Advancing NZ hospital seismic readiness: creating a post-earthquake functionality dashboard

B.J. Mayer & M. Boston
University of Waikato, Hamilton.

ABSTRACT

Continued functionality of critical infrastructure systems, such as hospitals, shortly after an earthquake is expected. However, experience indicates that there may be some disruption due to damage, outages, or access that vary in size and duration. While damage to structural components can have significant life safety and economic implications, damage to non-structural components or failures of the interconnected and interdependent supporting infrastructure systems can also have a substantial impact on the operability. A functionality dashboard to rapidly identify drops in functional performance is needed. The dashboard must be based on real and possible disruptions, including data from previous disruptive events. The dashboard utilises a functionality database and risk analysis tools to holistically predict a level of post-disaster functionality. Creating a functionality database from past earthquake events provides the necessary information to create a representative event tree of hospital performance. Drops in functionality are governed by fault trees that are created based on the data gathered in the functionality database. These tools provide the engine for a hospital functionality dashboard for estimating hospital functionality to scenario events. Use of the dashboard will help determine critical links between hospital components impacting functionality and provide needed information for improving facility design. It will also be useful for testing the implementation of emergency procedures linking the physical environment with human and organisation requirements.

1 EARTHQUAKES AND BUILDING FUNCTIONALITY

Building standards and codes lead to safe buildings, but not necessarily functional structures after a disruptive event. Historically, following an earthquake, building design and performance is deemed successful if the building does not collapse and occupants are safe. However, to ensure the ongoing safety, operability, and continuity of communities affected by an earthquake, it is necessary to move beyond designing primarily for safety and instead design for functionality. Pivotal to this is understanding and incorporating the human organisation and systems that use and occupy the structure into the design process when considering post-disaster building functionality. One class of structures that are critical to community wellbeing and long term recovery are healthcare facilities, yet historical and recent disasters around the globe have shown the fragility of these crucial systems (Kirsch 2010, Ochi 2014, Jacques 2014). These buildings are essential during the immediate aftermath of an earthquake and vital to a community's long term recovery. As governments and designers move towards performance-based design and incorporate functionality requirements into the design process, it is necessary to understand the specific functional requirements of a healthcare facility.

1.1 Growing need to consider hospital functionality

The importance of healthcare facilities has prompted extensive research into improving the structural design of hospitals, strengthening nonstructural components (OSHPD 2001), and defining operational and functionality requirements (WHO 2015). While there is increasing understanding of the structural and nonstructural requirements, the links between physical damage and organisational disruption is still lacking. Healthcare facilities are complex systems with strong interdependencies between human and physical systems. To best define and design for ongoing functionality, it is important to understand the interrelationships between hospital services and the physical infrastructure. Defining unique relationships between hospital staff, stuff and space will enable a better understanding of the functional requirements of a hospital and lead to improvements in the hospital design.

1.2 Building blocks for hospital functionality dashboards

This paper presents an ongoing research project investigating the links between physical damage and the functionality of a healthcare facility. The project aims to create a functionality dashboard for hospital buildings that can predict different levels of hospital functionality for various scenario events. This dashboard will be beneficial to identifying critical paths that lead to detrimental drops in the ability to provide hospital services and in defining design solutions for improving hospital performance during the aftermath of a hazardous event. The initial work focuses on developing risk analysis tools specific to define the functionality of an emergency department (ED). Much work internationally has focused on the operability of EDs, providing a good benchmark for the results of this study.

The basis of the functionality dashboard rests in the field of risk analysis. A basic background of existing hospital functionality work and risk analysis is provided in section 2. The hospital functionality dashboard is created through a series of steps that are further discussed in section 3. These steps include 3.1. creating a functionality database to collate and summarise hospital functionality from past earthquakes, 3.2. constructing event trees to outline possible sequences of events that will lead to different levels of hospital functionality, and 3.3. formulating fault trees to evaluate each gate in the event tree. Section 4 introduces how the event and fault trees are used to estimate functionality for a scenario event and how this will be used to create a functionality dashboard for an entire hospital. Some conclusions will be provided in section 5.

