Strategies to improve the performance of openings subject to water ingress during tropical cyclones and severe storms

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Submitted in fulfilment of the requirements of the degree of
Master of Philosophy

August 2020
Abstract

Tropical cyclones and severe storms around the world generate destructive winds and heavy rain causing devastating effects to buildings. Over the years, many countries have created or improved their buildings codes after a hazard has happened. Tropical Cyclone Tracy, in 1974 devastated the city of Darwin in Australia, and after that event the Australian Building Code was significantly upgraded to ensure that building structures could withstand cyclonic wind speeds. Since then, the incidence and severity of structural failure in both normal and extreme operating conditions has reduced substantially in Australia. However, tropical cyclones and severe storms still cause repeated serviceability issues in Australia, that impact on local communities, the construction industry, the insurance industry and governments. Insurance losses due to cyclones over the past two decades in northern Australia have totalled $2.4 billion, which averages around $115 million per year. Some non-structural elements remain subject to minor failure, causing loss of amenity and damage to structural building components over time. Buildings investigations have consistently revealed that windows and external glazed doors are affected by wind-driven rain, associated with each individual storm event, causing internal leakage and subsequent damage issues such as mould, termites and infestation. Research indicates that the water ingress may not be excessive but repeated serviceability damage has a cumulative cost impact generally to building owners, insurance and government. This repeated minor to moderate damage has not been sufficiently actioned since they do not lead to structural failure or loss of life.

To enhance the performance of building envelope openings subject to wind-driven rain during tropical cyclones and severe storms in the North of Queensland, the attainment of a clear understanding of the interdependencies in current practices for the entire supply chain of windows and external doors is essential. Therefore, reliable tools to predict performance of building envelope openings is essential for decision-makers to better target and prioritise investments. This aim was achieved by addressing the following three core study objectives: (1) to identify the key factors affecting the performance of window and external glazed doors to wind-driven rainwater ingress during tropical cyclones; (2) to develop an openings’ wind-driven water ingress performance prediction model; and (3) use scenario analysis to identify the most appropriate management interventions that could lead to a greater performance of
window and door openings subject to wind-driven rainwater ingress during tropical cyclones and severe storms.

An integrated approach was used in the study. Firstly, expert interviews and workshops were used to gain a clear insight on the entire supply chain and quality oversight of window and external glazed door installations within the Australian construction industry. This was followed by workshops to develop and operationalise a probabilistic Bayesian Network (BN) model that enabled the identification of workable strategic pathways to improve the performance of openings to mitigate water ingress during tropical cyclones and severe storms.

The findings from the expert workshops and interviews revealed some key contributing fault factors and correction recommendations to improve current practices. These recommendations predominately related to upgrading practices related to documentation, inspection liability assignment and installation training for building windows and doors, especially in locations where severe winds are frequent (i.e., northern Australia) and was designed for the use of governments and industry projects.

The overall research project finding demonstrates the importance of implementing a multi-pronged change to: openings standards (refers as improvements in the serviceability resistance test to water penetration), standards knowledge and training (refers to improvements in skills and knowledge of designers, builders and installers in design specification, openings installation and waterproofing practices) and in construction documentation (level of design specification). The three practices enforced together, will likely enhance the performance of building envelope openings (upgrade to 66.6% against the current condition 32.2%) and substantially reduce the likelihood that windows and door openings will experience serviceability failure during their lifespans.
Statement of Originality

This work has not been previously submitted for a degree or diploma in any university. To the best of my knowledge and belief, this thesis contains no material previously published or written by another person except where due reference is made in the thesis itself.

___________________________________

Juliana de Faria Correa Thompson Flores
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Acknowledgements

First, and foremost, I would like to thank to my principal supervisor, Prof. Rodney Stewart who provided me with this research opportunity. His outstanding enthusiasm, enlightening inspiration and continuing encouragement helped me throughout the research.

I would like to sincerely thank Dr Oz Sahin and Dr Edoardo Bertone, also my supervisors at Griffith University for their consistent encouragement, support and guidance in many different ways.

Between laughs and tears, each one of you three always provided a positive attitude during this journey. My sincere thank you.

A special thanks to all industry participants from my phone interviews that kindly shared their knowledge with me. To all industry and government workshop participants that were essential and enriched this research.

I would like to express deep gratitude to the Kris Harm for the generous support and invaluable knowledge and suggestions into the development of the recommendations designed for the use of governments and industry projects.
List of Publications

The following paper and industry reports were produced to disseminate results from the research undertaken by the author during the course of this research study.

Journal Paper


Industry Reports


Chapter 1: Introduction

1.1 Introduction
This chapter provides an overview of the thesis and its structure, which is provided in the following sections. Section 1.2 introduces the research background. Section 1.3 describes the research gap. Section 1.4 provides the rationale of this study. Section 1.5 details research questions and objectives. Section 1.6 briefly details the research method and outlines the key analytical techniques undertaken in the study. Lastly, Section 1.5, the structure of the dissertation is presented.

1.2 Background
Many nations’ have a long history of natural hazards. The destructive outcomes of severe storms and tropical cyclones, also known as hurricanes and typhoons. Thus, highlighting the susceptibility of some non-structural building elements in several building types in many coastal areas of numerous countries. Each year, damage costs associated with severe storm events globally exceed trillions of dollars. Especially local communities, the construction industry, the insurance industry and governments are constantly impacted by these natural hazards which still present challenges to overcome. Strengthening the performance and resilience of buildings has become ever more critical particularly during and post extreme weather events (Ladipo et al., 2019). A particular recurring problem in residential construction is water ingress from unbroken windows and external glazed doors, which damages the building’s interior and its contents (Lstiburek et al., 2005, IBHS, 2009). Water damage associated with each individual storm or a tropical cyclone event may not be extreme but repeated serviceability damage has an accumulative cost impact and frequently causes more severe long-term issues with a building (e.g. mould, termite infestation, etc.).

Hurricane Andrew (1992) prevails as one of the most significant hurricanes in the USA, as it was a big stimulus for conducting building code changes involving wind design considerations as it was one of the costliest to date. About US$4 billion or approximately 25% of the insurance losses were attributable to construction that failed to meet the code due to poor enforcement and poor quality workmanship (FEMA, 2011a).

In Australia, the greatest economic loss from a single tropical cyclone was in December 1974, Tropical Cyclone Tracy, which caused more than AU$5 billion in
insured losses (ICA, 2019). Between 50% and 60% of the houses and buildings were destroyed, which resulted in 65 lives lost due to building failure, with only 6% classified as intact after the event. At that time, the performance of houses and small buildings was not fully structurally engineered compared to larger buildings. Cyclone Tracy had notable importance on changes to the Australian Building Code (a performance-based regulatory system), in the incorporation of the Australian Standards, in Australian building regulations and in various design manuals for housing. As a result, from the 1980s, the building construction all over Australia was positively impacted by Cyclone Tracy (Walker, 2010).

Worldwide, building codes are the principal policy mechanism regulating the design and construction of buildings (Kurth et al., 2019). Through an analytical assessment, a cost-benefit study managed by the Multi-hazard Mitigation Council of the National Institute of Building Sciences for wind and seismic code provisions, verified the degree to which mitigation activities would result in future savings for the USA, as the country will always be vulnerable to natural hazards. The outcome was that every public US$1 spent on mitigation strategies, especially exceeding codes, saves communities an average of US$4. The savings would probably grow to US$16 when these perils are addressed through groups of code requirements. Money spent on reducing the risk of natural hazards is a sound investment. Prevention is sufficiently cost effective to warrant federal funding on an ongoing basis, both before disasters and during post-disaster recovery (MMHMC, 2005, NIBS, 2018).

Scientists have tried to identify the stages in which general buildings’ defects begin. Between 50% to 60% of building defects arise from design issues (Chong and Low, 2006, Sommerville, 2007) and 60% of these defects would have been avoidable with better design (Chong and Low, 2006). Josephson and Hammarlund (1999) examined defect costs and found that 32% originated in the earlier phases of development (including design), 45% originated on site and 20% were related to materials and machines. Forcada et al. (2012), stated that poor workmanship, poor supervision, lack of skills, knowledge and experience, and lack of motivation, have been featured in the literature as the direct cause of building defects, when, indeed, the causes have been attributed to organisational practices. As stated by Jingmond and Ågren (2015) arguments, ‘in order to minimize the incidence of defects, endeavor is needed to
change procedures in project management, as these are more likely to have greater impact than either further training or changes in routines on the construction site.

An excellent performance of both, the structural part and building envelope (containing the exterior doors, windows, exterior wall coverings, soffits and roof systems), are crucial to preventing loss and minimising damage to a building and are especially critical for buildings exposed to high wind events. An appropriate performance of a building requires solid design, materials, installation, maintenance and repair. A significant shortcoming in any of these five elements can risk the performance of the building.

In Australia, the Cyclone Testing Station (CTS) of James Cook University (JCU) has been investigating buildings damage from tropical cyclones since Tropical Cyclone Tracy in 1974. As a result of the improvement of the Building Code and the introduction of the Standards in the early 1980s, a reduction in structural damage was noticed. However, continued poor performance of non-structural elements such as windows, external doors, roof coverings and attachments, such as guttering, fascia and eaves, has caused a loss of amenity and damage to structural building components over time, especially related to water ingress (Henderson et al., 2006, Boughton et al., 2011, Boughton et al., 2015, Boughton et al., 2017). The National Construction Code (NCC), a performance-based code, sets minimum standards for the construction of buildings (Australian Building Codes Board, 2019).

In response to increased hazards and the lessons learned from past storms, regulatory requirements for construction in coastal areas have increased over the past decade in the USA. Nevertheless, the design and construction community should incorporate the lessons learned from past events to avoid repeating past mistakes and to break the disaster-rebuild-disaster cycle. Building design is considered an important factor for a successful coastal building, and certain design flaws still exist and are observed each year. During the construction phase, careful preparation of design documents and attention to construction details can reduce damage to coastal homes (FEMA, 2011a).

1.3 Research Gap
The building investigations conducted from CTS (JCU), revealed that wind and rain will penetrate undamaged windows and external doors, which have small failures around the windows’ seals, the doors or waterproofing elements, leading to water
damage to interior finishes and facilitating mould growth. They also may be sucked out of the house if they have not been properly installed, due to a lack of or inadequate fixing of the frames to the house structure (Boughton et al., 2017, Boughton et al., 2015, Boughton et al., 2011, Henderson et al., 2006). In field investigations in houses hit by several hurricanes in the USA, issues with the entrance of wind-driven rain and glazing were also found and stated. Failures consisted of the entrance of wind-driven rain through exterior doors between the door and its frame, the frame and the wall and the threshold and the door; for windows, the failures were caused by inadequate attachment of the window frame to the wall (FEMA, 2011a). Water intrusion can be prevented by homeowners installing a plastic sheet sill extension on the inside face of the window (CTS, 2018) or the use of storm shutters on the exterior face of the window, though shutters will likely not significantly decrease the wind-driven rain damage to the glazed assembly (FEMA, 2010, CTS, 2018). Also, a range of industry guidelines with information related to the selection of openings and installation (AWA, 2015, AWA, 2019) addressed to homeowners and the construction industry is accessible.

In conclusion the research gap was identified as insufficient information of all factors encompassing water ingress from openings during tropical cyclones and a clear understanding of its interdependencies for the entire openings supply chain. An inclusive approach could provide a clear understanding for decision makers. Nowadays, this lack, limits the ability of decision makers from making decisions.

1.4 Rationale of a study
The literature review (Chapter 2), has critically encapsulated the non-structural failure of windows and external glazed doors due to wind-driven rain from tropical cyclones and storms that affects a wide range of groups, including the government, insurance sector, industry groups and the general community. To prevent the impacts of non-structural serviceability issues, this study attempted to unveil best-practice quality and regulatory management practices that be implemented to improve the entire supply chain, including, designers, manufacturers, builders, contractors and inspectors. Specifically, this study sought to identify, understand and unpack interdependencies in current practices for the entire supply chain of windows and external doors exposed to wind-driven rain events. Eradication of all water ingress in all severe events is not likely be possible; however, unnecessary repeated water ingress during moderate
events must be eliminated. Hence, identifying the most effective management intervention, that can increase the performance of openings subject to wind-driven rain during a tropical cyclone or a severe storm should be the first step for decision-makers to promptly visualise the interaction and effects of the factors and to make decisions.

1.5 Research Questions and Objectives
The identification of a gap in the literature review, trigger this study to explore the performance of windows and external glazed doors in tropical regions of Australia, which than led to the following research questions:

**RQ1:** What are the current practices affecting the performance of windows and external glazed doors subject to wind-driven rainwater ingress?

**RQ2:** How does this management factors interact and affect the performance of openings?

**RQ3:** Are there any management interventions that could lead to greater performance of window and door openings subject to wind-driven rainwater ingress during tropical cyclones and severe storms?

Following the questions, the study objectives were established:

**Objective 1:** to identify the key factors, in current practices, that affects the performance of windows and external glazed doors to wind-driven rainwater ingress during tropical cyclones and investigate if the failure occurs during severe storms;

**Objective 2:** to develop an openings’ wind-driven water ingress performance prediction model using a BN modelling approach;

**Objective 3:** use BN scenario analysis to identify the most appropriate management interventions that could lead to a higher performance of openings subject to wind-driven rainwater ingress during tropical cyclones and severe storms, providing decision makers with a simple communication and support for better targeting and prioritization of investments.

1.6 Research method overview and scope
Firstly, a qualitative interview data collection method, using an integrated approach, was adopted to increase the theoretical and practical understanding of current policies
and management practices with relevant industry groups affecting the performance of openings. From that, a probabilistic modelling approach was used to quantify the management practices resulting in the valuation of the performance of windows and external glazed doors, concluding with the best combinations of management practices to help reduce water ingress. This research work was conducted in Queensland, Australia, with the support of several local industry and government participants who had knowledge and work experience with windows and external glazed doors in tropical cyclone-prone regions.

The scope for this research was limited to:

- New Social Housing\(^1\);
- Single skin block and brick veneer construction; and Residential buildings NCC Class 1 and 2\(^2\).
- Natural hazards cyclone and severe winds in coastal cities and towns located in northern Australia (i.e. wind regions C and D according to AS/NZS 1170.2:2011 R2016);
- Water ingress into the building envelope through openings, particularly through windows and external glazed doors;
- This case study was conducted in Queensland, Australia, with the support of several local industry and government participants who had knowledge and work experience with windows and external glazed doors in tropical cyclone-prone regions.

1.7 Thesis structure

This section outlines the organization of the thesis which consists of seven chapters. This chapter introduces the present research study by addressing the research

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\(^1\) Social Housing according to the DHPW includes public housing, community housing and state-funded affordable housing targeting low to moderate income households (DHPW).

\(^2\) The Building Code of Australia, provides buildings classifications. This research refers to Class 1 and Class 2. The respectively definitions are: Class 1, A single dwelling being a detached house, or one or more attached dwellings, each being a building, separated by a fire-resisting wall, including a row house, terrace house, town house or villa unit attached or detached, and single, double or multiple-storey; and Class 2, a building containing 2 two or more sole-occupancy units each being a separate dwelling (QBCC).
background, research gap, research questions and objectives, as well as providing an overview of the research method and scope.

**Chapter 2** provides an extensive review of the pertinent literature.

In **Chapter 3**, the research method is detailed. The key issues relating to the research approach, research design, and relevant analytical techniques adopted in the study are addressed. Specifically, the chapter describes the procedures related to both the qualitative and quantitative research methods employed.

Following the research method, **Chapter 4** presents the development of the qualitative interview method and **Chapter 5** presents the development of the probabilistic approach based on the findings from Chapter 4.

**Chapter 6** summarises the key research outcomes and results of the analysis performed from the qualitative interview based upon the data collected from phone interviews and workshops and as well as the results from the probabilistic approach.

