18TH WORLD CONFERENCE ON EARTHQUAKE ENGINEERING
WCEE2024
MILAN

MILAN, ITALY
30TH JUNE - 5TH JULY 2024
www.wcee2024.it

UTILISING RISK ANALYSIS TO PREDICT POST-EARTHQUAKE FUNCTIONALITY OF CRITICAL HEALTHCARE FACILITIES

M. Boston[1] & B. Mayer[2]

[1] University of Waikato, Hamilton, New Zealand, megan.boston@waikato.ac.nz

[2] University of Waikato, Hamilton, New Zealand

Abstract: *Hospitals, particularly emergency departments, are vital to a community's resilience and earthquake recovery by providing emergent and ongoing critical care. Building standards and codes have higher structural requirements for hospital structures to help ensure continued functionality; nevertheless, hospitals are often damaged, evacuated or closed following design-level earthquakes. While post-earthquake hospital functionality has been the focus of recent research, it remains challenging to predict hospital functionality in a relevant and meaningful manner. Existing methods to quantify functionality are based on patient wait time, bed count, or available services. This work focuses on improving existing hospital functionality frameworks to predict various levels of hospital functionality using a combination of fault and event trees to provide a probabilistic prediction of different levels of functionality based on available services and bed counts for hospital emergency departments and whole hospitals. Fault and event trees were created using published data on hospital damage, evacuations, and operations following earthquakes and combined with international guidelines on hospital requirements and local hospital emergency procedures. The fault and event trees relate physical damage, staff shortages, and equipment failures to various hospital and emergency room functionality levels. Event trees provide a sequence of events (availability of critical staff, structural damage, and non-structural damage) leading to various levels of hospital functionality (full, partial, or not functional). Each event has an associated probability of occurring determined by a developed fault tree specific to that event failure. The methodology was validated using an additional hospital dataset to hindcast the functionality of the hospital facility. The hindcasted results match the published functionality data, indicating that this method provides a way to predict levels of functionality, which can indicate what types of services and space will be available for treatment following an earthquake.*

1. Introduction

Buildings in earthquake regions are prone to damage that can disrupt building functionality. Most building codes require buildings to be designed for life safety. However, a building designed for life safety can potentially still have significant structural, non-structural, or utility damage, rendering these structures unfit for occupation or unable to maintain functionality. Critical facilities, such as hospitals and other healthcare facilities are commonly designed to a higher standard to preserve their critical functionality. Yet, despite this higher level of design, experience has shown that hospitals are still prone to damage (Chen et al., 2018; Perrone et al., 2019), loss of functionality (Jacques et al., 2014), or even extended closures in the aftermath of large-scale earthquakes (Nagata et al., 2017). Hospitals and other healthcare facilities are essential during the immediate earthquake recovery and for the community's long-term recovery.

1.1. Building functionality

Building functionality is an indication of a building's ability to serve its intended purpose. In recent work to develop standardised methods for assessing functional recovery, ATC-138 defines three basic levels of recovery: reoccupancy, functional recovery, and full functionality. Functional recovery refers to the ability of a structure to be used for its basic intended purpose, though the level of function may be less than expected or full functionality (ATC, 2021). Likewise, Mieler and Mitrani-Risier (2018) define six levels of functionality: none, restricted entry, restricted use, reoccupancy, baseline, and full. Of these six, only the last two, baseline and full, consider the ability of the structure to cater for its intended purpose. Functional recovery is not a clearly defined state (Li et al., 2023), but an indication that the building can be used as intended, while full recovery occurs when all of the repairs are complete and the buildings is returned to its pre-earthquake condition. Different levels of functional recovery for a building can depend on its intended use and what can be done within the damaged environment or while repairs are being completed. A functional building may have reduced services or capacities until it is fully repaired. Functionality can be plotted over time as a resilience curve (Bruneau et al., 2003) to provide an visual indication on how functionality changes over time.

1.2. Hospital functionality

Assessing hospital functionality is an ongoing topic of international research (Mahmoud et al., 2023). Measurement of functionality has been quantified in different forms, including bed count (Jacques et al., 2014), patient waiting times (Cimellaro et al., 2011), or number of services that can operate (Boston, 2017).

As hospitals in their entirety are complex systems, much of the existing literature focuses on quantifying functionality based on the performance of the hospital’s emergency department (Chen et al., 2018; Cimellaro & Piqué, 2016; Shang et al., 2020). Such efforts have the benefit of focusing on a smaller subset of the hospital while still capturing much of the complex internal and external dependencies of the larger hospital system. The functionality of an emergency department can be used to project the estimated functionality of the wider hospital. Further, emergency departments are vital to a community's immediate and ongoing recovery (Palomino Romani et al., 2023). Developing functionality assessment tools focused on the emergency department allows for the assessment of the immediate functionality of one of the most critical pieces in delivering healthcare aid following an earthquake.

As hospitals are complex systems offering a range of emergent and long-term medical care, functional recovery is not a clear binary event where the hospital is either functional or not. Rather, the facility will likely have a range of functionality levels indicative of available medical procedures or services, the number of patients that can be served, or the time frame for receiving care. To this end, this paper presents a methodology for assessing discrete levels of emergency department functionality using a combination of fault and event trees. Following earlier research on emergency departments, the methods presented here focus on defining functionality states for an emergency department.