2 BACKGROUND

1. 2.1 Quantifying hospital functionality

Research into hospital functionality has been ongoing for the past two decades. Past research has focused primarily on defining the capacity of an ED as a representation of the entire hospital with functionality measured by wait time or bed count (Cimellaro 2010). Existing hospital functionality work has also focused on the preparation, response and recovery phases of a disaster against key components of staff, infrastructure, management, and logistics (Jolgehnejad 2020), while others have focused on organisational or equipment requirements (Zhong 2015). However, there is a lack in considering the structural and non-structural damage in combination with the organisational and human environments (Fallah-Aliabadi 2020).

Quantifying hospital functionality is an ongoing challenge that requires extensive modelling of the hospital's physical and operational requirements. Risk analysis tools, such as fault and event trees, are useful for breaking down hospital operations to identify critical failure paths. Initial work on developing fault trees for component failures in hospitals has worked on linking staffing, supplies, and infrastructure to hospital functionality (Jacques 2014, Boston 2017). Further work in this area has also considered the spatial distribution of physical damage and the significance of the damage to the operability of individual hospital services (Boston 2017, 2018). However much of this work is deterministic in nature and provides high-level binary functionality results. Continuing from this work, there is a need for more extensive fault trees that provide more granular insights on hospital requirements and the addition of event trees for distinguishing between levels of operability of hospital services during the aftermath and ongoing recovery of a hospital.

2. 2.2 Use of event trees and fault trees

Fault trees and event trees have been developed and used as risk analysis tools where the cost of failure is high, e.g. nuclear power plants or space shuttles (Haasl 1981, NASA 2011). Fault trees are a bottom-up approach that breaks down a system failure into discrete basic components that can be well understood. A top-level failure, such as major non-structural damage to an examination room, is broken down into all the events and components that would cause the failure. AND and OR logic gates are used to move up the fault tree from the basic components to the intermediate events to the top-level event. Failure of the system can be broken down into specific cut-sets that identify critical failure pathways.

An event tree is a sequence of events that can lead to different levels of failure (Pate-Cornell 1984, NASA 2011). Event trees are constructed by starting at an initial event and then mapping all the possible subsequent events. These events are branches in the event tree that will lead to different outcomes. In a hospital scenario, the event tree could be looking at different levels of functionality for the ED. One of the gates leading to reduced functionality is the availability of examination rooms. The event tree gate can be defined by a fault tree. At the gate, the event tree will branch to different levels of functionality depending on the outcome of the fault tree defining the examination room availability. Creating event trees for all departments and services in a hospital and the corresponding fault trees provide estimations of the level of hospital functionality after a disaster.

3 CREATING A FUNCTIONALITY DASHBOARD

3.1 Development of hospital functionality database

The database is a collation of information related to hospital functionality after disaster events that has been compiled by reviewing documents and transcribing details about healthcare facility operation levels post-disaster. This provides an overview of the various factor and subsystems that may render a hospital partially or totally non-functional. All disaster types are accounted for, as the intent is to understand all possible damage or disruptions that may occur. As standards and practices tend to improve, only events from the year 2000 onwards are included.

To create the database, data relating to healthcare functionality after disaster events are extracted from published sources. At the time of writing, this includes:

- Earthquake Engineering Research Institute’s Learning from Earthquakes Reconnaissance Archive. The digital archive includes photo galleries, reports from virtual and field reconnaissance teams, links to news articles, and presentations and proceedings from conferences.

- Federal Emergency Management Agency (FEMA) Mitigation Assessment Team Program reports: 28 field investigation reports that thoroughly discuss the performance of key facilities (including healthcare facilities) in the aftermath of tornadoes, hurricanes, and terrorist attacks.

- Auckland DHB and Waikato DHB emergency response plans.