Finally, **Chapter 7** highlights the contributions made by the study to the existing body of knowledge. It also addresses the limitations of the study and presents recommendations for future research.
Chapter 2: Literature review

2.1 Introduction
This chapter presents a complete literature review carried out to gather the existing knowledge within the subject of research as well as be forming the basis for the identification of the ‘research gap’. Firstly, it reviewed the natural hazards tropical cyclones and severe storms and its devastating effects along the history along with its damage costs. Then the performance of non-structural elements focusing on the building envelope windows and external glazed doors which is viewed with different requirements (interests) from the openings supply chain. Next, some assessment methods were reviewed.

2.2 Tropical Cyclones and Severe Storms
During the warmer months from November to April, tropical cyclones develop over the warm oceans to Australia’s north, generates destructive winds, heavy rain and flooding to many coastal areas in Queensland, Northern Territory and Western Australia. They lead to increasing then decreasing winds along with changing wind direction, over a period of several hours. The diverse impacts of a cyclone can be felt over many days, over an area of hundreds of square kilometres, with the most destructive winds experienced just outside the eye of the cyclone. These destructive winds can generate windborne debris and cause extensive property damage. The rain damages buildings when the wind drives rain into the building, or by causing flooding and, or by triggering landslides (Middlemann, 2007). Decaying tropical cyclones can also impact non-cyclonic areas and cause significant damage (Ginger, 2010).

The Australian Bureau of Meteorology (BoM) categorizes cyclones with increasing severity from 1 to 5, in terms of the Australian Cyclone Severity Scale, according to the sustained wind and maximum expected wind speed (Table 2.1). It quotes wind speeds measured under standard conditions – in flat, open terrain (such as in airports) at a height of 10m above the ground, using a 10-minute averaging time for reporting the sustained winds. The wind speeds measured at house sites can be different from those measured under standard conditions, even in the same area, as the proximity of buildings and topographic landscape features affect wind speeds at house sites (BoM, 2019).
### Table 2.1 Maximum expected sustained winds and estimated wind gusts near the centre of a tropical cyclone

<table>
<thead>
<tr>
<th>Category</th>
<th>Sustained Wind (km/h)</th>
<th>Strongest Gust (km/h)</th>
<th>Typical effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>63 - 88</td>
<td>Below 125</td>
<td>Negligible house damage. Damage to some crops, trees and caravans. Watercraft may drag moorings.</td>
</tr>
<tr>
<td>2</td>
<td>89 - 117</td>
<td>125 - 164</td>
<td>Minor house damage. Significant damage to signs, trees and caravans. Heavy damage to some crops. Risk of power failure. Small watercraft may break moorings.</td>
</tr>
<tr>
<td>3</td>
<td>118 - 159</td>
<td>165 - 224</td>
<td>Some roof and structural damage. Some caravans destroyed. Power failures likely (e.g. Winifred).</td>
</tr>
<tr>
<td>5</td>
<td>Over 200</td>
<td>Above 279</td>
<td>Extremely dangerous with widespread destruction.</td>
</tr>
</tbody>
</table>

Strong and hazardous winds, commonly associated with heavy rain, snow, hail, ice and/or lightning and thunder are the result of severe storms which are atmospheric disturbances (Middlemann, 2007). Severe storms (related to wind gusts not associated with tropical cyclone, produces gusts of 90km/h or more with peak wind gusts exceeding 160km/h in the most damages storms) (Australia, 2020) and its variations cause buildings damages ranging from structural and non-structural failures as well as tropical cyclones. Its paid insurance claims are greater than those for tropical cyclones.

Severe storm events are sometimes called and classified differently around the globe. In the United States, the primary storm types are named straight-line winds, down-slope winds, thunderstorms, downbursts, northeasters, hurricanes, and tornadoes. Of all the storm types, hurricanes have the greatest potential for devastating a large geographical area and, hence, affect the greatest number of people (FEMA, 2007).

The Hurricane Research Division of the National Oceanic & Atmospheric Administration (USA) uses the Saffir-Simpson hurricane intensity scale for the Atlantic
and Northeast Pacific basins to give an estimate of the potential flooding and damage to property given a hurricane's estimated intensity (Table 2.2) (NOAA, 2019).

Table 2.2 Saffir-Simpson Scale utilized by NOAA in the USA

<table>
<thead>
<tr>
<th>Category</th>
<th>Maximum Sustained Wind (m/s)</th>
<th>Damage Level</th>
<th>Damage Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>33-42</td>
<td>Minimal</td>
<td>People, livestock, and pets struck by flying or falling debris could be injured or killed. Older (mainly pre-1994 construction) mobile homes could be destroyed, especially if they are not anchored properly as they tend to shift or roll off their foundations.</td>
</tr>
<tr>
<td>2</td>
<td>43-49</td>
<td>Moderate</td>
<td>There is a substantial risk of injury or death to people, livestock, and pets due to flying and falling debris. Older (mainly pre-1994 construction) mobile homes have a very high chance of being destroyed and the flying debris generated can shred nearby mobile homes.</td>
</tr>
<tr>
<td>3</td>
<td>50-58</td>
<td>Extensive</td>
<td>There is a high risk of injury or death to people, livestock, and pets due to flying and falling debris. Nearly all older (pre-1994) mobile homes will be destroyed.</td>
</tr>
<tr>
<td>4</td>
<td>59-69</td>
<td>Extreme</td>
<td>There is a very high risk of injury or death to people, livestock, and pets due to flying and falling debris. Nearly all older (pre-1994) mobile homes will be destroyed.</td>
</tr>
<tr>
<td>5</td>
<td>Over 70</td>
<td>Catastrophic</td>
<td>People, livestock, and pets are at very high risk of injury or death from flying or falling debris, even if indoors in mobile homes or framed homes. Almost complete destruction of all mobile homes will occur, regardless of age or construction.</td>
</tr>
</tbody>
</table>
2.3 Performance of buildings elements during cyclonic events

During major cyclone/storm events, the interaction between wind and buildings, causes both positive and negative pressures to occur concurrently. Loads exerted on the building envelope are transferred to the structural system, where in turn they must be transferred through the foundation into the ground. The magnitude of the pressure is a function of a number of factors, such as building shape, internal pressure, building height, topography, basic wind speed and exposure (FEMA, 2007). Investigations on building damage after severe storm events have usually shown that buildings that are well designed, well-constructed and well maintained, offer acceptable structural performance but may still have potential for water ingress (Henderson et al., 2014).

2.3.1 Building Code

Buildings codes are used worldwide with the purpose of ensuring safety. The Building Code of Australia has the same objective: the performance requirements for a building or structure are that it must remain stable and not collapse, prevent progressive collapse and avoid causing damage to other properties (Henderson, 2013). Building codes are drawn up by the Australian Building Codes Board; its job is to set minimum standards for the design, construction and performance of buildings to withstand extreme climate events related to natural hazards. Standards support the Building codes and buildings and houses must be designed according to them. However, it is suggested that there is still missing a large scope for increasing performance and reducing the risk of loss if homes only meet the current standards (Suncorp, 2015).

The National Building Code of Australia defines the building envelope “as the part of a building’s fabric (basic building structural elements such as the foundation, floors, walls, beams, columns, roof and non-structural elements such as ceilings, panels, windows and doors as well as equipment’s) that separate artificially heated or cooled spaces from the exterior of the building” (The Australian Building Codes Board, 2016, ABCB, 2019). The building’s envelope function is to protect the structure against rain, wind, sleet and snow. Whenever there is a failure in an element of the building envelope, for instance a window with glass failures or the frame, a significant quantity of water may enter the building causing damage to the inside of the home ( Boughton et al., 2015).
Some Building Codes were created or reviewed after a hazard happened. In Australia, the Building Codes have undergone a review in relation to wind speed against buildings, after Cyclone Tracy in 1974 devastated the city of Darwin, considered a big disaster, exacerbated by engineering failure (Walker, 2010). The cyclone destroyed between 50% and 60% of the houses and buildings and only 6% remained intact. Therefore, the performance of houses and small buildings were not fully structurally engineered when compared to larger buildings that were (Walker, 2010). From the economic side, Tropical Cyclone Tracy, caused more than $5 billion (2007 AUS dollars) in insured losses (ICA) and is acclaimed as the greatest economic loss from a single tropical cyclone in Australian history.

The decision of imposing requirements for housing to be structurally engineered to resist wind loads as well as the zoning of the cyclone regions and recognition of the importance of fatigue failure of cladding fastening systems and internal pressures in the wind code, was a direct consequence of cyclone Tracy (1974). Wind engineering research and development was another major beneficiary from Tropical Cyclone Tracy, which provided the implementation of the limit state approach to structural design in Australia (Walker, 2010). A claim analysis supported by Suncorp data, demonstrated that properties built in north Queensland prior to the introduction of modern building codes were more likely to suffer structural damage in the event of a cyclone (Suncorp, 2015).

In the USA, Hurricane Andrew (1992) did great damage in Florida, in response, the new Florida Building Code was adopted in 1994 based on the Australian studies and standard requirements developed after Cyclone Tracy (Salzano et al., 2010). In Hurricane Andrew, the poor enforcement of the buildings and a poor quality workmanship were the responsible for the construction failures which caused approximately 25% of the insurance losses (about US$4 billion) (FEMA, 2011a).

Henderson (2013) reported that strata property and detached houses often use the same building materials and are built to the same Australian Building Code; thus, they have similar vulnerability in a wind event. In most respects, strata property and contemporary houses should be capable of resisting design wind events if properly designed and constructed. For instance, water ingress from wind-driven rain has been identified as a key factor in insurance claims. This risk could be minimized by seeking
a better understanding of the relationship of wind gusts and intensity of rain and identifying possible economic solutions in reducing the amount of water ingress and resultant damage. Even though the Australian Building Code seems to be appropriate with respect to wind loading for the design strength limit state, when specific elements that warrant changes to building regulations are identified, a process is instituted to secure these relevant improvements are taken into account (e.g. recent changes to Australian standards to improve garage doors, soffit linings and tile roof).

2.3.2 Financial losses due to tropical cyclones events
The Insurance Council of Australia (ICA) collects catastrophe related claims data from the Australian market, recording insurance loss estimates for declared insurance catastrophe. ICA provides a most up to date summary data that can be accessed through the ICA webpage. Table 2.3 summarizes the estimated insurance losses of 16 major severe events in Australia since 1967 (ICA, 2019).

Table 2.3 Estimated insurance losses of severe events in Australia

<table>
<thead>
<tr>
<th>State</th>
<th>Event Name</th>
<th>Event Date</th>
<th>Original estimated insurance loss value</th>
</tr>
</thead>
<tbody>
<tr>
<td>QLD, NSW</td>
<td>Cyclone Debbie</td>
<td>March 2017</td>
<td>$1,403,000,000*</td>
</tr>
<tr>
<td>NSW, QLD, VIC, TAS</td>
<td>East Coast Low</td>
<td>June 2016</td>
<td>$421,696,229</td>
</tr>
<tr>
<td>NSW</td>
<td>East Coast Low</td>
<td>April 2015</td>
<td>$949,615,700</td>
</tr>
<tr>
<td>QLD</td>
<td>Severe Tropical Cyclone Marcia</td>
<td>February 2015</td>
<td>$544,163,458</td>
</tr>
<tr>
<td>VIC</td>
<td>Melbourne Severe Storm</td>
<td>February 2011</td>
<td>$526,651,637</td>
</tr>
<tr>
<td>QLD</td>
<td>Cyclone Yasi</td>
<td>February 2011</td>
<td>$1,531,573,196</td>
</tr>
<tr>
<td>QLD</td>
<td>Cyclone Tasha</td>
<td>December 2010</td>
<td>$393,000,000</td>
</tr>
<tr>
<td>NSW</td>
<td>East Coast Low</td>
<td>June 2007</td>
<td>$1,675,000,000</td>
</tr>
<tr>
<td>QLD</td>
<td>Cyclone Larry</td>
<td>March 2006</td>
<td>$799,000,000</td>
</tr>
<tr>
<td>QLD</td>
<td>Cyclone Justin</td>
<td>March 1997</td>
<td>$650,000,000</td>
</tr>
<tr>
<td>NSW</td>
<td>Sydney Region Storms</td>
<td>January 1991</td>
<td>$625,000,000</td>
</tr>
<tr>
<td>WA</td>
<td>Cyclone Joan</td>
<td>December 1975</td>
<td>$398,000,000</td>
</tr>
<tr>
<td>NT</td>
<td>Cyclone Tracy</td>
<td>December 1974</td>
<td>$4,090,000,000</td>
</tr>
<tr>
<td>QLD</td>
<td>Cyclone Althea</td>
<td>December 1971</td>
<td>$648,000,000</td>
</tr>
</tbody>
</table>
Many areas of Australia are at high risk of natural hazards. However, northern Australia’s cyclone risk is unique. Cyclone events result in significantly higher losses than other natural hazards, including hail and riverine flood (Suncorp, 2015), and the risk to communities is only increasing as the impacted regions becomes more developed.

In the USA, the top 5 costliest hurricanes by estimated insured losses (based on USD in 2018) recorded are Hurricane Katrina at US$51.9 billion, Hurricane Maria (2017) at US$30.7 billion, Hurricane Irma (2017) at US$25.6 billion, Hurricane Harvey (2017) at US$20.4 billion and Hurricane Sandy (2012) at US$20.4 billion (III, 2019). In August 1992, Hurricane Andrew struck the southeast Atlantic coast of USA. This hurricane remains one of the most memorable hurricanes to hit this region and was a major catalyst for building code changes in the USA involving wind design and was one of the costliest to date. Approximately 25% of the insurance losses (about US$4 billion) were attributable to construction that failed to meet the code due to poor enforcement and poor quality workmanship (FEMA, 2011a).

In addition to the cost of repairing building damage, which is often converted to insurance losses, cyclones cause noticeable economic and social losses on communities. Risk Frontiers estimates the social costs of disasters to be between 20% and 200% of the insured property damage. In the case of Cyclone Yasi in 2011, this cost could have amounted to more than $1.5 billion, including business interruption, disruption to local infrastructure, community upheaval, dislocation of families, higher crime rates, loss of leisure time, and death and injuries. Insurance losses are modelled to average $632 million per year; however, in any given year there is a 1 in 10 probability that cyclones could cost $1.4 billion and a 1 in 100 probability they could cost as much as $7 billion (Suncorp, 2015).

Cyclone Larry in 2006 in Australia, led to over U.S. $1 billion in damages (Holmes, 2001), of which 20% was only with housing. Interestingly, Ginger et al. (2007)
estimated that approximately 60–80% of damage caused by Cyclone Larry arose from damage to residential construction in houses built before enhanced building standards were implemented in North Queensland from the early to mid-1980s. Given that the population and property at risk are increasing dramatically in cyclone prone areas, i.e. there is significant development of coastal communities in North Queensland in Australia, the potential for larger losses exists (Li and Stewart, 2010). As reported in 2015 by the Northern Australia Insurance Premiums Taskforce (NAIP), insurance losses due to cyclones in northern Australia over the past two decades have totalled $2.4 billion, which is around $115 million on average per year.

According to Smith and Henderson (2015a), there is a clear indication that water ingress (e.g., ingress through windows/roofing), window and roofing damage (e.g. cladding failure, broken glass or casing damage) are the major causes of losses during cyclones for claims of all sizes. Thus, a mitigation program targeted to reducing vulnerability to these damage modes would reduce losses from insurance claims. In addition, even a slight frequency reduction of severe claims would likely decrease loss potential by a great extent.