2. Risk analysis tools

Historically, risk analysis tools, such as event and fault trees, have been used for assessing failure in nuclear power plants or space shuttles where the cost of failure is high. Over the past two decades, the use of these tools in other fields has been increasing. They have proven to be a powerful tool for understanding failure modes and the probability of different types of failure. More recently, fault trees have been used to help determine the functional recovery of buildings. ATC-138 uses a series of fault trees to assess reoccupancy and functional recovery, with different fault trees being used to assess building safety, egress, and tenant safety and use requirements (ATC, 2021). Specific to hospitals, fault trees have been used to determine the functionality of entire hospital systems (Hassan & Mahmoud, 2018; Jacques et al., 2014), functionality of individual hospital services (Boston, 2017), hospital emergency department functionality (Shang et al., 2020), and critical hospital utilities (Zhai et al., 2022). While fault trees can be a powerful tool to determine if a system is functioning, their use to easily define the function or various functionality levels of complex systems is limited. Combining fault trees with event trees, similar to what is done by NASA for space shuttles (NASA, 2002), adds a greater level of detail in the risk assessment and provides a quantitative method to define and measure different levels of functional recovery (Prassinos et al., 2011).

2.1. Event trees

Different to fault trees, event trees represent a sequence of events that lead to different levels of failure or damage states (NASA, 2002; Paté-Cornell, 1984). Event trees start with an initiating event and then map out all the possible sequences of subsequent events. Each subsequent event is a branching point of the event tree leading to a different potential failure scenario. As with fault trees, event trees can be used deterministically and probabilistically. In a deterministic evaluation, each event is a binary yes or no question. Logic moves left to right along the event tree, with each question narrowing down on the final determinate level of functionality. In a probabilistic analysis, each event has a probability of occurring. These probabilities are transferred along the event tree using probability theory to provide the probability of the overall system ending up in each of the end states. Figure 1 shows an example of a deterministic event tree with each event decision leading to a different outcome.

Mitrani-Rieser's proposed virtual inspector tool (2007) uses an event tree model for determining building tags (unsafe, limited entry, and safe) based on four pivotal events: collapse, exterior structural damage, moderate structural damage, and interior damage. The event trees can be expanded to account for functionality with the addition of further branching points and catered to specific facilities. Doing so will enable a rapid assessment of functionality immediately after an earthquake and throughout the recovery period.