- Published journal articles previously collated by one of the authors.

Figure 1 shows an extract from the database for an earthquake that occurred in Anchorage, Alaska, in 2018. Title pages are included for each event. This page states the date, local time, and size of the event based on a relevant scale (e.g. moment magnitude scale for earthquakes, Saffir-Simpson winds scale for hurricanes). The number of casualties, serious injuries, and total injuries is noted, as these factors relate to hospital demand and the hospital's functionality requirements. Images of hospitals within a 30-minute radius of the event's epicentre are included for reference, and their location is plotted on a map.

A summary of general healthcare facility damage and functionality after each event is then provided as some sources, such as news reports, tend to only provide an overview of the healthcare system. This summary is followed by more in-depth information about individual hospitals and facilities. All information that could affect hospital functionality is transcribed, such as renovations, legislation and practices, structural and non-structural damage, equipment damage, disturbances to infrastructure that delay transportation or communication, and distribution and well-being of staff. Information about other healthcare and non-healthcare facilities, such as nursing homes, blood banks, medical centres, and energy plants, is also included for each event, as a decrease in the functionality of these services can impact hospital functionality (e.g. having an adequate blood supply, being able to transfer patients to other facilities in anticipation of increased demand). Finally, recommendations given in the literature are recorded, along with the data collector's reflections on the event and queries that require further investigation.

3.2 Development of event trees

To create the event trees, information related to the functionality of a specified department after the disaster events is extracted from the database. This is completed by noting the state of the department, followed by reviewing the data for possible causes as to why the state occurred. Causes for the state may be related or unrelated to the disaster event.

Due to the complexity of each hospital department, the event trees are reduced into several smaller sub-trees for simpler visualisation and comprehension. Each event tree represents a category that can affect a hospital's functionality: space, staff, auxiliary services, medical equipment, egress, capital equipment, utilities, and supplies. Within each category, the causes of the reduced functionality are grouped together further to form key events that are the top events in the tree.

The dependency between the department functioning and each event is empirically ranked from 0 to 4. This ranking system is shown in Table 1 and is an adjusted form of the ranking system in the Department Plan for Emergency Incident Response used by the Waikato DHB.

Table 1: The ranking system used

0	1	2	3	4
No dependency	Low dependency	Medium dependency	High dependency	Critical dependency
No impact on functions	No dependency for the first 24 hours	Could continue to function with some inconvenience	Causes restriction in service delivery	Service is unable to function

Figure 1: Database extract showing title page format and outline of facility's functionality.

An example of this process for an ED is shown in Table 2, including defining the state of the department, the causation, sorting of variables into categories and events, and ranking the dependencies.

Table 2: Example of categorisation of components

State	Cause	Category	Event in tree	Dependency
Patients evacuated	Flooding occurred due to pipe fracture	Utilities, space	Freshwater available; space available	3, 4
Patients evacuated	Significant damage to columns	Space	Space available	4
Fully functional	Community hospital staff relocated to the main ED	Staff	Medical staff available	4
Limited access	Elevators were out of service	Egress	Means of egress available	3
Limited access	COVID-19 social distancing restrictions*	Supplies, space	Capital outlays available, space available	3, 4

* Indicates reasons unrelated to the disaster event.

In event trees, events are typically ordered so that events that lead to an immediate failure state (in this case, the department being completely non-functional) are given first. This minimises the size of the tree, as the occurrence of the event will lead to failure, meaning the success of other events need not be analysed. Therefore, all events that were determined to have a dependency of 4 were arranged in the first reduced event tree, regardless of what category they may have belonged to. All other reduced event trees were created by ordering events within each category based on their dependency ranking.