2.3.3 Non-structural building elements impacts

When comparing the performance of newer construction over older buildings (pre-1980) in recent windstorms in Australia, it is evident that housing standards promoted significant improvements. However, that does not mean that some aspects of design and construction cannot be enhanced. Contemporary buildings may still present certain vulnerabilities to withstand cyclonic wind loads. In newer buildings, a great proportion of roller doors fail under wind loads, resulting in dominant openings. Many buildings that were built prior to the release of the Queensland Home Building Code have been refurbished, but structural details remain the same, meaning that they are still susceptible to wind damage (Ginger, 2010). Although modern building codes have ensured that new buildings are structurally more resistant to cyclones, there is no requirement for windows and doors and other non-structural elements in general to meet the same standards. If not properly protected, these become the weakest points in the building, and once breached, wind and water can enter the house, causing damage to interiors and contents (Suncorp, 2015). Table 2.4 summarizes the most vulnerable features and its possible impacts during a cyclone event (CTS, 2008).
Table 2.4 Summary of possible impacts due to failure on vulnerable features

<table>
<thead>
<tr>
<th>Vulnerable feature</th>
<th>Possible Impacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof connections</td>
<td>Water ingress, uplifting of entire roofs or walls</td>
</tr>
<tr>
<td>Gable end walls</td>
<td>Structural collapse</td>
</tr>
<tr>
<td>Windows and doors</td>
<td>Water ingress, wall and roof failure</td>
</tr>
<tr>
<td>Garage doors</td>
<td>Roof and walls failure</td>
</tr>
<tr>
<td>Roof eaves</td>
<td>Ceiling and wall lining damage</td>
</tr>
<tr>
<td>Attachments and equipment</td>
<td>Flying debris breaking windows and doors</td>
</tr>
</tbody>
</table>

The predominant practice seems to accept low levels of building and infrastructure asset performance to severe events, meaning that such assets are at high risk of non-structural damage and are repeatedly being rebuilt to the same standard after each severe event (Suncorp, 2015). However, it is worth acknowledging that there are no universal design guidelines to protect buildings from all sort of events, therefore, different natural phenomena present a variety of challenges, and each hazard requires a different approach and a particular set of recommendations (FEMA, 2007).

2.4 Water ingress into windows and external glazed doors

Damage investigations after tropical cyclones have consistently shown that windows and external glazed doors are affected by wind and rain, causing openings leak and damaging the interior of the building. Windows and doors are very weak elements in new buildings and also critical components of a building’s envelope. Wind and water (wind-driven rain) get into the building causing damage, even if closed or undamaged; however, most of the houses did not suffer structural issues. The water passes through small spaces and weepholes in windows and doors (Henderson et al., 2006, Boughton et al., 2011, Boughton et al., 2017, Boughton et al., 2015).

A pilot study presented by the CTS on the examination of building risks from cyclonic weather through policy claim data, found water ingress into housing through storms and cyclonic weather remains an issue in Australia (Henderson, 2013) and was a key insurance loss driver in through the events of cyclones Yasi (2011) and Larry (2006) (Smith and Henderson, 2015b). In Middlemann (2007) report to Australian Government, brought that water ingress is becoming a significant component of total damage in new structures even though with the improvement of building standards and consequent reduction in structural damage. Direct rain and wind penetrate
buildings from walls, windows or roofs causing damage. (Ginger, 2010) suggests that water ingress into the building is associated to non-structural elements when heavy rain occurs, with wind speeds higher than 108km/h. The same study states that buildings performance was reduced owing to errors in design and construction in houses-built post 1980’s.

In Australia, tropical cyclone Debbie (March 2017) and past cyclones (for instance Yasi 2011, Larry 2006) caused significant levels of damage through water ingress through windows (Boughton et al., 2017, Boughton et al., 2011, Henderson et al., 2006). Similar types of failure were detected in Florida after hurricane events, with most of the damage restricted to building envelope elements such as windows, doors, soffits and roof cladding. The failure from those components allowed wind-driven rain to enter buildings and causing damage (Baheru et al., 2014). Providing details of the interface between the window and the wall to the extent possible, are helpful practices for design professionals. The consequences of waterproofing defects are water ingress and moisture. Sealants are not the primary protection but the secondary line of defence against water infiltration. If a sealant joint is the first element of defence, a second one should be designed to intercept and drain the water that drives past the sealant joint (FEMA, 2011b). Due to the monetary cost of repairing water ingress related damage to building interiors and contents, USA industry has made considerable efforts to make windows have a greater performance to wind-driven rain. However, the prevalence of these products and systems in hurricane prone areas is still sparse (Lopez et al., 2011). In Australia, the Australian Window Association

2.4.1 Water ingress into windows, doors and roofs and its failure modes

Building failures occur when winds produce forces on buildings that they were not designed or constructed to withstand. Other failures may be attributed to poor construction, improper construction techniques, and poor selection of building materials (Flores-Colen and de Brito, 2010). An indication that design improvements are required is when problems arise from accelerated deterioration or repeated failure necessitating designs to be refined (Takata et al., 2004).

Appendix A summarises the failures caused by water ingress into the building elements windows, doors and roof and its failure modes, the table presenting the following information in separate columns: building elements (windows, doors, roof
etc.); buildings components (seals, weep holes, sashes, bolts etc.); root cause of failure (provided whenever possible); and suggestions for design, specification, checklists and options for mitigation. Appendix A was developed based on reports completed by CTS (JCU) from the results of extensive building damage surveys conducted on residential buildings and larger residential structures (resorts and holiday units) after Cyclone Debbie (2017) and Yasi (2011), as well as results of a report made to the Insurance Council of Australia. Typical building type information was obtained from a quick visual inspection from street side, namely, the estimated decade of construction, style of the construction, building orientation, windows size, type of cladding materials of the walls and roof geometry and roof materials (Boughton et al., 2017, Boughton et al., 2011, Henderson, 2013). Based on the Appendix A, a graph providing the categorisation of failure modes was developed (Figure 2.1).

Figure 2.1 Categorisation of failure modes from surveyed buildings (adapted from Boughton et al., 2017, Boughton et al., 2011; and Henderson, 2013).

As indicated by Hartkopf et al. (1986), the performance of a building is identified with the structure walled in area respectability from visual, mechanical and physical properties, for example, natural disasters. As expressed by Wilde (2018), the structure functionalities and execution must go to partners necessities. Clients desires are that the structure will have an incredible execution regarding usefulness, comfort, safeness. Owners focus on investment decisions related to costs with enhancing workers’ productivity and from the professionals and organisations responsible for the operational management of the building (Bortolini, 2018). Buildings performance
execution is affected by numerous variables which are specific dubious, for example, plan and development mistakes (Silva et al., 2016). As per Bortolini (2018) the components influencing building execution are: plan and development mistakes, building activity and upkeep, building deformities and issues, ecological specialists, for example, natural disasters, building properties (age, geometry, type of constructive solution, and so on).

2.4.2 Windows and Doors Supply Chain
The openings (windows and doors) supply chain includes the building approval process which commences before the construction starts when seeking for approval by a Building Certifier. Architects and designers have to follow the Australian Building Code and Standards. Building Certifiers must check building applications to ensure that the work will comply with relevant building codes and standards (QRA, 2011). During the construction phase, Builders supervises the work and constructs it in compliance with approved plans and building regulations including checking the quality of the building’s finishes (QLD Government, 2011). Building Certifiers will inspect the construction stages for which as inspection is mandatory. Windows and external doors are allocated at the final inspection in a total of five mandatory stages. Alternatively, the building certifier may accept a certificate of inspection for windows and external doors (DHPW, 2011) which in the state of Queensland is Form 16 that has to be completed for the finalization and approval of window and doors installation. Windows and doors manufacturers must comply with performance requirements in accordance with AS 2047 (Australian Standards, 2014, Australian Window Association, 2015a) and provide installation process for each of their products.


Windows need to be tested for a number of conditions that will impact on their performance and durability. The AS 2047 – 2014 provides generic requirements. AS/NZS 4420.1:2016 “Windows, external glazed timber and composite doors – Methods of test. Part 1: Test sequence, sampling and test method” provides details of
the tests which are: 1. design wind pressures; 2. deflection/span ratio, 3. Operating force test; 4. air infiltration; 5. water penetration; and 6. ultimate strength.

Focusing on the water penetration test which determines the resistance to water penetration occurs under a static wind load in all classes of buildings. The water is sprayed uniformly and continuously over the exterior face of the test specimen.

Boughton et al. (2015) estimated the wind pressure on a window and compared it to the water penetration test pressure (AS/NZS 4420.1:2016), the estimated wind pressure was over two times the test pressure suggesting the current test method does not reflect the conditions that cause wind-driven rain ingress through undamaged windows during high wind events. The current Standard test for water penetration, requires that openings can resist water on a normal windy day, but they are not tested to ensure that they will not leak in an ultimate limit states design wind event such as a cyclone. Boughton et al. (2011), suggested the development of a new standard for testing for weather tightness at or near the ultimate limit states wind speed.

Manufacturers must provide to all residential windows and doors a performance label which provides information from the design performance and energy rated according to the Australian Standard (Figure 2.2).

Figure 2.2 Windows label for accredited manufacturers from the AWA

The Australian Window Association (AWA) represents its manufacturers and suppliers and has been providing valuable information through guidelines and videos related to installation and materials selection (Australian Window Association, 2015b, Australian Window Association, 2012, Australian Window Association, 2010). The installation instructional videos are designed to give industry guidance on the correct installation of windows and doors in different types of construction. There is substantial emphasis in the correct installation of flashings. Flashings are impervious material installed to prevent the passage of water into a structure from a joint or as part of a weather resistant barrier system. The Australian Fenestration Training Institute is part of the
AWA and provides training classes and workshops to the industry (Australian Fenestration Training Institute).

The AWA declared that building plans usually do not designate the relevant wind loads for a building; this lack of quality specification causes important implications for choosing the correct window due to the diversity of requirements found in Australia for a diverse variety of buildings (Australian Window Association, 2017). During the construction phase, a random audit in Mackay in 2014 with 112 buildings found 9.82% (11 buildings) did not meet cyclone standards (Maddison, 2014). Many window defects, due to the lack of a good specification, present no increased risk of injury or damage to other property, but nevertheless affect the property owner or tenant or body corporate in the form of loss of use, diminution in value, and extra expenses incurred while defects are corrected. In addition, the replacement process might significantly inconvenience residents (Boughton et al., 2015).

Building Certifiers or Superintendents have the responsibility to provide building approvals based on site inspections, if the building work complies with the building assessment. A compliance certificate is given based on provisions of the Building Act 1975 (BA) and the building development approval which includes the BA, the Building Regulation 2006 (BR), the National construction code and the Queensland Development code or relevant code from other States or Territories. Two certificates are given; the first one after excavation of the foundation material and before the footings for the building are laid; and a second certificate, named the Final Inspection Certificate, in the approval for the final stage of the building works. The “Guidelines for inspection of class 1 and 10 buildings and structures” developed by the Queensland Government (DHPW, 2011) provides broad advise to Building Certifiers and Builders about their responsibilities in relation to mandatory inspections. There are three mandatory inspections, windows and external glazed doors inspection happens during the frame stage. The frame stage is the phase before the cladding or lining is fixed, or, for reinforced masonry construction, before the wall cavities are filled.

2.4.3 Mitigation strategies
There seems to be an under-investment in mitigation and a significant over-investment in disaster recovery, with only 3% of disaster funding being directed to mitigation and
prevention activities (Suncorp, 2014). The predominant practice is to accept low levels of building and infrastructure asset performance to severe events, meaning that such assets are at high risk of non-structural damage and are repeatedly being rebuilt to the same standard after each severe event. In the long term there will be a necessary spike in insurance premiums and/or significantly greater reliance on government support. Instead, the solution is linked to better planning controls for developments in high risk areas, strengthening standards for new buildings and retrofitting existing buildings (Suncorp, 2015). However, it is worth acknowledging that there are no universal design guidelines to protect buildings from all sort of events, therefore, different natural phenomena present a variety of challenges, and each hazard requires a different approach and a particular set of recommendations (FEMA, 2007).

JCU identified mitigation opportunities (Suncorp, 2015) to make homes more cyclonic resilient such as:

- **Window coverings**: DIY window coverings can be installed for around $1,360, and can reduce the cost of a claim by up to $15,000;
- **Roller doors**: Around 90% of modern homes have roller doors, and their failure contributes to almost one in three large claims. After-market bracing costs just $300, and could prevent up to $10,000 worth of damage in the event of a cyclone;
- **Roof upgrades** (for pre-1980 houses only): The options are full replacements, additional strapping or over-battens, ranging in cost from $3,000 to $30,000. All upgrade options focus on tying the roof to the ground to handle high wind speeds.

When accounting only for the water ingress problem, partly originated from the overpressure developed across the building envelope during windstorms which can exceed the serviceability test pressures specified in AS 2047 for window resistance, performance could be improved by (Ginger, 2010):

- **Occupant education** to the likelihood that wind driven rain will enter the house;
- **Using water resistant internal linings**;
- **Reducing water ingress** by complying with a higher serviceability test pressure.
Smith and Henderson (2015a) indicated that an effective mitigation program would require a combination of traditional inspections completed by a qualified inspector, in conjunction with asset users completing self-assessments through smart-phone technologies. Although, the following activities are still required:

- Continued discussions with building associations to promote skills and market niche branding for structural retrofitting of older housing;

- Collaboration with building product manufacturers to explore economies of scale opportunities for creating low-cost severe event performance retrofitting components (e.g. shed tie-down, fence supports, gutter brackets, door braces, roof space framing connectors);

- Engagement with building and construction commissions, regarding the development of building certification documentation for retrofitting work to older housing, to allow homeowners and insurers to demonstrate effective structural mitigation.

For Henderson et al. (2014), establishing a suite of rectification measures for existing buildings, continuing education of builders and designers in resilient construction, developing resilient materials for use in new buildings, and improving design details, would certainly enhance buildings performance.

Some informative guidelines have been produced by Queensland and Western Australia Governments regarding cyclonic events performance for buildings. For instance, the guideline “Planning for a more resilient North QLD – Part 2 Wind resistant housing”, which the main purpose is to advise homeowners that reside in Queensland regions prone to severe wind conditions, of key issues associated with rebuilding, repairing and maintaining their home. Specifically, provides information on building components, material selection and installation. Looking at the selection of materials used in cyclone regions is the need to be fit-for-purpose in other words, they must be able to withstand wind loads and have good durability. Products that are part of the structural frame of the house (including roof and wall cladding, windows, skylights, etc.) must conform to relevant standards and be suitable for use in North Queensland (QRA, 2011)
A brochure was to create awareness for homeowners of the main causes of cyclone damage to houses and it highlights critical building components and maintenance issues that homeowners may need to address to ensure that their house is sufficiently ready to withstand tropical cyclones (CTS, 2008).

A cost-benefit analysis study found that for each public US$1 spent on mitigation strategies, for instance and in particular exceeding codes, can save to population and states moderate US$4, with specific scenarios increasing that estimate to US$16; so proving that mitigation policies are a cost-effective strategy to deal with extreme events (MMHMC, 2005, NIBS, 2018).

2.5 Assessment methods

Buildings are complex systems with many disciplines involved and with a long life cycle (Wilde, 2018). In order to assess the dynamically interaction of the parts of the openings system, three techniques were studied: Fault Tree (FT), System Dynamic (SD) and Bayesian Network (BN) summarized below.

A Fault Tree (FT) is a graphical model relating failure to its causes (Mohaghegh et al., 2009). The technique consists of binary events (satisfactory/non-satisfactory, yes/no) in which each event is independent statistically. The technique approach only considers a fixed time horizon during which each component can fail only once (Ruijters and Stoelinga, 2015). The construction of a FT occurs from the event to their causes, until failures are obtained (Bobbio et al., 2001). Fault Tree Analysis (FTA) technique is used for dependability analysis offering a structured way to list possible failures and the consequences of these failures. FTA can be divided into quantitative and qualitative analysis. Qualitative considers the structure of the FT and are used to detect system vulnerabilities. Quantitative analysis is used when probabilities of the failures are known to calculate the probability of the occurrence of the top event. This techniques do not capture non-linearity and dynamics. (Bobbio et al., 2001, Ruijters and Stoelinga, 2015).

Systems dynamics (SD) is a deterministic modelling and simulation methodology which is used in complex and dynamics systems for decision making dealing with dynamic management problems (Sterman, 2010, Vlachos et al., 2007). The allowed feedback loops in SD, provides feedbacks within a system and enable to investigate the behaviour of the system components over time based (Sušnik et al., 2013)
(Mohaghegh, 2010), although, it cannot explicitly deal with uncertainties. Uses scenario analysis to help decision makers understand the system and initiate better management strategies.