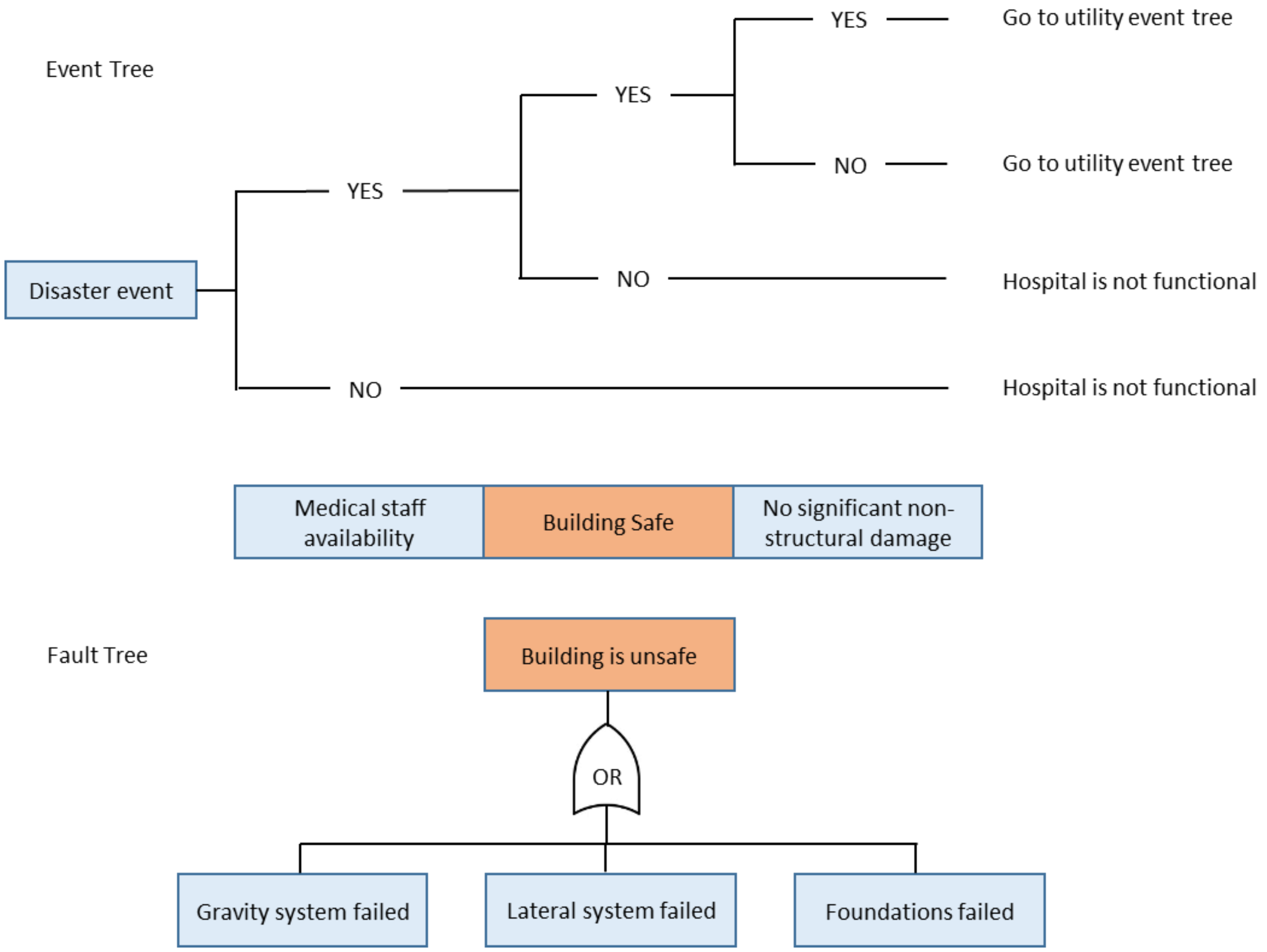

Figure 1. Example of a combined event and fault tree for assessing levels of hospital functionality

2.2. Fault trees

Fault trees are a risk analysis tool that assess failures of a high level event or system failure, defined as the top event, by breaking down the failure into smaller quantifiable and discrete components with well defined failures. For example, a fault tree assessing building safety for reoccupancy could have the building being unsafe and receiving a red tag as the top-level event. Red tagging a building can be broken down into a series of intermediate events, such as failures in the gravity system, the lateral load-resisting system, or the building foundations, see Figure 1. Each of these intermediate events can be further broken down into discrete events with easily assessed or quantifiable failures known as basic events. The basic and intermediate events are linked to the top event through a combination of AND and OR logic gates that define the relationships of the lower events with each other and the top-level event. Analysis is done by working from the bottom of the tree, defining failures of the basic events, either deterministically or probabilistically, and moving up the tree through the various logic gates. Failure of the top-level event is based on failure of enough critical pathways leading to the top-level event. When used probabilistically, the result is a probability of system failure. When deterministic values are used, the end result is binary, meaning the top-level fails or does not fail.

2.3. Combining fault and event trees

Using a combination of fault and event trees allows for the detailed analysis of certain failures of the hospital and the ability to look at sequences of failures within the wider hospital to determine different potential levels of functionality. NASA uses a combination of event and fault trees for performing risk analysis on space shuttles. The event trees developed by NASA provide event sequences with pivotal events that lead to different possible outcomes or damage levels. Each pivotal event in the event tree represents a system failure defined by a separate fault tree. Probabilities are determined for each basic event in the fault trees and propagate up to determine a probability of the system failing. The failure probability transfers to the event tree and transmitted across the tree to determine the probability of reaching different damage states (NASA, 2002). This methodology also has the advantage of providing a clear means of communicating risk and propagating failure with engineers and other stakeholders.

The same principle can be applied to assessing various levels of hospital functionality (Mayer & Boston, 2022). Combining fault and event trees provides a richer context for assessing the impacts of damage. A supporting fault tree can define each event in the event tree. Then, moving along the event tree, different functionality levels can be determined. A generalized example of a combined fault and event tree is illustrated in Figure 1. In this example, the event tree, shown at the top of the figure, progresses from the initiation of the disaster, through a sequence of three events and assesses the availability or safety of different systems. A supporting fault tree determines the failure or success of each of the events in the tree. In this example, a limited fault tree assessing structural safety of the buildings is shown. When doing a deterministic analysis, the fault tree will be used to determine if the event is true or false, which will indicate the branching direction of the event tree. For this example, if the fault tree determines that the building is unsafe due to the gravity, lateral, or foundational systems being compromised, then the event tree will branch in the 'NO' direction, resulting in a functionality level of 'hospital is not functional'.

3. Fault and event tress for an emergency department

A combination of event and fault trees has been created to represent different functionality levels for a hospital. As hospitals are large and complex systems, focusing on a smaller subset of the entire hospital is useful for discussion. In this case, the event and fault trees developed for an emergency department are presented as a representation of the larger study. The event and fault trees were developed utilizing information from a hospital functionality database that collated information on hospital functionality after natural disasters (Mayer & Boston, 2022), operating procedures from local New Zealand hospitals, and hospital design guidelines (FGI, 2022).

3.1. Event tree for emergency departments

An event tree for the emergency department is created first to determine the critical branching points that will lead to different levels of functionality. These branching points become the top-level events for the supporting fault trees. As the event tree graphically branches at critical events leading to different functionality levels, it is important to identify all critical branching events and order these events based on dependencies to reduce the size of the tree (Mayer & Boston, 2022), The events are ordered based on the severity of lost function. The events that have a higher impact on overall functionality are listed first (towards the left), while those with less contribution to the emergency department functionality are listed last.

Following this logic, the event tree first considers events that will cause the emergency department to lose all or most functionality, followed by events that will decrease the quantity or quality of functionality, but not eliminate it. The event tree developed for an emergency department is depicted in Figure 2. In this event tree, the initiating event is the occurrence of an earthquake or similar disruptive event. From there, events are ordered based on relevance for providing medical services and emergency healthcare. The first event is the availability of critical staff. Without the required staff, the hospital cannot provide medical care and would lose functionality. The following two events assess the physical damage to the hospital. First, the structural damage is assessed based on building safety. This is followed by assessing non-structural damage. As shown, structural damage will lead to a complete loss of functionality for the emergency department, whereas non-structural damage will reduce, but not eliminate, functionality. Depending on the type and severity of the non-structural damage, reduced functionality can be a reduction of available hospital beds due to limited space, a reduction of available services, or longer wait times due to a decrease in accessible space.