3.3 Development of fault trees

Existing studies (Jacques 2014, Boston 2017) tend to analyse hospital functionality by only using fault trees. However, this method is limiting, as hospitals analysed using only fault trees can be rendered completely non-functional if even one minor component is unavailable or non-functional. Comparably, using only event trees is also limiting. The method described in the previous section only provides a general overview of the key events and the dependency between them and hospital functionality, but does not expand on what can cause these events to be successful or unsuccessful. Therefore, a combination of event and fault trees provides both a generalised and in-depth analysis of hospital departments, reflecting the real-world complexity of the system and the likelihood that partial functionality is more likely to occur than a fully functional or non-functional state.

The top-level failure of each fault tree is directly related to the top events in the event tree, but as it is a failure, it has a negative connotation. The tree is developed by breaking down the various failure events that lead to the top-level event occurring. These events are determined by analysing information from the database and other published documents that outline design guidelines and practices in each hospital department. Events are linked either by an AND gates, showing that all failure events must occur to move up the tree, or OR gates, showing that at least one of the failure events must occur to move up the tree. Events are continuously broken down into smaller components until at the most basic level.

4 ESTIMATING HOSPITAL FUNCTIONALITY

3. 4.1 Example of combined event and fault trees for ED

An example of a combined event tree and fault tree for an ED is shown in Figure 2. The initiating event of the event tree is a disaster event. To analyse the ED's functionality, the first event tree gate relates to the availability of medical staff. If staff are available, the state of the next gate can be investigated. If staff are unavailable, the ED is classed as non-functional, as no medical services can be provided and the intended function cannot be fulfilled.