*Bayesian Network* (BN) is acknowledged as a very powerful and useful modelling framework in the field of probabilistic knowledge representation reasoning (Cai et al., 2014). Broadly, Bayesian Network (BN) is a probabilistic method which describes probabilistic relations among elements of the model. When objective data is lacking, use of expert opinion is necessary. However it is incapable of expressing dynamic aspects such as feedback loops (Mohaghegh, 2010).

An advantage of this method compared to the ones previously described is that it can easily manage missing or few data and can typically generate adequate prediction accuracy, even with a small sample size, provided that the model structure is well defined (Uusitalo, 2007) or with high uncertainty (Knochenhauer et al., 2013). It is also possible to combine different sources of data, or where hard data are not available, probabilities based on expert knowledge can be provided to the model (Uusitalo, 2007). Bayesian Networks provide a suitable modelling tool to integrate experts’ opinions with hard data and the outcomes from other models. Stakeholder’s participation is a key requirement of good model development, particularly when models are to address management questions. The likelihood of better outcomes becomes an opportunity for stakeholders to learn about interactions in their system and likely consequences of their decisions, actively seeking their feedback on assumptions and issues and exploiting the model results through feedback and agreed adoption (Jakeman et al., 2006). Bayesian Networks also represent a suitable support tool for decision-makers, as the costs and risks associated with different management strategies can easily be assessed (Uusitalo, 2007). Chen and Pollino (2012) have stated that the rapid propagation of information through the network is one of the major advantages of BNs, in that, they can be used to quickly view how decisions and observed conditions at one node will affect the system as a whole. The choice of BNs as a modelling tool also presents some challenges. Morgan et al. (1990) have stated that it may be difficult to convert experts’ opinions into probability distributions, especially when many states or many nodes are involved. It is rational to keep the BN simple in order to restrict the number of conditioning factors, as it has been proven cognitively difficult to think of conditional distributions with several conditioning factors.
However, Charniak (1991) considers experts' opinions as often reliable. Finally, feedback loops, which could be informative in understanding how the system operates, are not easily supported in BNs (Nielsen and Jensen, 2009).

2.6 Summary
This chapter provided an extensive review of the literature pertinent to the vulnerability of some non-structural building components from the building envelope, particularly on windows and external glazed doors to cyclonic forces and its financial losses. Next, three assessment methods concepts were discussed.

Specifically, Sections 2.3 and 2.4 formed the basis for the identification of the research gap described in Chapter 1, Section 1.3 Research gap. Damage investigations, from tropical cyclones in Australia and hurricanes in developed countries have been indicating repetitive water ingress, to non-structural elements such as windows and external glazed doors. Buildings performance studies brought up the opening’s performance is reduced owing to errors in design, construction and buildings materials. The compilation of the failure modes in Appendix A (Section 2.4.1) associated with the literature review concerning the openings supply chain as well as the current mitigation strategies establish support to identify the research gap. The insufficient information of all factors encompassing water ingress from openings during tropical cyclones and a clear understanding of its interdependencies for the entire openings supply chain provided a limited understanding for the researcher. An integrated approach could provide a clear understanding for decision makers. Nowadays, this lack, limits the ability of decision makers from making decisions. Research questions and objectives were developed based on the research gap. The next chapter explains the methodology used to achieve answer the research questions and research objectives of this study.
Chapter 3: Research method

3.1 Introduction

In this chapter, the details of the research methods and relevant analytical technique undertaken in this study are presented. A qualitative method, using an integrated approach, followed by a quantitative method, using a probabilistic approach were used in this study. The qualitative method was used to firstly gain a clear insight into construction industry towards the current management practices within the industry openings regarding water ingress into the building from windows and external glazed doors during tropical cyclones. The findings from the qualitative method were used to develop a probabilistic graphical model using a Bayesian Network to identify the most effective management practices that can increase the performance of openings. According to Bluhm et al. (2011), “a qualitative research detects experience and processes while a quantitative research is suitably self-assured to go along with the qualitative beginnings by improving or gauging the understanding of an experience, uncovering the prevalence of an individual's experiences, and generalizing those experiences to a larger population. Thus, both methods have strengths, but using one to the exclusion of the other, although effective, does not offer adequate support of any management experience. In fact, each method is complementary to the other, answering issues raised by the other” (Bluhm et al., 2011).

The structure of the chapter begins with the introduction (this section). Then, Section 3.2 presents the research process and research design, which details the stages of this study, along with the research methods, activities and objectives. Section 3.3 explains the compilation of knowledge acquisition (Literature review). Section 3.4 delineates the concerning details of the qualitative expert's interview conducted, including the identification of industry experts participating in the relevant data analysis technique. Section 3.5 explains the detailed process to the BN model development; and Section 3.6 summarises the chapter.

3.2 Research Design and Process

The research process and the research design are outlined in this section. The research process started with an extensive literature review to gather fundamental knowledge and to identify the research gap. This then led to the research questions and research objectives. To answer the research questions and objectives, the
research method was defined, based on the various literature reviews. The study process continued with an expert qualitative interview, employed to seek input from the construction industry to identify the factors that affect the performance of openings. The Bayesian Network model development started with the conceptual model, which was based on the identified factors provided during the qualitative interview as well as literature reviews, leading to the development of the Bayesian Network structure. Another round of data collection, with domain experts was performed, for the parameterisation of CPTs and MDPs. Subsequently, the model validation followed by a sensitivity analysis was conducted. Next, the creation of different scenarios and analyses. Finally, the findings from the qualitative method and the probabilistic approach were considered, and conclusions were drawn. The research design and process is provided in Figure 3.1.

![Figure 3.1 Research design and process](image-url)
Each stage of the study had its own methods, activities and objectives which are summarised in Table 3. 1.
<table>
<thead>
<tr>
<th>Research stage</th>
<th>Research methods</th>
<th>Research activities</th>
<th>Research activity objectives</th>
</tr>
</thead>
</table>
| First          | Literature review| Compilation of knowledge | - To gather fundamental knowledge pertaining to tropical cyclones worldwide and its effects in non-structural building elements  
- To define the knowledge gap, research questions and research objectives  
- To define the research methods  
- To supplement knowledge acquisition to support this study |
| Second         | Qualitative expert interview and analysis | Phone interviews and workshops with experts  
Thematic analysis research | - To identify the factors affecting the performance of windows and external glazed doors  
- To identify if this failure occurs during other events, such as storms, since they are prevalent in the north of Queensland  
- To gain knowledge on the issues related to the manufacture, design, installation, inspection and certification of windows and doors in residential buildings in order to provide recommendations on effective practices to improve building performance during cyclones and severe storms and further develop a probabilistic model to quantify the performance of openings  
- Transcribed the data collected making use of codes |
| Third          | Bayesian Network design and scenario analysis | Conceptual model developed through consultation with experts  
BN structure and operationalisation  
Parameter learning  
Model validation | - To synthesise previous knowledge into a system to provide a BN structure  
- To convert the conceptual model into a BN structure  
- To obtain the marginal probability distributions (MPDs) and conditional probability tables (CPTs) to identify the most effective management practices that can increase the performance of openings  
- To confirm the model would achieve its objectives |
| Sensitivity analysis and scenario testing and analysis | • To perform a sensitivity analysis to highlight potential management leverage points to carry out some scenario testing  
• To learn how posterior distributions change when parameters are altered  
• To identify potential management interventions under different scenarios |
3.3 Research stage 1: Literature review
The objectives of the literature reviews were: 1) to gather fundamental knowledge pertaining to tropical cyclones worldwide and its effects on non-structural building elements; 2) to identify the research gap; research questions and research objectives; 3) to build the appropriated research methods and 4) to supplement knowledge acquisition within the study. This research activity was undertaken through a critical and comprehensive review of the national and international academic publications and national and international grey literature (e.g. industry and government reports) as described in Chapter 2.

3.4 Research stage 2: Qualitative expert interviews and thematic analysis
Qualitative methods have a long record and historical convention within management research and business, and have an acknowledged pedigree (Cassell and Symon, 2004). According to Bluhm et al. (2011), “qualitative research is essential for uncovering deeper processes in individuals, teams, and organizations, and understanding how those processes unfold over time. Furthermore, qualitative research is critical for gaining an understanding of both what individuals experience and how they interpret their experiences” (Bluhm et al., 2011).

The aim of this study stage was to conduct a systematic investigation into current perceptions of management practices within the industry, as water ingress inside the building has been a recurrently issue for windows and external glazed doors during tropical cyclones.

Methods of qualitative data collection and analysis are not standardized. Therefore there are different data collection possibilities and flexible analysis techniques (Bluhm et al., 2011). For this study, a series of open and structured questions were conducted with experienced practitioners working within the construction Industry and construction Government. A participatory modelling approach (Bertone et al., 2016) was chosen which included workshops and phone interviews. The given approach was applied to gain industry knowledge on current management practices related to the manufacture, design, installation, inspection and certification of windows and doors in residential buildings. The target respondents included the construction Industry and construction Government sector, and its associated professionals with knowledge and work experience of windows and external glazed doors in tropical cyclone-prone
regions of Queensland. Companies and contact numbers were found randomly through Google searches.

Phone interviews and workshops involved questions that were developed based on the literature reviews. The main purpose of the questions was to establish the factors and issues surrounding openings subject to wind-driven rain and to get detailed information from the respondents. Other information was also recorded from respondents, such as years of experience and position. Thirty-nine participants were involved in phone interviews and workshops. The practitioners' work experience was between 15 to 45 years in construction, with positions including Managing Director, Operations Director, Building Certifiers; Builders; Architects and others. Four major themes were identified: Standards, Inspection regime, Installation quality regime and Liability and recourse.

The specific objectives for the qualitative expert’s interview were:

- To identify the management factors affecting the performance of windows and external glazed doors during cyclonic events
- To identify if this failure occurs during other events, such as storms, since these are prevalent in the north of Queensland
- To explore the views of those who regularly work with openings.
- To gain knowledge on the issues related to the manufacture, design, installation, inspection and certification of windows and doors in residential buildings.

Actively employing such an approach provided the means to identify underperforming processes and practices. The participants were actively involved and were able to provide recommendations thus creating paths for achieving continuous process improvements.

3.4.1 Data collection
The data collection involved recording data from phone interviews and workshops. Participants were initially contacted by e-mail or telephone, then they were formally invited to take part in the data collection via e-mail where it was outlined the nature of the project and the contribution that the participant could make to this study. At the beginning of the workshop, it was explained to participants that the workshop would
be recorded but that the material gathered would be considered confidential within the research. An addition request was to take photos of the participants during the workshops. Most of the participants were happy to contribute to the project, with many providing some practical recommendations.

Phone interviews were conducted with industry practitioners based in Cairns, Townsville, Brisbane and the Gold Coast where respondents would be experienced with issues related to high wind events. The phone interviews included both structured and open-ended questions and are provided in Section 4.2.1, Chapter 4. The approach used during the interviews, initially explained the purpose of the phone call on behalf of the Griffith University team using some key topics/questions and allowing interviewees to talk first about their experiences related to the issue. This approach was used to help the respondents feel comfortable about talking when providing their knowledge about the problem, their work process, their concerns, complaints and recommendations. The questions were generated based on the literature review and from researcher working experience as a Civil Engineer and a research assistant, who is also a Civil Engineer. The research assistant helped to make some of the phone interviews. The nine questions were undertaken as pilot interviews during the three initial phone interviews of each one. After each one completed three interviews, a feedback meeting was arranged to discuss the questions made.

Three workshops were facilitated, with the following participants and locations: 1) a large manufacturing company of aluminium windows and doors and glass products based in Brisbane, 2) building and asset service staff from the Queensland Department of Housing and Public Works and a major building contractor staff at Townsville and 3) The Cyclone Testing Station specialist researchers from James Cook University in Townsville.

3.4.2 Thematic Analysis

Responses from the data collection phase were recorded and transcribed. The analysis followed a thematic analysis (Trangkanont et al., 2018, Wipulanusat et al., 2019). The thematic analysis consisted of the following steps: (1) dataset familiarisation (i.e. writing transcripts and interpreting data); (2) keywords were highlighted through all the data sets, capturing main ideas and how they were related; (3) keywords were grouped into codes; (4) the codes were aggregated to develop four
themes, which represented the core opinions of the interviewees; (5) the list of themes was revised to ensure consistency and a summary results table was populated.

3.4.3 Findings
The data collection provided a rich source of data concerning current perceptions of the management factors and barriers to openings subject to wind-driven rain. These findings were used to drive recommendations for improving the performance of windows and door openings in residential buildings.

3.5 Research Stage 3: Bayesian Network model development
3.5.1 Bayesian Network description
Bayesian Networks are probabilistic graphical models that represent a set of variables and their conditional interdependencies via a directed acyclic graphic (DAG) and probabilistic rules to enable a learning and reasoning process (Pearl, 1988). The DAG represents the cause-effect relationship and accurately details how each variable is influenced by its parents. The causal graphic structure representation allows for understanding by stakeholders and non-technical users (Chen and Pollino, 2012).

In terms of representation, the variables in a DAG are called nodes and the causal relationship between two nodes is represented by a directed arrow, leading from the parent node (cause node) to the child node (effect node). In terms of representation, the structure is a directed acyclic graphic (DAG), consisting of a node set that represent variables. The conditional dependence between variables is represent by a directed edge, leading from the parent node (cause node) to the child node (effect node) (Figure 3.2).

Figure 3.2 DAG, basic structure of a BN (e.g. A and B are parent nodes and C is the child node)
The strength between the variables (the child node and its parent node[s]) is quantified by conditional probabilities, which are represented in a conditional probability table (CPT) attached to each node (Chen and Pollino, 2012). The parent nodes are described by marginal probability distributions (MDPs) and can be either populated by empirical data sets or expert judgment. CPTs and MDPs can be populated by either empirical datasets or expert judgment (Pollino and Henderson, 2010). The Bayes’ rule describes how existing beliefs can be modified when new evidence becomes available. By applying this rule, the BNs allow for reasoning under uncertainty, which proves to be important for decision-making (Pearl, 1988).

The formula below can be read as, the probability (P) of A (cause) given that B and C (effects), have occurred, P (A|B; C).

\[
P(A|B; C) = \frac{P(B|A) \cdot P(A)}{P(B)} \quad \text{OR} \quad P(\text{Cause}|\text{Effect}) = \frac{P(\text{Effect}|\text{Cause}) \cdot P(\text{Cause})}{P(\text{Effect})}
\]

When there are many variables and links, as in most real-world models, and where the number of states for each variable is large, calculations become daunting or impossible to do manually. Algorithms such as the Lauritzen-Spiegelhalter, Gibbs sampling, and others are built into most BN software estimate the conditional probabilities based on the network structure and dataset (Fenton, 2012).

The validation of the model includes the conceptual methodology validation, which is focused on the analysis of objectives, assumptions and outputs of the model, and on checking the accuracy of transforming the problem formulation into a model specification (Sargent, 2013). The second step is data validation, which consists of assessing the model behaviour with the use of accurate and consistent data (Chen and Pollino, 2012). When no data exists, it was found that a common technique for validating a BN is based on expert opinion. This process consists of asking experts whether they agree with the model structure and parameterization (Pitchforth and Mengersen, 2013). When the probability distributions of each node have been defined, the network is able to be ‘solved’. Sensitivity analysis refers to the analysis of the influence and influence degrees of multiple causes (node states) on result (target node). These analyses rank the variables in order of importance relative to the final output (Chen and Pollino, 2012). From that, the BN is complete and can be used for
scenario analysis. The scenario testing is accomplished by enter evidence into a node by defining a fixed distribution on a node. The effect of the scenario is examined for its effect on other nodes through probability distribution which are used for understanding the impacts of any change in the model (Pollino and Henderson, 2010).

The construction of a BN network involves the following steps: firstly the structure learning which consists to determine the factor variables (nodes) related to the research study based on prior knowledge or expert experience so as to determine the relationship between the nodes (dependent or independent) creating a DAG structure; secondly, parameter learning, the BN structure can be created using a software and then parameter learning can be conducted, thus defining the MPD’S and CPT’s for each node; thirdly: conduct a sensitivity analysis which is used to identify the sensitive factors with a significant impact on the target node, based on the sensitivity analysis results run scenarios testing and analysis. (Zou and Yue, 2017, Pollino and Henderson, 2010).