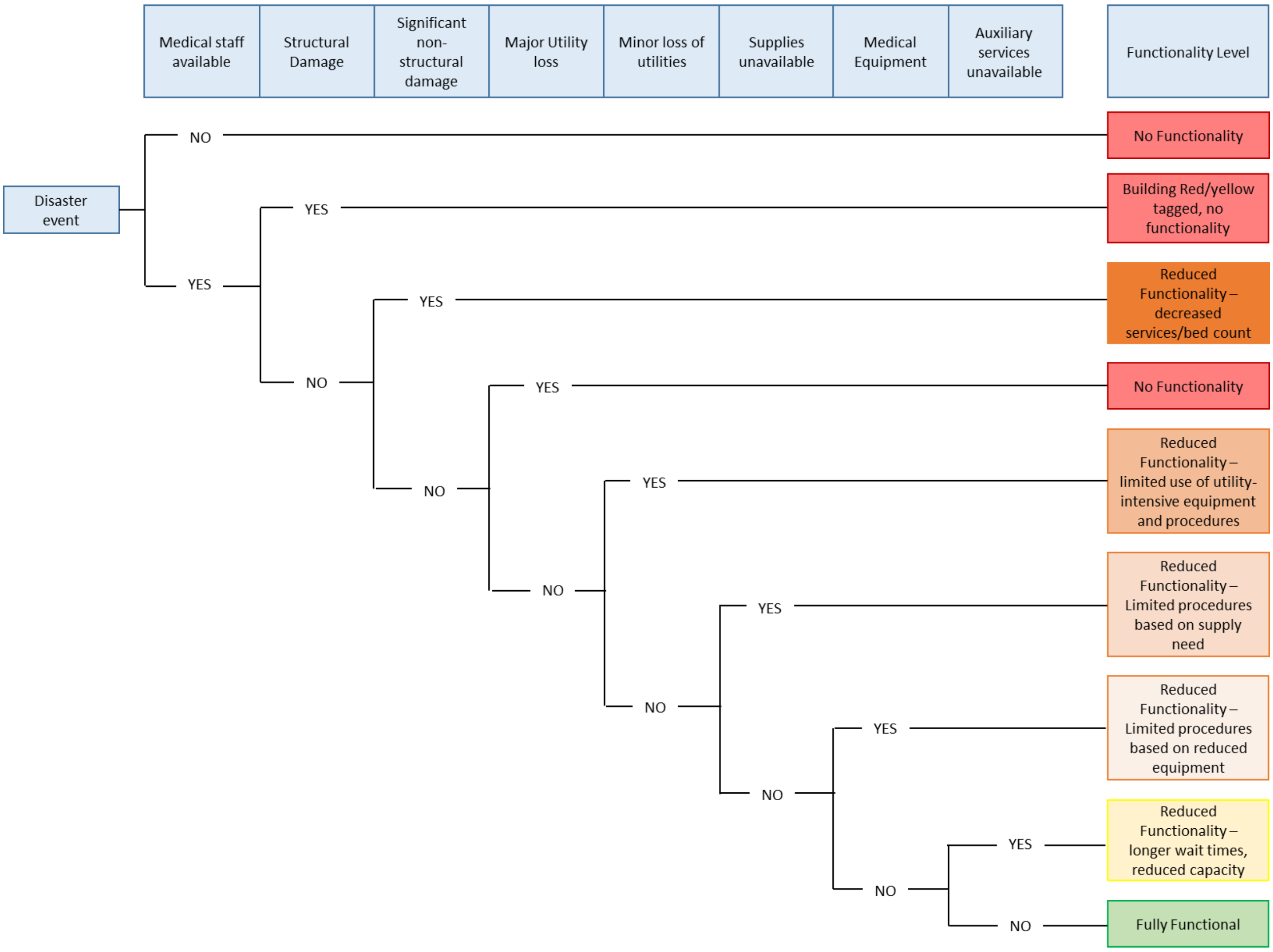

Figure 2. An event tree for a hospital emergency department indicating levels of functionality ranging from fully functional to fully non-functional.

Continuing along the event tree, the next two events consider utilities. The first accounts for a major loss in utility services that would prevent the hospital from functioning. This could be a complete loss of electrical power, water, or other utilities used to maintain medical equipment, sterilization, or pressurization of critical areas. A reduction or minor loss of supplied utilities will reduce the functionality of the emergency department, but not necessarily remove all functionality. An example would be a drop in supplied electricity to the hospital from main or backup generators. A reduction of supplied power will limit the ability to do energy-intensive procedures or to do detailed scanning and imaging with MRIs or CTs (Jacques, 2016).

Following the loss of utilities, the availability of supplies, medical equipment, and auxiliary services is considered next. Loss of any of these would result in reduced hospital functionality. The reduction of functionality would vary for the different losses. Losing some medical supplies will limit the types of medical care that can be provided (Jacques, 2016). Similarly, losing medical equipment will reduce functionality by reducing the medical procedures to those that can be completed without medical equipment. Similarly, the loss of auxiliary services such as laundry, cleaning services, medical records, and computer systems will reduce the functionality of the emergency department, likely by reducing patient capacity and throughput due to delays in processing medical records, sanitizing examination areas, or getting clean gowns and linens.