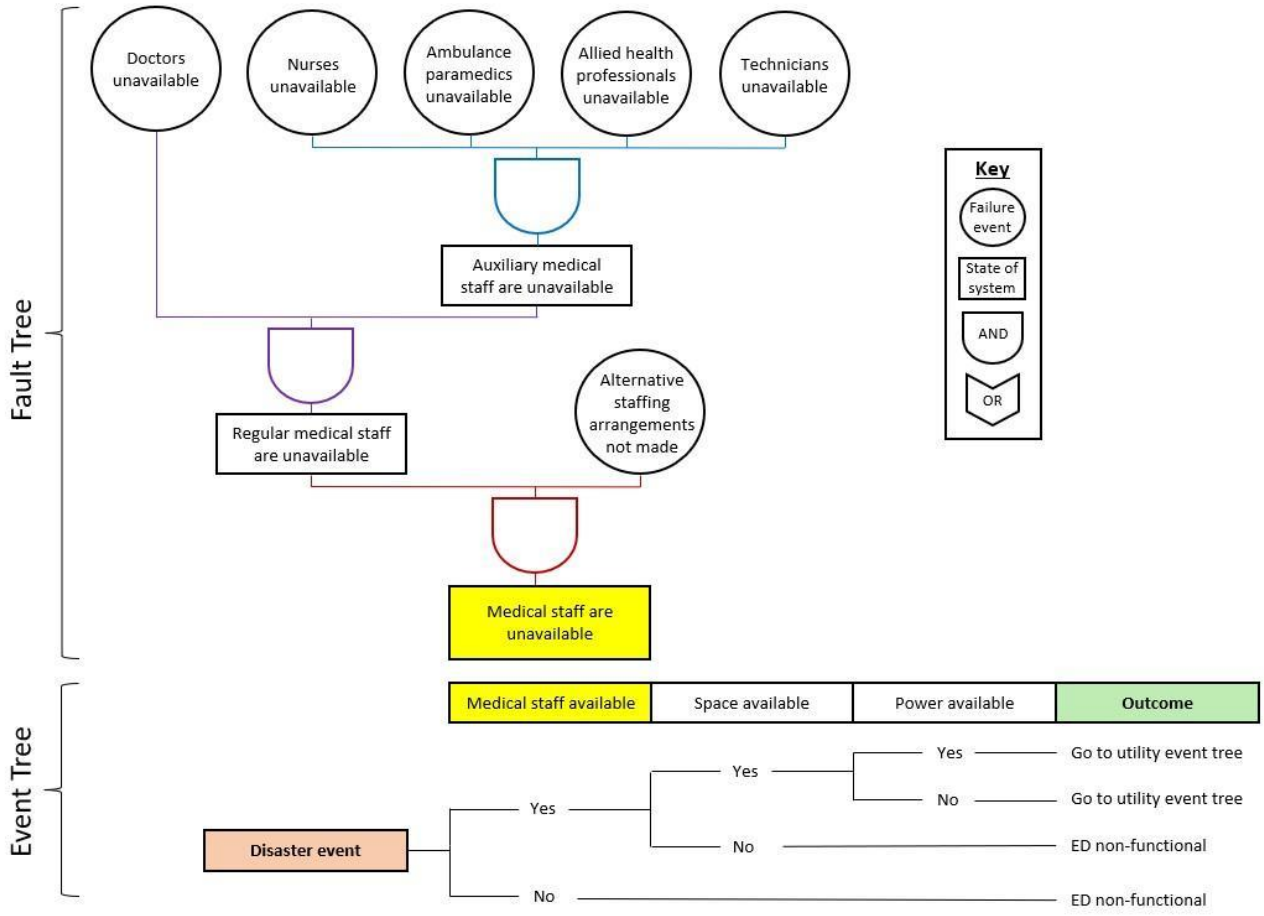

Figure 2: Sample of event tree and fault tree construction and connection

A fault tree assists in evaluating the availability of medical staff. The top-level failure, 'medical staff are unavailable', requires two scenarios to occur, as indicated by AND gate and red branches: the regular medical staff working at the ED must be unavailable, *and* alternative staffing arrangements must not be made.

The fault tree continues to define the availability of regular staff along with the purple branches: both doctors *and* auxiliary medical staff must be unavailable. While the levels of care differ between doctors and each auxiliary staff member depending on their training and qualifications, all can provide some treatment to patients. If only limited medical staff are available, the ED can be classed as partly functional, as some form of treatment can continue. This is a development from existing studies, which typically use an OR gate in place of the AND gate, thus rendering the ED non-functional even if only one type of staff member is unavailable.

The final branch of the fault tree, shown in blue, defines the various members of the auxiliary medical staff. To reiterate, all staff members must be unavailable to render the ED completely non-functional.

4. 4.2 Application

Once completed for an entire hospital service, e.g. the ED, the event trees will be able to estimate different levels of functionality such as loss of triage and transfer patients, minor procedures and emergency care, emergency operations, emergency and inpatient services, complete loss of function, or fully functional. The different levels of service will be useful for understanding where additional support is needed or where it is most critical to invest in mitigation measures and emergency response operations.

The risk analysis tools being developed show the functionality at a single point in time. However, recovery from a disaster is not static, and changes to internal and external conditions around the hospital can change the functionality. During the recovery period, hospital functionality can increase as repairs are made, or decrease if there are subsequent events that cause further damages. The fault trees and event trees can be re-evaluated as changes are made to basic events that define hospital functionality. Utilising existing repair curves for utilities and building components (FEMA 2018, Almufti 2013), the recovery time for the hospital and hospital services can be estimated (Boston 2017). The functionality of the hospital should be reassessed at different points of the recovery period to provide further insight into the level of functional recovery over time.

It should be noted that due to COVID-19 restrictions, collaboration with hospital staff and emergency management teams from New Zealand DHBs was limited. Further refinement is needed and can be completed through focus groups, interviews, and peer reviews of developed trees.

5 CONCLUSIONS

Initial work has focused on creating the hospital functionality database to inform the creation of event trees to define different levels of functionality. Event trees and fault trees are a promising method for holistically evaluating building functionality by providing a uniform method for combining impacts from the built environment, organisational requirements, and internal or external dependencies. Further work will expand the existing tools to other areas and components of a hospital to create a comprehensive risk analysis engine that will assess the functionality of an entire hospital. The tool will be useful for predicting loss in functionality for scenario events and can be used for emergency planning and design improvements.

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