The detailed process executed in this study to the BN model development is explained in six mains steps:

1. Conceptual model development; identification of the variables (nodes) related to the research study and the relationships between these based on prior or expert knowledge;
2. The conversion of the conceptual model into a BN DAG structure;
3. Parameter learning, based on the BN structure completed through either expert data or expert’s opinion or a combination of them;
4. Model validation;
5. Sensitivity analysis; and
6. Scenarios test and analysis.

3.5.2 Conceptual model development

The purpose of the model was established during the literature review which is to create a model to reveal the most appropriate management interventions that could lead to greater performance of window and door openings subject to wind-driven rainwater ingress during tropical cyclones and severe storms. The conceptual model is the identification of the key variables influencing the model purpose. The variables consist of the factors that affect the performance of openings. For the conceptual model, experts’ feedback may help in identifying key variables or processes, especially
if the model is used as a management model (Chen and Pollino, 2012). Existing knowledge should be synthesized into a conceptual model to provide a visual summary of how the variables are linked to each other. All nodes in the model must affect the final output or be affected by a node. During the conceptual model, it process is also states that all nodes should be identified. (Chen & Pollino, 2012).

3.5.3 The conversion of the conceptual model into a BN structure
In most engineering areas, the BN model structure, is constructed based on the knowledge and experience from experts’ (Nguyen et al., 2016). The definition of the BN structure in collaboration with experts’, according to Fenton (2012), is a reliable method which considers the information that is really needed for the model. The BN modelling tool used in this study was the Netica software (Norsys Software Corp, 2006) as it is largely used by the scientific community, and is considered to be versatile and has a user friendly interface.

3.5.4 The parameterisation of the CPTs and MDPs
A conditional probability table (CPT) that is attached to each node, represents the strength between the child node and its parent node[s]). The marginal probability distributions (MDP) represent the previous beliefs of a node (Chen and Pollino, 2012). Each node identified during the conceptual model should have states specified. A node may have binary states such as “High” and “Low” or may have multiple states such as “High”, “Medium” and “Low”. The states of the nodes can be identified based on available data and expert opinion. To keep the size of the CPT’s and MDP’s manageable, it is recommended to have the smallest number of states possible in each node (Pollino and Henderson, 2010).

The approach to obtain conditional probabilities include (Chen & Pollino, 2012):

- Databases, from field monitoring or laboratory studies;
- Datasets, derived from models;
- Information elicited from experts or stakeholders which is based on past observation, knowledge and experience.

In this study, the parameterisation of MPDs and CPTs was based on several expert’s knowledge acquired through workshops and phone interviews.
3.5.5 Model validation
Two steps include the model validation: 1) the conceptual methodology validation, which is focused on the analysis of objectives, assumptions and outputs of the model, and on checking the accuracy of transforming the problem formulation into a model specification (Sargent, 2013); 2) and assessing the model behaviour with accurate data. If there is no data, a common technique for validating the BN model is based on expert opinion which consists of asking questions to experts about whether they agree with the model structure, and parameterization (Pitchforth and Mengersen, 2013). The validation of the BN model in this study was conducted with three Academic experts in BN.

3.5.6 Sensitivity analysis
A sensitivity analysis is a form of quantitative evaluation of the model. The sensitivity analysis ranks the variables in order of their importance, relative to the variable of interest, typically the final output (Chen and Pollino, 2012). The analysis results may provide a better understanding of the most significant factors in a decision scenario and can be used to verify whether the model’s response has the expected behaviour (Chakraborty et al., 2016). In this study, the sensitivity analysis was made using a function in Netica software.

3.5.7 Scenarios test and analysis
The scenarios test is also a form of quantitative evaluation of the model. The scenarios are used for understanding the impacts of any change in the model (Chakraborty et al., 2016). The computerized model evaluation consists of applying different scenarios of parts or the whole of the model by assessing its behaviour and examining whether the resulting probabilities are reasonable and logical (Chen and Pollino, 2012).

3.5.8 Summary
This chapter outlines the research methods employed to address the research question and objectives, along with the research process and research design. The study employed a qualitative research method employing interviews and workshops, for the analysis of the data, thematic analysis was applied. The second approach was a probabilistic approach using a Bayesian Network model. The findings provided from the qualitative research and within thematic analysis, served as the base of the conceptual model and further BN structure and model. Chapters 4 and 5 present the
details and results of the qualitative method the Bayesian Network model undertaken in the study.
Chapter 4: Qualitative interview research

4.1 Introduction

The objective of the qualitative research stage, using an integrated approach, was to identify the factors affecting the performance of windows and external glazed doors during cyclonic events, which allow water ingress into the building, and to identify if this failure occurs during other events, such as storms, since they are prevalent in the north of Queensland (objectives described in Chapter 1). The data collection included workshops and phone interviews. This stage started with the identification of industry experts that would suite this research. The participants incorporated different areas of expertise in order to obtain a wide overview. Participants included: Building Certifiers, Installers/Builders, windows and doors Manufacturers, Architects, Designers, Researchers, Construction Managers, Project managers. From the Queensland Government, Managers, Superintendents and Architects.

4.2 Data Collection

The data collection ran from November 2017 to March 2018, reaching a total of 39 participants through both phone interviews (27) and workshops (12). The given approach was applied to gain industry and government knowledge on current management practices in relation to the design, manufacturing, installation, certification and inspection processes of windows and doors in residential buildings and social housings.

The methods used for the collection of respondent data are described below.

4.2.1 Phone interviews

The distribution of phone interviews participants was: (a) 12 Building Certifiers; (b) 10 Installers/Builders; (c) 1 Aluminium Window/Door Manufacturer; (d) 2 Architects; and (e) 2 Construction companies.

The following questions were applied in the numbered order most of the time as the most important was to provide a comfortable environment to the interviewer providing them freedom to share their experiences, their work process, their concerns, complaints and recommendations.

The full list of questions asked are listed below:

1. What are the most critical causes of water ingress in windows/doors/building envelope? How can they be mitigated?
2. What type of damage occurs due to rain driven water ingress in the building envelope (e.g. carpets replacement, plasterboard softening, mould, termite, etc.)? Can the incidence and severity of damage be reduced with some good strategies - their opinions?


4. What type of inspection is conducted for waterproofing of building envelope? Particularly windows/doors? Is this a challenge to inspect? Is this work inspected before block work or internal walls are completed?

5. Documentation related to the waterproofing of the building envelope/windows/doors/flashings/etc. Apart from builders providing certificates on window quality, is there any quality documentation provided about window installs and building envelope waterproofing such as flashing, etc.? Would inspectors like builders to provide them with some sort of quality documentation about the window/door/building envelope installation process in addition to the product quality information?

6. Perceptions of installer labour and skills in region? What qualification the installers have? Training/qualifications? Do installers of windows and waterproofing of building envelope receive sufficient training on recommended practices (e.g. AWA and manufacturer guidelines)?

7. Is the level of specification provided by builders sufficient for DHPW inspectors to inspect works? We have been told that builders are only required to provide light specification for HPW projects. Is it contractually difficult for DHPW inspectors to state that builders have not confirmed to requirements for windows/doors/building envelope waterproofing? What level of documentation would they like to have?

8. Do the inspectors notice whether builders of public/domestic housing are using lower quality windows (i.e. potentially inferior windows)?

9. For Building Certifiers, how do they conduct the windows inspection? What stage and how they see they could improve? Form 15/16 enough responsibility?
4.2.2 Workshops
The first two-hour workshop was held on 1\textsuperscript{st} of March 2018, in Brisbane, in the office of G. James Glass & Aluminium, which is a large Australian supplier of aluminium windows/doors and glass products. Participants at the workshop included the Branch Network Operations Manager, Senior Product Designer, Structural Engineer and the Commercial Technical Advisor. The workshop involved the themes of standards, documents, quality procedures, design, manufacturing and the installation process. Themes of questions/topics discussed at this workshop were about:

- The main failure modes for windows from cyclones and heavy winds, inspection practices, standards, quality of labour, documents and inspections.
- The design, manufacturing and installation process, including product specification, manufacturing process (what makes a product different from non-cyclonic areas to cyclonic areas), product delivery to the construction site, installation process, and product quality guarantees.
- Quality procedures to ensure high standards of workmanship for the installation, of windows.

The second three-hour workshop was in Townsville on the 22\textsuperscript{nd} of March 2018 took place at the Department of Housing and Public Works (DHPW) office (Figure 4.1). Participants at the workshop included two Acting District Managers, an Acting Delivery Manager and a Senior Superintendents Representative from DHPW, as well as a North Queensland Manager and Project Manager from building contractor Paynter Dixon. This workshop focused on understanding the involvement of DHPW from the design to the construction and inspection stages. The following questions served as guide to generate a discussion between the participants:

1. What are the most critical causes of water ingress in windows/building envelope? How can they be mitigated?
2. Have you noticed a trend of greater wind-driven caused issues after cyclone events?
3. What are the main issues (minor/moderate damages) caused by the wind-driven rain through the building envelope (windows)?
4. Is the level of specification provided by Architects/Designers sufficient for DHPW inspectors to inspect works? Any suggestion for an improvement?

5. Apart from builders providing certificates on window quality, is there any quality documentation provided about window installs and building envelope waterproofing such as flashing, etc.?

6. Are there any issues with waterproofing of the building envelop, particularly windows?

7. Do/can building inspectors inspect the building envelope (windows) for waterproofing?

8. Do installers have skills to do the job, or receive any formal training? Do the inspectors believe they follow practices or cut corners when it comes to these details?

9. Is it contractually difficult for DHPW inspectors to state that builders have not confirmed to requirements for windows/building envelope waterproofing? Is there any procedure for reporting any irregularities in windows/waterproofing?

Figure 4.1 Workshop in Townsville with DHPW participants

The third workshop was held in the afternoon of the same day in Townsville at James Cook University (JCU) with the Director and a Senior Research Fellow from the Cyclone Testing Station (CTS). The workshop with the specialist CTS researchers included an open discussion about window and waterproofing testing procedures and
the adequacy of Australian Standards for achieving adequate serviceability standards. At this final workshop, the research team had the opportunity to access the test rigs where two simulations were performed. Firstly, a simulation of the impact of debris in a window. Secondly a simulation of a window receiving a wind driven rain pressure with a high dynamic pressure, replicating a cyclonic pressure. Specifically, the second test was been performed as the current standard (AS 2047 – 2014 and AS/NZS 44020.1:2016) only determines the resistance to water penetration under a static wind load. According to the AS/NZS (2016) 4420.1:2016 standard, “water should be sprayed uniformly and continuously over the exterior face of the test specimen” (AS/NZS, 2016) 4420.1:2016.

4.2.3 Workshops and phone interview participants
This section provides the respondent codes.

Table 4.1 Workshops participants

<table>
<thead>
<tr>
<th>Code</th>
<th>Workshop 1: G. James</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>Operations Manager Branch</td>
</tr>
<tr>
<td></td>
<td>Senior Product Designer</td>
</tr>
<tr>
<td></td>
<td>Commercial Technical Advisor</td>
</tr>
<tr>
<td></td>
<td>Engineer</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Code</th>
<th>Workshop 2: DHPW Government Team and Paynter Dixon</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>Acting District Manager (HPW)</td>
</tr>
<tr>
<td></td>
<td>Acting District Manager (HPW)</td>
</tr>
<tr>
<td></td>
<td>Senior Superintendent (HPW)</td>
</tr>
<tr>
<td></td>
<td>Acting Delivery Manager (HPW)</td>
</tr>
<tr>
<td>CC1</td>
<td>Manager North Queensland (Paynter Dixon - Construction Company)</td>
</tr>
<tr>
<td></td>
<td>Project Manager (Paynter Dixon - Construction Company)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Code</th>
<th>Workshop 3: Cyclone Testing Station (JCU) experts</th>
</tr>
</thead>
<tbody>
<tr>
<td>IA</td>
<td>Director</td>
</tr>
<tr>
<td></td>
<td>Senior research fellow</td>
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Table 4.2 Phone interviews participants

<table>
<thead>
<tr>
<th>Code</th>
<th>Building Certifiers</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC1</td>
<td>All Construction Approvals</td>
</tr>
<tr>
<td>BC2</td>
<td>GMA Certification Group</td>
</tr>
<tr>
<td>BC3</td>
<td>Taylor Civil &amp; Structural</td>
</tr>
<tr>
<td>BC4</td>
<td>National Building Certifiers</td>
</tr>
<tr>
<td>BC5</td>
<td>Townsville Certification Group</td>
</tr>
</tbody>
</table>
4.3 Thematic analysis

To facilitate the thematic analysis, the workshop with G. James Glass & Aluminium and with the Department of Housing and Public Works (DHPW) were recorded and later transcribed. The workshop with the CTS team was more informal than the other two workshops and responses were handwritten during the workshop and later revised providing the formal answers from this workshop, thus enriching the data collection results. During the phone interview, the responses from each participant were simultaneously transcribed into a spreadsheet next to each question. The responses were revised after the end of each phone interview thus enriching the answers provided. The responses also included comments from the participants.

Wind and rainwater ingress through openings were frequently mentioned during the investigation stage, confirming the existence of failure, which occurs during severe storms and tropical cyclones, acknowledged as a significant cause of claims and minor
to moderate repair in northern Queensland. Standards; inspection regime; installation quality regime; and liability and recourse were the themes that had emerged from the thematic analysis.

**Table 4.3, Table 4.4, Table 4.5 and Table 4.6** present the findings from of the thematic analysis. These tables include the barriers and preliminary recommendations mentioned by respondents. Respondent codes are provided in **Table 4.1** and **Table 4.2** in section 4.1.3. Insights from the interviewees are available in Appendix B.
### Table 4.3 Participant responses in the Standards category

<table>
<thead>
<tr>
<th>Respondent Group</th>
<th>Issue</th>
<th>Respondent code</th>
<th>Issue consequences</th>
<th>Issue mitigation recommendations</th>
<th>Recommendations made by</th>
<th>Respondent code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturers, Architects, Builders, Building Inspectors</td>
<td>Standards for water penetration serviceability requirements inadequate (AS 2047-214 and AS/NZS 4420.1:2016)</td>
<td>BC11; BC6; M1; IA; A2; I/B1; I/B3; I/B10; BC10; BC11; BC12</td>
<td>Water ingress through the windows/doors frames, seals and glazing</td>
<td>CTS from JCU is conducting tests to replication high dynamic range (HDR) pressure similar to a cyclonic pressure. They intend to propose HDR testing as a requirement in AS 2047-214 and AS/NZS 4420.1:2016</td>
<td>Manufacturers, Architects, Builders, Building Inspectors</td>
<td>IA</td>
</tr>
<tr>
<td>Builders, Installers and Building Inspectors</td>
<td>Lack of knowledge with Australian Standards for specification, installation and waterproofing of windows and external glazed doors</td>
<td>M1; M2; BC1; BC3; BC4; BC6; I/B3; I/B7; I/B10; G</td>
<td>Poor quality and low level of inspection of work related to the preparation of the window/door opening, its installation and waterproofing, which leads to instances of water ingress</td>
<td>Industry training to improve familiarisation with relevant windows and glazed doors installation and waterproofing standards</td>
<td>Builders, Installers and Building Inspectors</td>
<td>M1; G; BC1; BC7; BC9; I/B1; I/B2; I/B4; I/B5; I/B8; I/B10</td>
</tr>
</tbody>
</table>
Table 4.4 Participant responses in the Inspection regime category