3.2. Fault trees for emergency department events

Fault trees for each of the pivotal events in the event tree were created or adopted from existing literature (Boston, 2017; Hassan & Mahmoud, 2018; Jacques et al., 2014) and the hospital functionality database (Mayer & Boston, 2022). Each fault tree breaks down the event into definable and quantifiable basic events. A fault tree for medical staff availability considers the availability of critical staff, including doctors, nurses, and auxiliary medical staff. The structural damage fault trees consider the structural integrity of the building, building safety, and egress. The non-structural damage fault tree evaluates different types and levels of nonstructural damage that would disrupt the ability to perform medical procedures, affect available space, or make the emergency department unsuitable for continued use.

The major and minor utility loss fault trees are shown in Figure 3 as an example of some of the fault trees used. The major utility loss fault tree considers main and backup utility supplies for power, general water, potable water, and wastewater. For each utility, the main and backup supply would fail for the intermediate event to be true. If any intermediate event fails, the major utility loss event triggers as true. This transfers to the event tree to indicate the direction of logic flow to get the final functionality level.

Likewise, the remaining fault trees breakdown supplies, medical equipment, and auxiliary services based on what supplies, equipment, or services are available.

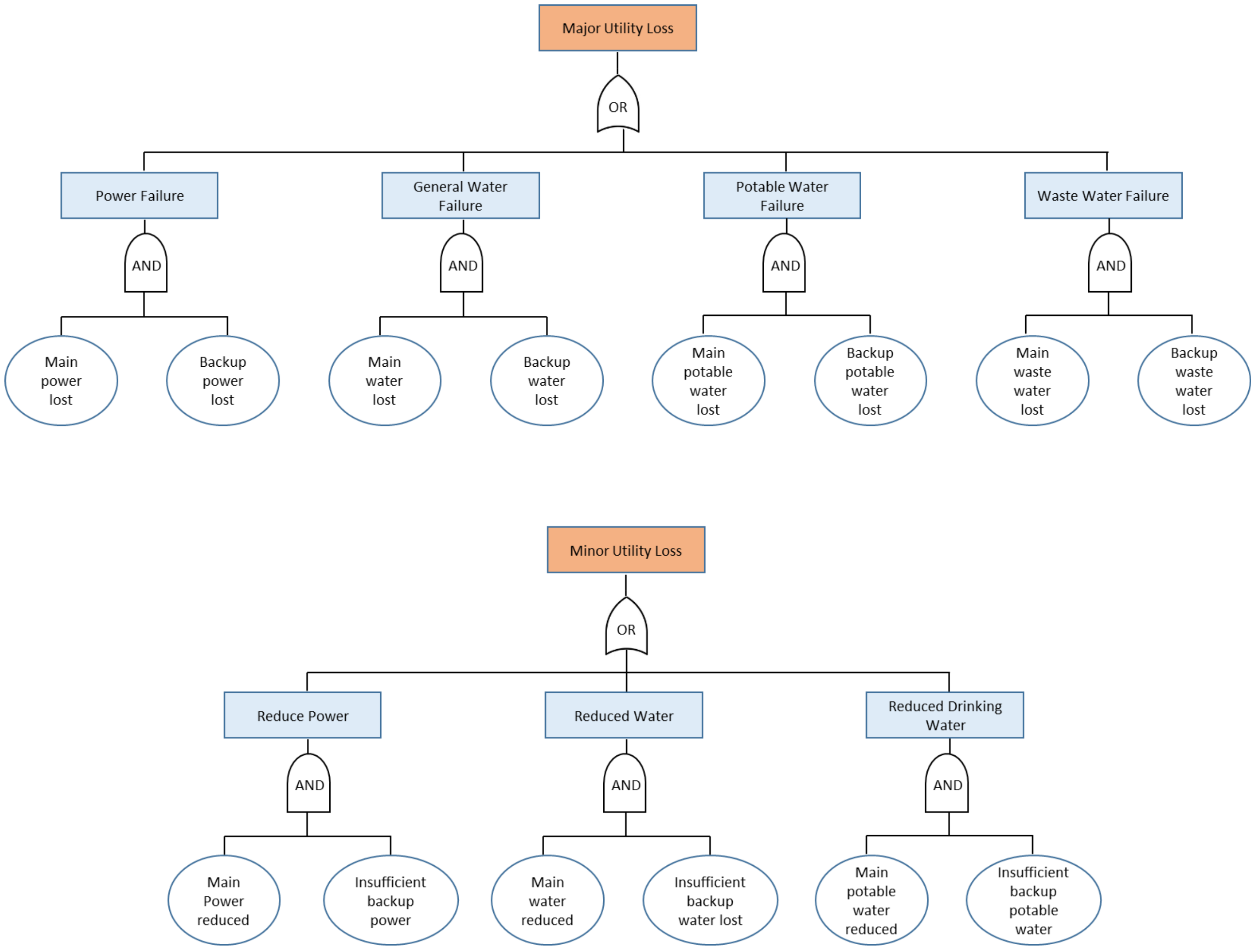

Figure 3. Fault tree for major and minor utility loss

4. Case study: Using fault and event trees to assess functionality

The use of the combination of event and fault trees for an emergency department is assessed using data from the Christchurch hospital following the 22 February 2011 earthquake. This magnitude 6.3 earthquake occurred beneath the city of Christchurch, causing significant damage throughout the city centre (Bradley & Cubrinovski, 2011). The Christchurch Hospital, which was located near the city centre, experienced some minor structural and non-structural damage which did not impact the emergency department. Wider spread outages to utilities impacted the entire hospital facility (Jacques et al., 2014). Additionally, imaging equipment, such as MRI and CT machines, and X-rays and ultrasounds, were unavailable for some time after the earthquake occurred. A summary of the damage and outages that affected the emergency department are summarized in Table 1. Using a deterministic analysis for the event and fault trees, damage and outages would trigger a failure of some basic event in different fault trees, potentially signaling the failure of the top fault tree event. Failure of the top-level event in a fault tree indicates a direction to follow in the event tree leading to a description of the reduced functionality. Repeating this process at each time step of the recovery period provides a narrative on how functionality changes as repairs are completed.

Table 1. Damage and outages potential leading to drops in emergency department functionality, (Jacques et al., 2014).

Event tree relationship	Damage or outage	Duration
Medical staff	None	
Structural damage	None	
Non-structural damage	Some damage to suspended ceilings, wall partitions, windows	No significant damage affecting the emergency department
