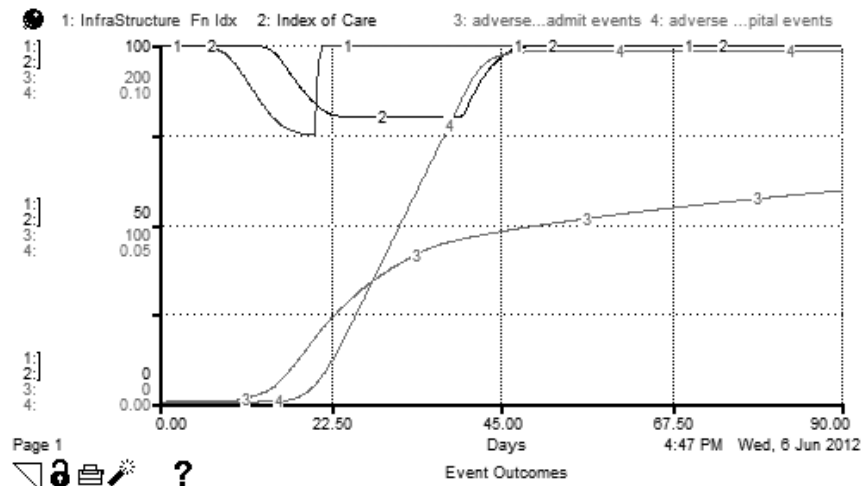


Figure 4 Behaviour-over-time graph showing the effects of a heatwave scenario without electricity outage on (1) access functionality index; (2) index of care; (3) adverse non-admit events; and (4) adverse hospital events

After establishing the base scenario, we then reconfigured the model parameters to simulate a power outage scenario, assuming that it will extend the heatwave crisis and delay the start of the recovery process by 4 days. The new behaviour-over-time graph (Figure 5) shows that in the event of a power outage during a heatwave, the “index of care” decreases significantly to 60% of its full capacity and takes slightly longer to recover afterwards. Cumulative “adverse non-admit events” increase from 109 to 158 events by day 90, and the “adverse hospital events” also increase from zero events to 0.5 events.

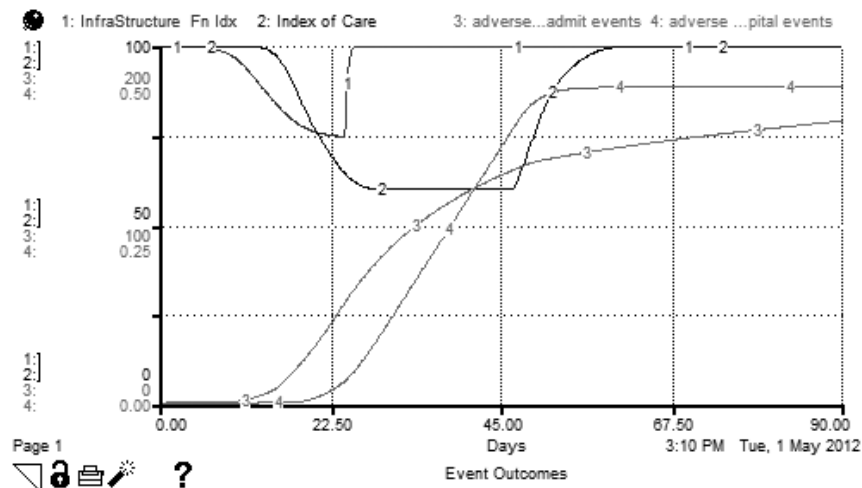


Figure 5 Behaviour-over-time graph showing the effects of a heatwave scenario without electricity outage on (1) access functionality index; (2) index of care; (3) adverse non-admit events; and (4) adverse hospital events