<table>
<thead>
<tr>
<th>Respondent Group</th>
<th>Issue</th>
<th>Respondent code</th>
<th>Issue consequences</th>
<th>Issue mitigation recommendations</th>
<th>Recommendations made by</th>
<th>Respondent code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building Certifiers</td>
<td>Not actively inspecting windows/doors</td>
<td>M1;BC1;BC2;BC3;BC4;BC6;BC8;M1;I/B1;I/B3;I/B7;G</td>
<td>There are four mandatory stages requiring inspection, the third stage is the frame stage which considers before the cladding or lining is fixed or, for reinforced masonry construction, before the wall cavities are filled. There is no appropriate timing to inspect the preparation stage (waterproofing system) to finally, the opening installation.</td>
<td>Audit a certain percent of installed windows/doors by builders and inspectors</td>
<td>Building Certifiers</td>
<td></td>
</tr>
<tr>
<td>Superintendents /Inspectors from DPHW</td>
<td>Superintendents have less work oversight than previously when traditional construction documentation was more detailed. Builders are tendering and constructing works with lower levels of design documentation than previously due to the current procurement method chosen by HPW.</td>
<td>G;I/B4;CC1;BC3</td>
<td>Less control of the building process. Previously, detailed design documentation was provided to prospective builders at the tender stage, which provided DHPW with greater control over the level of building specification they wanted. This also enabled inspectors to better review building works completed and to identify any deficiencies.</td>
<td>Either greater degree of design documentation by HPW or requirement for builder to provide more detailed as-constructed information and certification on works quality</td>
<td>Building Certifiers</td>
<td>G;I/B4;CC1</td>
</tr>
<tr>
<td>Respondent Group</td>
<td>Issue</td>
<td>Respondent code</td>
<td>Issue consequences</td>
<td>Issue mitigation recommendations</td>
<td>Recommendations made by</td>
<td>Respondent code</td>
</tr>
<tr>
<td>--------------------------</td>
<td>------------------------------------------------------------------------------------------------------------</td>
<td>----------------</td>
<td>--------------------------------------------------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------------------------------------------------</td>
<td>------------------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>Builders and Manufacturers</td>
<td>Installation work quality documentation (i.e. Form 16 in Qld) often not completed or completed with limited information (i.e. statement saying that works according to AS)</td>
<td>M1;M2; BC1;BC3; BC6;BC8; BC9;BC11; I/B7;G</td>
<td>Lack of work quality documentation means installers place less emphasis on critical serviceability aspects and greater rates of water ingress during high wind events</td>
<td>Require builders to provide clients a detailed windows/doors installation quality form including details of fixing requirements, waterproofing process and materials, photos, etc.</td>
<td>Building Certifiers</td>
<td>M1;G; BC9</td>
</tr>
<tr>
<td>Building Certifiers (Superintendents from DPHW)</td>
<td>Superintendents have less work oversight than previously when traditional construction documentation was more detailed.</td>
<td>G;I/B4; CC1;BC3</td>
<td>Lower involvement and thus ownership of the construction process by DHPW staff and a lower level of ability and authority to request builders to rectify substandard works</td>
<td>Provide more detailed specification at the design stage and require builders to provide detailed as-constructed information on the work completed including photos</td>
<td>Building Certifiers</td>
<td>M1;I/B4; G</td>
</tr>
</tbody>
</table>
Table 4.6 Participant responses in the Liability and recourse category

<table>
<thead>
<tr>
<th>Respondent Group</th>
<th>Issue</th>
<th>Respondent code</th>
<th>Issue consequences</th>
<th>Issue mitigation recommendations</th>
<th>Recommendations made by</th>
<th>Respondent code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Architects, Manufacturers, Builders, Installers</td>
<td>Poor quality work with regards to installing windows and doors</td>
<td>G;BC1;BC6;BC7</td>
<td>Water ingress through windows/diors during severe wind-driven rain events in prone areas of Australia</td>
<td>1. Better specification in drawings in relation to waterproofing systems and include in the windows/diors drawings, provided by manufacturers, type of fixing and spacing 2. Promote more training to trades 3. Make builders more responsible for meeting serviceability expectations</td>
<td>Architects 2. Builders to trades</td>
<td>BC6</td>
</tr>
<tr>
<td>Architects, Manufacturers, Builders, Installers and Building Certifiers</td>
<td>Limited documentation of installation work quality (i.e. Form 16)</td>
<td>BC1;BC2;BC6;BC11;BC12;I/B1;I/B12;M1;G</td>
<td>No evidence available to indicate whether installer / builder is responsible for poor quality work during building operation stage</td>
<td>clients a detailed windows/diors installation quality form including details of fixing requirements, waterproofing process and materials, photos, etc.</td>
<td>Builders and Building Certifiers</td>
<td>M1;G</td>
</tr>
<tr>
<td>Building Certifiers</td>
<td>Limited inspection of windows and glazed doors</td>
<td>M1;BC3;BC11;BC12;I/B3;I/B7;I/B12;G</td>
<td>Limited inspection means that installers are less focused on providing a very high standard of work quality for building elements that are viewed as being less critical</td>
<td>Audit a certain percent of installed windows/diors by builders and inspectors</td>
<td>Building Certifiers</td>
<td>M1</td>
</tr>
<tr>
<td>Professionals</td>
<td>Issue Description</td>
<td>DHPW Maintenance Team</td>
<td>BC4; BC6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------------------------------------------</td>
<td>------------------------------------------------------------------------------------</td>
<td>------------------------</td>
<td>----------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Architects, Manufacturers, Builders, Installers and Building Certifiers</td>
<td>Repetitive incidences of wind-driven rain water ingress</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Water ingress through windows/doors every severe wind event in northern Australia causing maintenance requests for minor to moderate repairs (e.g. change of carpet, change of plasterboard, paint walls, etc.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>1. Investigate the cause effectively with quality information to identify causes and responsibilities</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2. Development of KPI to monitor building performance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Develop targets and plans to reduce incidences</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4. Raise awareness of issue through internal communication in HPW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Builders, Installers and Building Certifiers</td>
<td>Industry culture whereby installers and builders have a lower level of concern for the serviceability of buildings elements such as windows and glazed doors</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Limited inspection and documentation of window and glazed door installations; Less focus on meeting serviceability requirements by installers and builders; limited education on relevant serviceability standards</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Educate builders and installers of the importance of quality installation of windows and glazed doors in order to reduce life cycle maintenance costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>DHPW Maintenance Team, Building Inspectors, Architects, Builders, Manufactures</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.4 Discussion of issues and factors

The thematic analysis revealed similar responses coming from different respondents. Four core categories of barriers were identified, including: a) Adequacy of Australian Standards and its adequate knowledge and training; b) Inspection regime; c) Installation quality assurance and control regime; and d) Liability and recourse. Table 4.7 presents an overview of the concepts that have been used to understand what affects the performance of openings from a holistic view. The findings reveal many opportunities to improve the current practices based on the participants’ collaboration and are detailed in Chapter 6.

Table 4.7 Four key issues emerged from the thematic analysis

<table>
<thead>
<tr>
<th>Category</th>
<th>Issues and factors raised by industry and government</th>
</tr>
</thead>
</table>
| Adequacy of Australian standards and its adequate knowledge and training | • Even though there is a water penetration test under the Australian Standard, water enters buildings through undamaged windows and doors during severe storms and tropical cyclone events  
  • Failures of waterproofing around windows referred to in Australian Standards (AS, 2012) cause water ingress, moisture and building damage  
  • Poor knowledge and level of skills of many designers, installers and certifiers in waterproofing practices and openings installation |
| Installation quality assurance and control regime | • The installation work quality documentation is frequently not completed or completed with little details. Substandard detailed design specifications for waterproofing (e.g., brick sill, brick rebate, frame sill and seal locations)  
  • Contracts with restricted scope description or clear rules in relation to the contractor’s responsibilities during the construction process regarding quality control |
| Inspection regime                      | • There is no active inspection of window and door installation by building certifiers  
  • There are no guidelines to assist the auditing process  
  • Inspection certificate for aspects of building work – limited evidence of the installation and no related waterproofing statement required on the current Queensland Form 16  
  • A lack of control during installation and in the inspection process |
| Liability and recourse                  | • Self-regulation is bad  
  • Building certifiers rely on Queensland Form 16  
  • Poor accreditation of installation workmanship  
  • Builders should be more responsible for checking the quality of the building’s construction  
  • Builders and tradesmen ‘cutting corners’ |
4.4.1 Adequacy of Australian standards and its adequate knowledge and training
This category is divided into: (1) Adequacy of Australian Standards and (2) Adequate knowledge and training.


(2) Adequate knowledge and training, participants raised a concern of poor knowledge and level of skills of many designers, builders, installers and certifiers in waterproofing practices and openings installation practices as water penetration was repeatedly mentioned as a constant and consistent problem, ‘requiring further training in the related standards. Waterproofing around windows and doors is referenced in *AS 4654.1-2012 Waterproofing membranes for external above-ground use Part 1: Materials* (AS, 2012). Water ingress through openings is a common issue that causes the deterioration of building elements such as carpets and gyprock, loss of amenity, undue dampness or deterioration. Australian Standards related to wet areas should be reviewed and amended to reflect the best practice and trade training needs to determine which should include waterproofing as a mandatory module (Johnston and Reid, 2019).

4.4.2 Installation quality assurance and control regime
The installation quality assurance and control regime category focus on design details, contract and project scope and quality control. This category presented issues related to work quality documentation involving limitations in design specification to waterproofing and limitations in the contract scope specification in relation to contractor's responsibilities during the construction process regarding quality assurance and control. Design specification is an essential component of a smooth
building construction process and reduces or eliminates rework, thus reducing the whole life-cycle cost and time (Guo et al., 2009). The contractor's responsibility is to perform the construction work according to relevant technical, management, and construction specifications (Trangkanont et al., 2018). The success of a construction work process from time, cost and quality considerations, thus the contractors' role in the construction process is crucial (Trangkanont et al., 2018).

4.4.3 Inspection regime
The inspection regime category focused on the difficulties in inspecting windows. As the data collection only involved participants from Queensland, Form 16 (Appendix G) was mentioned as the document used to certify window and door installation. This document is an inspection certificate which attests that an aspect of building work complies with the approved plans and relevant standards and codes (Queensland, 2007). Participants from the data collection in general indicated that when this form is completed, it is often with insufficient details, mostly just being a sentence stating that the window has been installed in accordance with relevant standards. Given that there is little in-depth inspection of windows and poor-quality documentation provided by installers, when preventable water ingress occurs after high wind events, there is little chance that a building owner can link failure modes to liable parties.

4.4.4 Liability and recourse
The final liability and recourse category focused on the importance of responsibility assignment for issues related to water ingress through windows and doors.

The majority of the participants mentioned that the lack of good documentation and specification for openings combined with a lower level of concern by builders and inspectors to check the quality of these non-structural elements, meant that there was a lower level of concern to ensure a quality installation than for other building elements. Moreover, the hidden nature of opening preparation and waterproofing, as well as window/door installation works, meant that it could be easily overlooked. Finally, given that water ingress results in only minor to moderate damage and does not result in any catastrophic failure or loss of life, the poor installation of window and glazed door openings is often not fully understood until a few years after construction has been completed. At this time, it is very difficult to determine the causal factors leading to the
problem, as well as the responsible parties, and owners will typically just complete minor repairs after each storm event on an ongoing basis.

4. 5 Summary
This chapter provided in detail the data collection process, thematic analysis and lastly a discussion of raised issues and factors. The raised issues and factors indicated that the current glazing process is sometimes of insufficient quality, resulting in recurrent repairs and the overall lower quality of the construction. There is little opportunity for government representatives to inspect and assure work quality with the current standard of documentation and during the preparation and installation currently provided. Standards were acknowledged of “currently not sufficient” and missing liability, thus providing poor construction. Chapter 6 bring up the research outcomes form the qualitative interviews as well as recommendations provided by construction industry and government experts.
Chapter 5: Bayesian Network model

5.1 Introduction

The identification of the most appropriate management interventions that could lead to greater performance of window and door openings subject to wind-driven rain water ingress during tropical cyclones and severe storms involves the analysis of multiple variables under uncertainty. It is difficult to use traditional methods to identify what management interventions can lead to a higher performance from such uncertainty variables. The previous chapter was fundamental to compose the BN model as factors were identified. Therefore, this chapter presented the development of a novel BN model to evaluate the openings performance. The model provided and effective way of assessing the performance of windows and external glazed doors under tropical cyclones and severe storms. The BN scenarios were elaborated based on the sensitivity analysis which were able to optimize management strategies.

The objectives for this modelling were:

- Propose a holistic view of the current management elements and system and its relationships and a consideration of how its parts dynamically interact with each other.
- Provide a graphical representation in a user-friendly way to demonstrate the interactions of the system to industry experts and government in order to parameterise the model.
- Run scenarios to analyse to identify the best combination of management strategies to enhance the performance of openings to water ingress.

Bayesian networks have the advantage for the user to obtain the reasons behind the model output, since the interactions between variables are clearly displayed, providing transparency for the user and promoting system learning (Chen and Pollino, 2012).

5.2 Conceptual model and conversion into a BN structure

According to the methodology discussed in Chapter 3, the first step to build a BN model is to conceptualize the model. The literature review initially conducted to understand the windows and doors supply chain and the life cycle management and along with the knowledge acquired from the “Qualitative interview research” provided an understanding of the system and facilitated the conceptualisation of the model.
Those findings were introduced to three Academic experts in Bayesian Network and a brainstorming activity was conducted, **Figure 5.1**.

**Figure 5.1 Conceptual model - brainstorming activity**

The conceptual model, including variables and variables’ effects on the others, which formed the basis of the BN structure was used to identify the best management interventions that can lead to a greater performance of openings, **Figure 5.2**. The purpose of the conceptual model was to provide a visual summary of the system. Chen and Pollino (2012), considered valuable to build a conceptual model to better structure the problem and to determine the casual chain, as well as to facilitate inputs from experts.
Figure 5.2 Conceptual BN model of the factors influencing the performance of openings

The conceptual model is composed of 12 variables, of which, seven are parent nodes and five are child nodes; lines between these nodes indicate the relationships among the variables. In terms of variable states, two states per node, which are relatively small and therefore easier to populate, were defined, since expert knowledge was required due to a lack of numerical data.

The variables included different groups, such as standards, training, policies and management and liability.

Table 5.1 lists the variables affecting the openings performance, which were determined during the conceptual model development stage of the research.
Table 5.1 Model variables, states and their description used in constructing the conceptual model and subsequently BN structure

<table>
<thead>
<tr>
<th>Variable</th>
<th>Variable states</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Opening Standards</td>
<td>Adequate</td>
<td>Serviceability test requirement for windows and external glazed doors for characterising storms and cyclonic events based on AS 2047-2014</td>
</tr>
<tr>
<td></td>
<td>Inadequate</td>
<td></td>
</tr>
<tr>
<td>2. Standards knowledge training</td>
<td>Adequate</td>
<td>Level of skills and knowledge in several professionals’ scales in design, installation and waterproofing practices</td>
</tr>
<tr>
<td></td>
<td>Inadequate</td>
<td></td>
</tr>
<tr>
<td>3. Inspection certificate document</td>
<td>Adequate</td>
<td>Level of information provided on Form 16 (Qld document)</td>
</tr>
<tr>
<td></td>
<td>Inadequate</td>
<td></td>
</tr>
<tr>
<td>4. Construction documentation</td>
<td>Adequate</td>
<td>Level of design specification</td>
</tr>
<tr>
<td></td>
<td>Inadequate</td>
<td></td>
</tr>
<tr>
<td>5. Contract documentation</td>
<td>Adequate</td>
<td>Level of scope detail on the Contract documentation</td>
</tr>
<tr>
<td></td>
<td>Inadequate</td>
<td></td>
</tr>
<tr>
<td>6. Inspection effectiveness</td>
<td>Effective</td>
<td>Level of inspection provided for windows and external glazed doors and its waterproofing</td>
</tr>
<tr>
<td></td>
<td>Ineffective</td>
<td></td>
</tr>
<tr>
<td>7. Contractor’s performance review</td>
<td>Monitored</td>
<td>Level of Contractors performance</td>
</tr>
<tr>
<td></td>
<td>Not monitored</td>
<td></td>
</tr>
<tr>
<td>8. Product’s performance</td>
<td>High</td>
<td>Level of product performance based on Openings Standards and Standards knowledge &amp; training</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>9. Monitoring &amp; inspection practice</td>
<td>Effective</td>
<td>Level of Monitoring &amp; inspection practice based on Inspection effectiveness and Contractor’s performance review</td>
</tr>
<tr>
<td></td>
<td>Ineffective</td>
<td></td>
</tr>
<tr>
<td>10. Liability evidence</td>
<td>Satisfactory</td>
<td>Level of liability evidence based on Construction documentation, Contract documentation and Monitoring &amp; inspection effectiveness</td>
</tr>
<tr>
<td></td>
<td>Unsatisfactory</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inadequate</td>
<td></td>
</tr>
<tr>
<td>12. Performance</td>
<td>Acceptable</td>
<td>Performance of windows and external doors based on the strength between Product’s performance and its variables, Quality Assurance and Control and its variables and Liability evidence and its variables</td>
</tr>
<tr>
<td></td>
<td>Need improvement</td>
<td></td>
</tr>
</tbody>
</table>
5.3 Parameter learning – current condition

Once the BN model structure was validated, the next step was the parameterisation of the CPTs and MDPs. The approach to obtain CPTs and MDPs was from elicited domain experts. Experts were asked to provide the most likely values for the variables under consideration. A workshop, phone interviews and a face-to-face meeting were organised to estimate probabilities. A BN booklet (Appendix C) containing the research briefing, variable descriptions, CPTs and MDPs' instructions was prepared and distributed to the experts in a systematic way so that in the different types of data collection, the elicitation process would be performed in a rigorous and consistent manner.