Utilities	Electricity - main	18 hrs
	Electricity - backup	1.5 hrs
	Water – main	7 days
	Water – backup	1 day
Equipment and supplies	Imaging equipment	1 day
Auxiliary services	Laundry services	3 days

Using the values listed in Table 1, the event tree shown in Figure 2, and the supporting fault trees for each of the events give an indication of the emergency department's functionality over time. Graphically, this can be depicted as a resilience curve (Bruneau et al., 2003; Mieler & Mitrani-Reiser, 2018), as shown in Figure 4. The resilience curve is a powerful tool as it allows a range of stakeholders to get an immediate overview of potential recovery timelines depending on what systems fail. As illustrated, there is an initial drop in the emergency department's functionality when the earthquake occurs due to a loss of main and backup electricity. The combination of these two outages would trigger a failure in the 'major utility loss' fault tree in Figure 3. This would subsequently lead to the 'major utility loss' event triggering as true, leading to no functionality in the hospital. In Figure 4, this is complete drop in functionality is shown in between 0 and 1.5 hours after the earthquake. This section is shaded to indicate that there is some amount of residual capacity that is likely to remain for short duration outages that is not captured with the event trees. It is likely that some amount of residual capacity that is likely to remain immediately after an earthquake, as patients in the emergency department will continue to be treated as resources and personnel allow due to human resourcefulness, similar to what was seen after the 2014 Pisagua Earthquake (Vasquez et al., 2017). However, a continued outage of both primary and backup electricity would likely trigger a complete loss of functionality in the emergency department.

The functionality of the emergency department is restored in stages. Once backup power is restored, the estimated functionality of the emergency department increases, but is not completely restored. There is still a reduction due to the backup power likely being inadequate to provide enough power to fully utilize all medical equipment, with power use likely prioritized to life and safety-critical uses. Further increases in functionality occur once main power is restored, imaging equipment is available, and auxiliary services are running. In each stage, the emergency department remains functional but at some reduced capacity level.

Comparing these results to documented results of the emergency department's functionality can provide an indication of the accuracy of the modelling and provide further insights into the different levels of functionality as services are restored. Interview data collected after the Christchurch earthquake indicates that the emergency department of the Christchurch hospital remained functional after the earthquake, but does not indicate if there were different levels of functionality after the event occurred (Jacques et al., 2014). The model presented here shows that some functionality remains in the emergency department but also provides some variation of the hospital functionality levels. Further data on emergency departments' immediate response and short-term recovery levels after an earthquake is required to define the various functionality levels.