Figure 6 shows how an electrical outage scenario would negatively impact on the efficiency of the hospital system. In the base scenario, it has been assumed that the

average length of stay at this hospital is 8 days. In a heatwave scenario, due to a surge in patient demand, patient treatment is delayed, and the total length of stay peaks to 20 days on day 39 before slowly readjusting to 12 days by day 90. Where an electrical outage occurs as well, the problem is exacerbated and the total length of stay peaks to 23 days on day 46. The graph demonstrates the realities of feedbacks and delays raised earlier: that although the heatwave event last 14 days, it will affect the hospital system for a much longer period. The severity to which it affects the hospital system depends in part on how badly the system is hit, and how long the system takes to begin to recuperate from the event. This graph shows the accumulation of a range of competing factors affecting delivery of care in hospitals. It demonstrates a holistic understanding of admission rates and occupancy during and immediately after heatwave events, allowing hospital facility managers to more adequately address facilities and spatial requirements for hospitals throughout times of need.

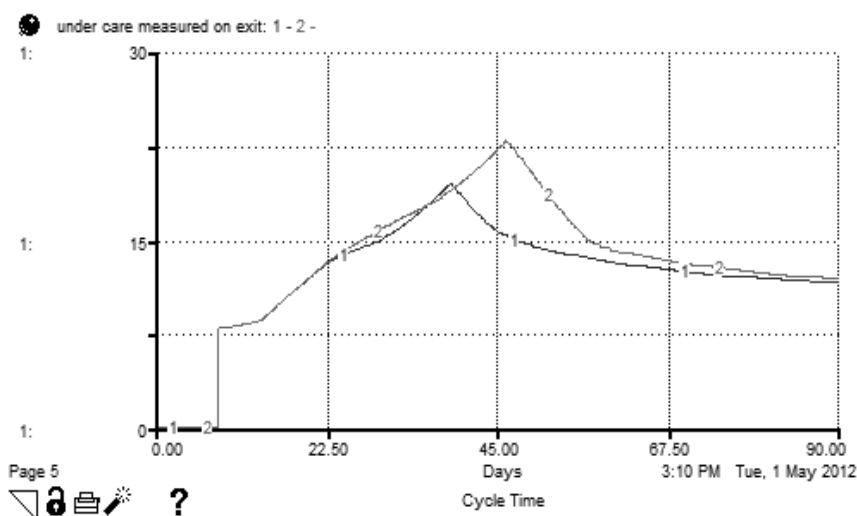


Figure 6 “Time under care” in the base heatwave scenario (1) compared with the generator failure scenario (2)

CONCLUSIONS

A proof-of-concept SD model of extreme weather events was used to replicate the history of a specific heatwave event, based on the known data from that event. Key performance indicators for the hospital system were selected and parameters were set to explore how the hospital system might cope first under the known heatwave scenario, and then when combined with a hypothetical outage scenario. A series of virtual experiments were conducted to test the extent to which vital functions, such as the “index of care”, would be lost, and how long they would take to recover fully.

By examining the interactions and co-dependencies of various parameters, this study demonstrates the importance of understanding stocks, flows and delays in a complex system such as a hospital system. It allows the user to test how changing a particular parameter, such as the duration of event or recovery time, may impact on the system as a whole, enabling a holistic instead of a myopic approach to problem solving. This general model can be used to aggregate experiences of a variety of extreme weather events. By focusing future data collection for extreme weather events on test strategies to improve resilience to a wide range of events and their consequences, this model can improve the rate of learning from past events. It can also safely test, in a virtual world,

specific intervention methods to determine their effectiveness in mitigating the loss of function in such events in the future.

Systems thinking and SD challenges existing linear and reductionist ways of approaching risk management, in the field of facilities and construction management. This paper has shown that it has significant potential to be used effectively to supplement existing risk management strategies for facility managers, who by necessity often view their facility in isolation from the surrounding infrastructure in which it is imbedded. Taking the systems view allows policy makers and managers to consider the connectivity and interdependency of their asset in the wider policy and strategic environment.

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