To populate the CPTs and MDPs, a total of ten experts from industry and governments in different fields attended the workshop in Brisbane (Figure 5.3). Four government and one industry expert participated in the phone interviews and one face-to-face meeting was conducted, thus reaching a total of 16 participants.

Participants at the workshop included representatives from Brisbane, from the Department of Housing and Public Works (DHPW) specifically from the Building Policy & Asset Services (BAS) and from the Building Legislation and Policy; as well as one representative of the Queensland Building and Construction Commission (QBCC); as well two representatives from one of Australia’s leading suppliers of aluminium windows and doors, as well as one representative of the Sector Leader Government from a construction company and a representative from the Australian Institute of Waterproofing (AIW). From Townsville, a representative from the Building Policy & Asset Services (BAS - DHPW) and from Sydney a representative from the Australian Window Association (AWA). The great diversity of roles provided a great discussion, with roles varying from Training and Quality Managers, Engineers, Technical Manager, Architects, Design Manager, Manager of Technical Standards, Superintendents and Construction Managers.

The workshop started with a half-hour of presentation covering the research background and findings. This presentation was then followed by half-hour of interactive discussion. The last one and a half-hour was dedicated to explaining with examples how the quantification of CPTs and MDPs should be headed following the quantification by participants.
The approach used during the phone interviews and the face-to-face meeting was similar to the structure of the workshop. The phone interviews counted with four representatives from the Building Policy & Asset Services (BAS – DHPW) from Townsville. Their roles range from senior manager to superintendent. A Construction manager from the Gold Coast was also interviewed. The BN booklet was sent via email prior to the interview. The interviews followed the same previous systematic. The two hours face to face meeting was held in Brisbane at the Construction company’s office with a Construction Manager.

The diversity of the roles of participants as well as industry experience (between 15 and 45 years), ensured reliable results. The elicitation process took approximately two months to be completed. The results from the data collection were than compiled in a spreadsheet and transferred to Netica.

The BN model after parameter learning is displayed in Figure 5. 4.
The displayed prior probabilities for each node reflect the expert input provided by the participants, provided the prior probability of the target node, Performance (state “Acceptable” 32.2% and state “Needs Improvement” 67.8%), adopted as the current condition according to current practices.
Figure 5.4 The Bayesian Network model after parameter learning – current condition
5.4 Sensitivity analysis

Later, a sensitivity analysis was carried out to identify the variables that are most influential on an acceptable performance. As displayed in Table 5.2, it can be seen that ‘product performance’ (0.16219), which means how well the product performs, exerts the greatest influence on the model when considering improving the performance, followed by ‘quality assurance and control’ (0.03612), and ‘opening standards’ (0.02021), meaning how applicable the serviceability test requirement for windows and external glazed doors is for characterising storms and cyclonic events.

Table 5.2 Sensitivity of ‘Performance’ to influencing variables

<table>
<thead>
<tr>
<th>No.</th>
<th>Variables</th>
<th>Mutual information Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Product performance</td>
<td>0.16219</td>
</tr>
<tr>
<td>2</td>
<td>Quality Assurance and Control</td>
<td>0.03612</td>
</tr>
<tr>
<td>3</td>
<td>Opening standards</td>
<td>0.02021</td>
</tr>
<tr>
<td>4</td>
<td>Standards knowledge and training</td>
<td>0.01299</td>
</tr>
<tr>
<td>5</td>
<td>Liability evidence</td>
<td>0.01117</td>
</tr>
<tr>
<td>6</td>
<td>Monitoring and inspection</td>
<td>0.00672</td>
</tr>
<tr>
<td>7</td>
<td>Contractor’s performance</td>
<td>0.00440</td>
</tr>
<tr>
<td>8</td>
<td>Construction documentation</td>
<td>0.00185</td>
</tr>
<tr>
<td>9</td>
<td>Inspection effectiveness</td>
<td>0.00115</td>
</tr>
<tr>
<td>10</td>
<td>Inspection certificate document</td>
<td>0.00094</td>
</tr>
<tr>
<td>11</td>
<td>Contract documentation</td>
<td>0.00088</td>
</tr>
</tbody>
</table>

5.5 Scenario analysis

Followed the sensitivity analysis, eleven scenarios were carried, by specifying the state for the input node, to predict the impact on the target node (and other nodes) (posterior probabilities). Initially, the seven parent nodes were tested individually, creating seven scenarios (1 to 7; Table 5.3) to predict the impact on the target node (performance), generating seven final acceptable performance scenarios. Based on the top three results from scenarios 1 to 7, four other scenarios (8 to 11) were tested (Table 5.3).

Table 5.3 Scenarios (1 to 11) with state and variable descriptions

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>State</th>
<th>Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100% Adequate</td>
<td>Opening standards</td>
</tr>
<tr>
<td>2</td>
<td>100% Adequate</td>
<td>Standards knowledge and training</td>
</tr>
<tr>
<td>3</td>
<td>100% Adequate</td>
<td>Construction documentation</td>
</tr>
</tbody>
</table>
In Netica, the BN model was set to 100% for one of the two states (see Table 5.1 for the variables states), according to each scenario proposed in Table 5.3. Figure 5.5 provides an example of implementing a heightened ‘Openings standards’ in Australia; this change signifies modifying the current serviceability test requirement with Australian Standards for windows and external glazed doors so that it better characterises the dynamic pressure fluctuations that realistically occur with storms and cyclonic events (i.e. change to 100% Adequate since all new products must conform to heightened serviceability standard). A change in this critical input node changes the openings performance level from an ‘Acceptable’ level of 32.2% (i.e. initial or business as usual acceptable performance) to 52% (i.e. an increase in performance of 19.8%).
Figure 5.5 Openings performance level prediction when the ‘openings standard’ node is changed to “100% Adequate” (i.e. Scenario 1)
For scenarios 2 to 11, the same exercise described above was conducted in order to verify the new probability on the target node Performance. Figure 5.6 outlines the results for the first 7 scenarios (Table 5.3).

The BN node that derived the second greater change in the rate of performance was ‘standards knowledge and training’, with an improvement in Performance of 8.9% (i.e. the initial acceptable performance changed from 32.2% to 41.1% if the skills and qualifications issues could be significantly improved). The third greater change in openings Performance resulted from the BN node ‘construction documentation’ being significantly enhanced. The study identified that low-quality design specifications were contributing to higher rates of water ingress through openings.

Figure 5.6 Final probability of “acceptable” performance for scenarios 1 to 7 (only individual BN nodes being changed) compared to initial prior probability for Acceptable Performance

The top three performance improvement strategies shown in Figure 5.6 were then used to create four portfolio strategies (i.e. Scenarios 8 to 11). The results of those
scenarios are shown in Figure 5.7

Figure 5.7 Probability of “Acceptable” Performance for scenarios 8 to 11 (i.e. concurrent change to 2 or more BN nodes)

The scenario 8 portfolio strategy concurrently enhanced the ‘opening standards’, ‘standards knowledge and training’ and ‘construction documentation’ BN nodes and led to an increase in the openings performance level from the initial 32.2% to 66.6% (i.e. 34.4% improvement). Scenario 9 was the second-best portfolio strategy; concurrent changes to the BN nodes ‘opening standards’ and ‘standards knowledge and training’ improved the openings performance node to 61.7% acceptable.

The overall ranking of the 11 examined individual and portfolio strategy scenarios is presented in Table 5.4.

Table 5.4 Scenarios ranking

<table>
<thead>
<tr>
<th>Ranking</th>
<th>Scenarios</th>
<th>Final acceptable performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8  Opening standards + standards knowledge and training + construction documentation</td>
<td>66.6%</td>
</tr>
<tr>
<td>2</td>
<td>9  Opening standards + standards knowledge and training</td>
<td>61.7%</td>
</tr>
<tr>
<td>3</td>
<td>10 Opening standards + construction documentation</td>
<td>56.3%</td>
</tr>
<tr>
<td>4</td>
<td>1  Opening standards</td>
<td>52.0%</td>
</tr>
<tr>
<td>5</td>
<td>11 Standards knowledge and training + construction documentation</td>
<td>44.7%</td>
</tr>
<tr>
<td>6</td>
<td>2  Standards knowledge and training</td>
<td>41.1%</td>
</tr>
<tr>
<td>7</td>
<td>3  Construction documentation</td>
<td>35.2%</td>
</tr>
<tr>
<td>8</td>
<td>4  Inspection effectiveness</td>
<td>35.0%</td>
</tr>
<tr>
<td>9</td>
<td>5  Inspection certificate document</td>
<td>34.5%</td>
</tr>
</tbody>
</table>
5.6 Summary

This chapter presented the development of a BN model to identify the most appropriate management interventions that could lead to a greater performance of window and door openings subject to wind-driven rain water ingress during tropical cyclones and severe storms. A conceptual model was proposed and validated turning it into a BN structure. Next the parametrization by eliciting experts was conducted, providing a rating for the current acceptable performance. A sensitivity analysis was carried out bringing up the most influential variables on the target node. From that, scenarios were carried out to predict the impacts on the target node. The next Chapter 6 reveals the outcomes from this stage of the study.
Chapter 6: Discussion of findings

6.1 Introduction

The research method employed in this study (Chapter 3), specified the use of a qualitative method followed by a quantitative method. Chapter 4 presented the qualitative method based on qualitative interviews with the aim to identify the factors affecting the performance of windows and external glazed doors, having the construction industry and governments experts as participants. Section 6.2 in this chapter presents the findings from the qualitative interview stage and Section 6.3 introduces a quality assurance process for both government and private industry projects participants who revealed many opportunities to improve the current practices.

Chapter 5 used a BN model to identify the most appropriate management interventions that could lead to a greater performance of window and door openings subject to wind-driven rain water ingress during tropical cyclones and severe storms. The model was based on the findings provided from the qualitative interviews (Section 6.2). Section 6.5 in this chapter, introduces the research results from this stage.

6.2 Qualitative interview outcomes

Wind and rainwater ingress through openings, during severe storms and tropical cyclones, were frequently mentioned during the investigation stage confirming the existence of the failure, acknowledged as a significant cause of claims and repairs in northern Queensland. Four salient themes emerged from the analysis of the respondents' transcripts, namely: (1) Adequacy of Australian standards and its adequate knowledge and training; (2) Installation quality assurance and control regime; (3) Inspection regime; and (4) Liability and recourse, described in Chapter 4, section 4.4 and subsections. The findings from each theme is described below:

6.2.1 Adequacy of Australian Standards and its adequate knowledge and training

Thematic analysis revealed that wind-driven rain in every cyclone or storm event can cause windows and external glazed doors to leak. This fact raised two issues related to the Australian Standards: (1) Some interviewees suggested that improvements to the Australian Standards related to windows and external glazed doors is required as they are currently not adequate; and (2) some interviewees were also concerned about the lack of knowledge and skills from many designers, builders, installers and certifiers
in waterproofing practices and openings installation practices. These two issues are further analysed below

(1) Adequacy of Australian Standards – The standards related to water penetration are the AS 2047 – 2014 Windows and external glazed doors in buildings (AS, 2014) and AS/NZS 4420.1:2016 Windows and external glazed, timber and composite doors - Method of test, Part 1: Test sequence, sampling and test methods and AS/NZS 4284:2008 Testing of building facades (AS/NZS, 2016, AS/NZS, 2008) as mentioned in Chapter 4, section 4.4.1. This standard aim to provide designers and manufacturers with a specified minimum requirement for windows, establishing performance requirements and specifications for the design and manufacture of openings (Smith, 2012). Even though the interviewees were aware of the existence of the standards, it was clear that there seem to be shortfalls. This problem was recognized as a substantial cause of maintenance in northern Queensland. This repetitive process of failure of these building elements and the resulting minor to moderate repair requirements afterwards is relatively commonplace in the coastal areas of northern Australia where high wind events are quite prevalent.

During the workshop with CTS (JCU) a visit to the test rigs was given where it was seen a Wind Driven Rain Simulator (WDRS) that was constructed to explore the performance of windows and doors during oscillating wind loads and rain as well as to test mitigation measures to reduce water ingress. The water penetration resistance test does not provide adequate pressure to prevent water ingress during cyclonic events (CTS, 2018, Suncorp, 2018). Some participants suggested that improvements to Australian Standards are required to reduce water ingress during extreme wind driven rain since “they are currently not sufficient”. After the workshop, a report from the CTS was edited revealing the WDRS along with mitigation measures suggested (CTS, 2018).

(2) Adequate knowledge and training - In terms of worker skills, the interviewees voiced a concern of poor knowledge and level of skills of many designers, builders, installers and certifiers in waterproofing practices and openings installation practices as water penetration was repeatedly mentioned as a constant and consistent problem, ‘requiring further training in the related standards’. Waterproofing around windows and doors is referenced in AS 4654.1-2012 Waterproofing membranes for external above-
ground use Part 1: Materials (AS, 2012). Water ingress through openings is a common issue that causes the deterioration of building elements such as carpets and gyprock, loss of amenity, undue dampness or deterioration. A recent paper supports this finding, indicating that relevant trade training should include waterproofing as a mandatory module (Johnston and Reid, 2019). Tyrell (2016) has argued that there are adequate sources of information about waterproofing in the Standards and other publications, but this information is not being widely read and implemented by the industry. He has also advocated that little is taught about waterproofing principles in university or trade courses. A challenge to be overcome is finding the best method of communication. Australia enjoys many information sources through an initiative of the Australian Window Association (AWA), which provides free online training by supplying videos and guidelines (https://www.awa.org.au/resources); however, as mentioned by some of the interviewees, this resource is often not accessed by those that need it the most. The National Construction Code (NCC) is available online for free (https://ncc.abcb.gov.au/), and it references the Australian Standards, which are not available for free.

6.2.2 Installation quality assurance and control regime category
The installation quality assurance and control regime category is focused on the quality assurance process during the detailed design, project scope and contract phases, to ensure that work has been completed according to expectations.

From the interviewee’s perspectives, design specifications are lacking. Responses included: “design details for waterproofing are absent; builders and tradesman should know what is required” or “general knowledge of the construction industry leads to knowledge of correct waterproofing” or “the design should clearly specify roof/window/door/flashing/waterproofing/gutter/fixings instead of just referring to clauses in Australian Standards”. Design specification is an essential component of a smooth building construction process and reduces or eliminates rework, thus reducing the whole life-cycle cost and time (Guo et al., 2009). Smith (2012) declared that in 75% of cases, a window leak problem is related to installation and has suggested a good attention to design details during the installation, to ensure no issues with water ingress. Likewise, issues related to contracts with limited project scope and lacking clear rules in relation to the contractors’ responsibilities of the quality control process during the construction process emerged during data collection. The Government
representatives at the workshop indicated that the terms in the contracts related to
design liability and the quality required are an issue that contributes to less specified
designs and creates less control from government over contractors. Contractors on
the other hand said that there were no clear rules for design specifications and quality
control in construction contracts. Quality control, therefore, should be clearly
addressed in the scope of the contract as it is an important clause. Determining
responsibilities through clear legal contract terms and conditions could ensure that all
stakeholders undertake their duties carefully.