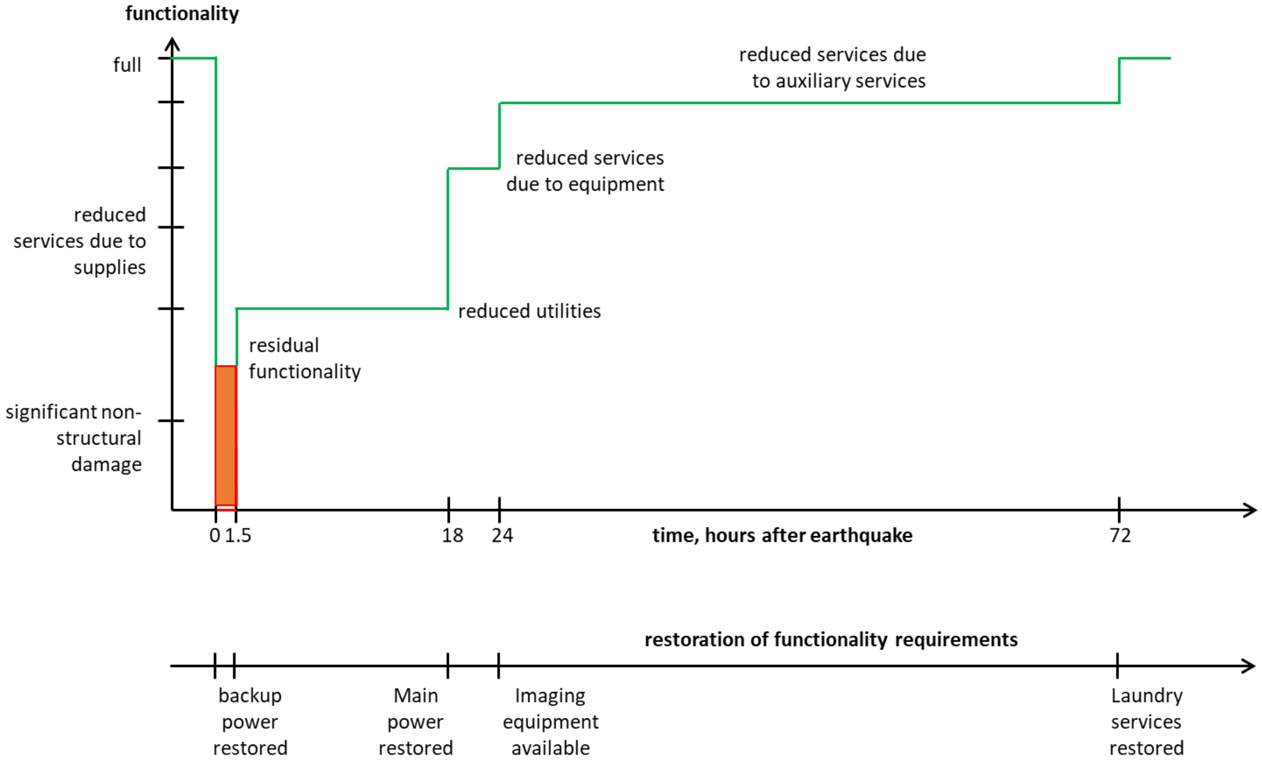

Figure 4. Estimated functional recovery timeline for the Emergency Department of the Christchurch Hospital

5. Expansion of the framework

The case study illustrated here provides an example of how this methodology can be implemented to determine levels of functionality for an emergency department. To provide more insights into how functionality changes as repairs and recovery are completed, the functionality levels can be better defined based on an individual facility's specific needs and requirements. The functionality levels provided here are generic, but provide a framework for creating facility-specific functionality levels to define the end events in the event tree.

The functionality of an emergency department is only an indication of the functionality of the entire hospital. Other departments and areas of a hospital can similarly be modelled using a combination of fault and event trees. This model would aid in providing predictions on the quality and quantify of hospital functionality during the response and recovery to an earthquake. Expanding this framework and incorporating probabilities of failure into the fault trees can provide insight into a hospital's probability of reaching different levels of functionality immediately after an event, which can then be used for emergency planning, mitigation decisions, and communicating the risk of hospital disruption to stakeholders.

Other critical or essential facilities can also be modelled using a combination of fault and event trees to estimate levels of functionality after a disruptive event. Using this framework combined with damage and loss assessment models, such as FEMA P-58, to predict the amount of damage and timeframes for repairs can provide an estimated timeframe for restoring functionality for these critical facilities.

6. Conclusions

This paper summarises initial work in developing a risk-based functionality framework for hospital facilities using a combination of event and fault trees. This framework provides a transparent method of determining varying levels of functionality for a hospital after an earthquake and throughout the recovery period. Event and fault trees are presented to assess the functionality of an emergency department. Using the Christchurch Hospital as a case study, the tools can be used to determine specific functionality levels at each step of the recovery period. Functionality levels range from a complete loss of functionality to a severe reduction of services and medical procedures available to minor service disruption to complete functionality. These functionality levels provide an indicator of the quantity and quality of care an emergency department or hospital will be able to provide.

While the current framework uses deterministic metrics to assess functionality, probabilistic values can be used in the fault and event trees to predict the probability of reaching different damage states or functionality levels for the facility. This can be a useful tool for emergency planning and design improvements to preserve the functionality of critical facilities after an earthquake.

7. Acknowledgement

The authors would like to acknowledge the contributions of Dylan Marshall and Liam Singer in the initial event and fault tree development. This work was partially supported by QuakeCoRE, a New Zealand Tertiary Education Commission-funded Centre. The QuakeCore publication number is 899.

8. References

ATC, A. T. C. (2021). *Seismic Performance Assessment of Buildings Volume 8 – Methodology for Assessment of Functional Recovery Time*. https://femap58.atcouncil.org/documents/fema-p-58/34-atc-138-3-volume-8-methodology-for-assessment-of-functional-recovery-time/file

Boston, M. (2017). *Building Resilience Through Design: Improving Post-Earthquake Functionality of Hospitals* [Thesis, Johns Hopkins University]. https://jscholarship.library.jhu.edu/handle/1774.2/60833

Bradley, B. A., & Cubrinovski, M. (2011). Near-source Strong Ground Motions Observed in the 22 February 2011 Christchurch Earthquake. *Seismological Research Letters*, *82*(6), 853–865. https://doi.org/10.1785/gssrl.82.6.853

Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., Shinozuka, M., Tierney, K., Wallace, W. A., & von Winterfeldt, D. (2003). A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities. *Earthquake Spectra*, *19*(4), 733–752. https://doi.org/10.1193/1.1623497

Chen, H., Xie, Q., Feng, B., Liu, J., Huang, Y., & Chen, H. (2018). Seismic Performance to Emergency Centers, Communication and Hospital Facilities Subjected to Nepal Earthquakes, 2015. *Journal of Earthquake Engineering*, *22*(9), 1537–1568. https://doi.org/10.1080/13632469.2017.1286623

Cimellaro, G. P., & Piqué, M. (2016). Resilience of a hospital Emergency Department under seismic event. *Advances in Structural Engineering*, *19*(5), 825–836. https://doi.org/10.1177/1369433216630441

Cimellaro, G. P., Reinhorn, A. M., & Bruneau, M. (2011). Performance-based metamodel for healthcare facilities. *Earthquake Engineering & Structural Dynamics*, *40*(11), 1197–1217. https://doi.org/10.1002/eqe.1084

FGI, F. G. I. (2022). *Guidelines for design and construction of Hospitals*.

Hassan, E. M., & Mahmoud, H. (2018). A framework for estimating immediate interdependent functionality reduction of a steel hospital following a seismic event. *Engineering Structures*, *168*, 669–683. https://doi.org/10.1016/j.engstruct.2018.05.009

Jacques, C. C. (2016). *Resilience of Healthcare in Disasters: A Systems Approach* [Ph.D., The Johns Hopkins University]. https://www.proquest.com/docview/2334393465/abstract/B1B25B824BD04188PQ/1

Jacques, C. C., McIntosh, J., Giovinazzi, S., Kirsch, T. D., Wilson, T., & Mitrani-Reiser, J. (2014). Resilience of the Canterbury Hospital System to the 2011 Christchurch Earthquake. *Earthquake Spectra*, *30*(1), 533–554. https://doi.org/10.1193/032013EQS074M

Li, L., Chang-Richards, A., Boston, M., Elwood, K., & Molina Hutt, C. (2023). Post-disaster functional recovery of the built environment: A systematic review and directions for future research. *International Journal of Disaster Risk Reduction*, *95*, 103899. https://doi.org/10.1016/j.ijdrr.2023.103899

Mahmoud, H., Kirsch, T., O'Neil, D., & Anderson, S. (2023). The resilience of health care systems following major disruptive events: Current practice and a path forward. *Reliability Engineering & System Safety*, *235*, 109264. https://doi.org/10.1016/j.ress.2023.109264

Mayer, B., & Boston, M. (2022). Advancing NZ hospital seismic readiness: Creating a post-earthquake functionality dashboard. *NZSEE Annual Technical Conference*. NZSEE Annual Technical Conference. https://researchcommons.waikato.ac.nz/handle/10289/14853

Mieler, M. W., & Mitrani-Reiser, J. (2018). Review of the State of the Art in Assessing Earthquake-Induced Loss of Functionality in Buildings. *Journal of Structural Engineering*, *144*(3), 04017218. https://doi.org/10.1061/(ASCE)ST.1943-541X.0001959

Mitrani-Reiser, J. (2007). *An Ounce of Prevention: Probabilistic Loss Estimation for Performance-Based Earthquake Engineering* [Phd, California Institute of Technology]. https://doi.org/10.7907/JXPV-1Q19

Nagata, T., Himeno, S., Himeno, A., Hasegawa, M., Lefor, A. K., Hashizume, M., Maehara, Y., & Ishii, M. (2017). Successful Hospital Evacuation After the Kumamoto Earthquakes, Japan, 2016. *Disaster Medicine and Public Health Preparedness*, *11*(5), 517–521. https://doi.org/10.1017/dmp.2016.180

NASA, N. A. and S. A. (2002). *Probabilistic Risk Assessment Procedures Guide for NASA Managers and Practitioners*. https://ntrs.nasa.gov/api/citations/20120001369/downloads/20120001369.pdf

Palomino Romani, G., Blowes, K., & Molina Hutt, C. (2023). Evaluating post-earthquake functionality and surge capacity of hospital emergency departments using discrete event simulation. *Earthquake Spectra*, *39*(1), 402–433. https://doi.org/10.1177/87552930221128607

Paté-Cornell, M. E. (1984). Fault Trees vs. Event Trees in Reliability Analysis. *Risk Analysis*, *4*(3), 177–186. https://doi.org/10.1111/j.1539-6924.1984.tb00137.x

Perrone, D., Calvi, P. M., Nascimbene, R., Fischer, E. C., & Magliulo, G. (2019). Seismic performance of non-structural elements during the 2016 Central Italy earthquake. *Bulletin of Earthquake Engineering*, *17*(10), 5655–5677. https://doi.org/10.1007/s10518-018-0361-5

Prassinos, P. G., Lyver, J. W., & Bui, C. T. (2011). Risk Assessment Overview. *Volume 1: Advances in Aerospace Technology; Energy Water Nexus; Globalization of Engineering; Posters*, 673–677. https://doi.org/10.1115/IMECE2011-63490

Shang, Q., Wang, T., & Li, J. (2020). Seismic resilience assessment of emergency departments based on the state tree method. *Structural Safety*, *85*, 101944. https://doi.org/10.1016/j.strusafe.2020.101944

Vasquez, A., Rivera Jofre, F., De La Llera, J. C., & Mitrani-Reiser, J. (2017, January 13). Healthcare network operation in Iquique after the 2014, Pisagua earthquake. *Proceedings of the 16th World Conference on Earthquake Engineering*. 16th World Conference on Earthquake Engineering. http://www.iitk.ac.in/nicee/wcee/sixteenth_conf_Santiago/

Zhai, C., Yu, P., & Wen, W. (2022). A Physical-organizational Method for the Functionality Assessment of A Hospital Subjected to Earthquakes. *Journal of Earthquake Engineering*, *26*(14), 7119–7139. https://doi.org/10.1080/13632469.2021.1947419