6.2.3 Inspection regime category
The inspection regime category focused on the challenges with windows inspections.
As the data collection only involved participants from Queensland, Form 16 (see
Chapter 4, section 4.4.3) was highly cited as the document used to certify window and
door installation issued by installers at the completion of a performed work on new
buildings. Participants indicated that when this form is completed, it is often with
insufficient details, mostly just being a sentence stating that the window has been
installed in accordance with relevant standards. Some interviewees mentioned that
‘no inspection is provided, relying on Form 16’ or ‘forms are issued saying that things
are okay when they have not inspected themselves basically because it is not their
role to check windows and doors’. As the inspector are covered by the Building Act
1975 which explicit says the inspection can be relied on tests, specifications, rules,
standards, codes of practice or other publications (Building Act, 2018). On the other
hand, from the building certifiers’ perspective, ‘it is not feasible to inspect all openings
since there are others involved in the construction process as well’. Inspecting
windows and glazed door installations is not viewed as a critically important milestone
for residential building construction (i.e. like frame stage) so it is often not carefully
inspected. Moreover, since there is a very limited time available to inspect windows
and associated waterproofing efforts, they are not often checked independently. Some
participants mentioned a few simple information requirements could be added to Form
16 thus builders would feel more responsible for the quality of their work.

To further support the issues mentioned, complementary information was found from
the Queensland government and authorities referring to the inspection regime as an
issue to be examined. A discussion paper produced by the Queensland Government
engaged stakeholders’ feedback which reported that the government needs to
improve building certifiers’ professional development, work practices and available resources (QLD Government, 2011). The Queensland Building and Construction Commission (QBCC) provided a compliance and enforcement strategy for 2018/19 with 10 priorities, one of which was prioritising the improvement of the quality of building work performed by QBCC licensees, which include building certifiers, although openings were not objectively mentioned in any of them (QBCC, 2018).

6.2.4 Liability and recourse category
The final liability and recourse category focused on the responsibility assignment for water penetration-related issues through windows and doors. Many of the interviewees suggested human error plays a significant role in building defects. Misuse of building products (due to lack of knowledge), poor workmanship, time pressure (cutting corners), poor supervision from builder and building certifiers, lack of training, lack of licensing and trade accountability were common factors identified as contributing to defective building work.

The current focus on productivity, not on quality during the waterproofing and further opening installation process was identified as a core issue, as well as on the inspection stage being largely focused on the provision of the certificate. The lower level of design details and specification including waterproofing combined with a culture in which installers, builders and building certifiers with less concern for windows and external glazed doors installation, mean that there is a lower level of concern on these non-structural elements. Finally, given that water ingress typically leads to only minor to moderate damage, the effects of poor installation of openings are often not fully quantified. Following construction, it becomes difficult to determine the causal factors leading to a certain minor problem, and in turn the responsible parties; as a result, owners typically complete minor repairs after each severe storm on an ongoing basis.

6.3 Quality assurance process
In multiple government and industry projects, the implementation of a quality assurance method proves to be an invaluable technique when developing ways to achieve an optimal result in a service or product. A number of recommendations were suggested by interviewees during data compilation, primarily related to improving the quality assurance process to prevent wind driven rainwater ingress through windows and external glazed doors. These opportunities include upgrades in practices related
to documentation, inspection liability assignment and installation training for building windows and doors, especially in locations where severe winds are frequent (i.e., northern Australia). The quality assurance process was designed for the use of governments and industry projects as it proposes common basis management practices. This section includes the authors industry research report and co-authors and co-authored industry report as follows:


The quality assurance process includes seven specific recommendations and are described below:

- Recommendation 1: Construction documentation – drawings and specifications
- Recommendation 2: Contract
- Recommendation 3: Preparation and installation procedure
- Recommendation 4: Auditing check list (AC)
- Recommendation 5: Installation quality form (IQF)
- Recommendation 6: Openings certificate (OC)
- Recommendation 7: Auditing check grade (AC grade)

**Figure 6.1** provides a schematic quality assurance process to be implemented throughout the design and construction of a project, including the seven core recommendations.
6.3.1 Recommendation 1: Construction documentation
6.3.1.1 Drawings and specification requirements

The Department of Housing and Public Works (DHPW) procures Social housing through two main procurement models. The differing nature of each method has an effect on the outcome for the performance of the completed wall openings; they are described below:

(a) Completion of detailed design and documentation before negotiating a contract for “Construction only”

For “Construction only”, DHPW directly controls the design and documentation to ensure that complete and thorough documents are used for the construction tender.
The construction documentation (drawings and specification) is completed by private Consultants and included within the tender documents for the construction tender. Once a tender offer from a builder is accepted, the Construction documentation (drawings and specification) then become part of the Contract that the builder agrees to (Figure 6.2).

![Construction documentation](image1)

**Figure 6.2** Procurement contract for “Construction only”

(b) Completion of a feasibility study and/or preliminary design before negotiating a contract for “Design and Construction”

For the “Design and Construction” process, DHPW enters a contract earlier but has less control of the design and documentation than in “Construction only”. Tender documents (including the Contract) are prepared by DHPW and then a tender is called for a developer to design, document and build the project according to criteria defined in the Contract. It is a different contract to the one used in “Construction Only”. Sometimes this Contract includes a preliminary design and/or specification that must be complied with, sometimes it doesn’t. The “Design and Construction” contract does not define the level of detail required in the Construction Documentation (drawings and specifications) to be prepared by the developer (Figure 6.3).

![Contract documentation](image2)

**Figure 6.3** Procurement contract for “Design and Construction”

The recommended quality assurance process (Figure 6.1) for use by DHPW, has to adapt the order of items 1 and 2 according to the “Construction only” and “Design and Construction” process explained in Figure 6.2 and Figure 6.3. For “Design and Construction”, Contract documentation is before Construct documentation.
(drawings and specifications) but for “Construction only”, the process in Figure 6.1 is the same.

Research on the current design specifications/details for Social Housing projects indicated that the move towards “Design and Construct” procurement for public housing in government departments, has resulted in poorer quality design and as-constructed information being produced by contractors. The workshop with DHPW identified this issue and the need for improved documentation. It was concluded that there is a need to provide more detailed requirements within the tender documents that indicate the level of detail required from the contractor when providing their construction design documentation.

This recommendation suggests that for “Design and Construction” arrangements, either:

- That process be limited to projects where detailed documentation is not required, or
- The building contractor be required to provide fully detailed construction documentation and specifications for the documentation stage and for as-constructed records on handover of the project.

For “Construction Only” projects, the recommendation is that:

- DHPW should ensure that fully detailed construction documentation and specifications are provided in the documentation stage and,
- The builder is required to provide as-constructed records on handover of the project. This documentation should include detailed design documentation and specifications to describe the installation of windows and external glazed doors.

6.3.1.2 Design details for wall openings
Generally, it was identified that simply providing a greater quality check and approval system incorporating design details for each wall opening can reduce the overall ongoing cost of the building. For windows and external glazed doors, a typical waterproofing system detail should include specifications for the substrate, sub-sill, waterproofing membrane system, head, side angles and watertight seal.
Related to buildings in Wind Regions C and D of Australia, there is a need for better construction documents for windows and glazed door openings. The following recommendations and specifications should be considered for the design phase. A complete description of the following recommendations and specifications is provided in Appendix D.

1. Durability and compatible sealants;
2. Preparing the substrate;
3. Preparing the opening with appropriate membrane system;
4. Curing;
5. Head, side angle flashing, sub-sill and dam ends;
6. Flashings, drip moulds, storm moulds and trims;
7. Fasteners; and
8. Consideration for storm shutters.

6.3.2 Recommendation 2: Contract documentation
The tendering process should include the recommended quality assurance process within the Contract for all forms of procurement. The Contract requires agreement between both the client and contractor. The contract should describe a quality assurance process relating to the preparation and installation of windows and external glazed doors in an effort to increase quality and direct liability in the construction phase. Examples to be implemented are provided below:

➢ Recommendation 3: Preparation and installation procedure
➢ Recommendation 4: Windows and external glazed doors installation quality form (IQF)
➢ Recommendation 5: Auditing check list (RAC)
➢ Recommendation 6: Openings certificate (OC)
➢ Recommendation 7: Auditing check grade (AC grade)

6.3.3 Recommendation 3: Preparation and installation procedure
Research has indicated that the correct wall opening preparation and installation can reduce the probability of failure; thus, reducing the life-cycle maintenance requirements.

The preparation and installation procedure of windows and external glazed doors to masonry openings is detailed in two stages; Stage 1 being the openings preparation
and Stage 2 being the openings installation. On completion of Stage 1 an acceptance inspection is required by the developer and superintendent. It is recommended that these procedures are included in the contract documentation. The complete description of Stage 1 and Stage 2 are provided in Appendix E.

In reference to Figure 6.1, the following tools and certifications are proposed to ensure the correct installation of windows and external glazed doors; and to ensure the quality of the construction.

- Recommendation 4: Auditing check list (AC)
- Recommendation 5: Installation quality form (IQF)
- Recommendation 6: Openings certificate (OC)
- Recommendation 7: Auditing check grade (AC grade)

6.3.4 Recommendation 4: Auditing check list (AC)

The Auditing checklist (AC) provided in Appendix F is designed to be completed during the inspection of windows or external glazed doors by superintendents. The objective of the AC is to check if the external openings have been installed adequately. Following this inspection, a grade will be given as Satisfactory or Unsatisfactory. The score obtained on the check list will provide evidence of work provided by the primary contractor.

The second objective of the AC is to place a degree of responsibility and liability on contractors and superintendents by emphasising the importance of windows and external glazed doors to the building envelope. The AC is to be completed by the superintendent, accompanied by the supervisor responsible for the activity.

The AC is to be completed in two stages of the construction phase; upon completion of the opening membrane and flashing system and on completion of the glazing installation. The superintendent must give reasonable notice (2 weeks) in advance to the primary contractor before performing the AC. A notice for an AC must be given in a format agreed between the builder and the building certifier. A building certifier may also inspect building work at any time, whether or not the certifier is given a notice for AC for the work. At this stage, the primary contractor should inform the superintendent when Stage 2 will commence to allow for the conclusion of the AC.

The number of windows and external glazed doors to be checked on site will be a minimum of 25%. These are to be identified by a unique identification tag or sticker to
prevent double checks on the same openings. An Installation quality form (IQF) (Section 6.3.5) completed by the primary contractor will display a unique sicker to ensure the appropriate number of inspections occur. Multiple level construction requires the auditing to be carried out evenly over all levels of the building. The frequency will vary according to the site schedule. Each opening will have its own independent check list. Before attending to the site, the Superintendent should plan the auditing visit verifying the numbers of openings that require the AC.

6.3.5 Recommendation 5: Installation quality form (IQF)

The primary contractor’s responsibility is to complete the Installation quality form (IQF) in conjunction with relevant installation documentation (e.g. in Queensland – Form 16, Appendix G) and provide this to the superintendent. The IQF must include photographic documentation of each completed stage of the installation as provided in Appendix H. The objective is to provide visual evidence to the superintendent that the openings were satisfactorily installed by the primary contractor according to the preparation and installation procedure.

The number of windows and external glazed doors to be documented is a minimum of 25%. This will ensure sufficient variations of openings are documented. An indicator (tag or sticker) must be allocated once the opening has been documented. The IQF must be held by the primary contractor, then signed and approved together with the superintendent. The objective is to ensure that both parties are taking responsibility for the installation.

The first objective of the IQF is to check if the external openings were installed satisfactorily. The second objective of the IQF is to raise liability and responsibility for contractors/builders in placing sufficient attention to windows and external glazed doors as a building element that is significantly important to the building envelope.

6.3.6 Recommendation 6: Openings certificate (OC)

Once the AC and IQF have been completed, the superintendent is able to provide the Openings Certificate (OC) to the contractor. The AC and IQF together will have documented 50% of the openings of the project.

The aim of the OC is similar to that of the AC and the IQF in that it documents responsibility for the information provided from both the contractor and superintendent.
For both government and private industry projects, the AC and IQF are recommended for inclusion to the requirements for all building projects located in Wind Regions C and D. Moreover, the approach could be considered for all building projects where vulnerability to wind-driven rain has been identified (e.g. coastal high-rise building windows and glazed doors).

For example, in Form 16 in Queensland (Appendix G), the AC, IQF and OC should be added in item “4 Description of component/s certified”. The first part of Form 16, “1 Indicate the type of certificate”, refers to “Aspects of building work”, Windows and external glazed doors satisfactorily installed.

6.3.7 Recommendation 7: Auditing checklist grade
The AC will be used as well to provide a grade to the work provided by the primary contractor for windows and external glazed doors. During the AC, all openings inspected must have 100% of the check list as “Yes” to provide a “Satisfactory” result as provided in Figure 6.4.

The grade highlights the importance of providing a satisfactory installation to mitigate the potential for water ingress. It is recommended to implement the AC and the IQF for different activities during the construction process and the results can be used as quality indicators of the as built construction and used in subsequent tendering. Where tenderers have a poor record of providing quality construction, they will receive poor experience ratings for subsequent government tenders.

This grade is provided for each of the primary contractors and should be reviewed on acceptance of the tendering process. This information can be used to provide an indication of the overall quality of future work. The procurement section of DHPW should consider implementing this work quality score process, so it can assess the scores when analysing future tender bids.
6.5 Bayesian Network model

The qualitative results provided the basis for the conceptual model forming the basis of the BN structure used to quantify the performance of openings. The conceptual model included the relationships among the variables including different groups, such as standards, training, policies and management and liability (Chapter 5, section 5.2).

6.5.1 Parameter learning - current condition

The BN model parametrization, to estimate probabilities, with domain experts during a workshop, phone interviews and a face-to-face meeting provided the likelihood of 32.2% “Acceptable Performance” for the current, business as usual conditions (or initial Acceptable Performance). Since there was not found in the literature such a measure, the likelihood was endorsed as the current acceptable performance for windows and external glazed doors that are subject to wind-driven rain arriving from tropical cyclones and severe storms in the north of Queensland (Chapter 5, section 5.3).
6.5.2 Sensitivity analysis
Following the model parametrization, a sensitivity analysis was conducted. The lack of existence of previous similar studies in provided no comparison for the sensitivity analysis. The top three variables more sensitive to changes in an acceptable performance were: Product performance firstly which relates to the level of product performance based on Opening Standards and Standards knowledge & training, secondly came Quality Assurance and Control which relates to the level of quality regime based on Inspection certificate document, Construction documentation, Contract documentation and Monitoring & inspection practice; and thirdly came Opening Standards which relates to the serviceability test requirement for windows and external glazed doors for characterising storms and cyclonic events based on AS 2047-2014. The less nodes sensitive to changes were Standards knowledge and training, Liability evidence, Monitoring and inspection, Contractor’s performance, Construction documentation, Inspection effectiveness, Inspection certificate document and Contract documentation respectively (Chapter 5, section 5.4).

6.5.3 Scenario analysis
As the rapid propagation of information through the network is a great advantage of BN, various scenarios were applied with the aim to identify which variables, or management aspects could effectively raise the initial Acceptable Performance of 32.2% (Chapter 5, section 5.5). Tackling the combination of the three variables: “Opening standards” and “Standards knowledge & training” and “Construction documentation”, increased the Acceptable Performance in 34.4%, jumping from the initial 32.2% to 66.6%, providing the best result in all scenarios. Opening Standards was the highest individual variable with 52%. Figure 6.1 presents the results of each scenario (Chapter 5, section 5.5). The best result is enhanced when a combination of management strategies is implemented.
### Table 6.1 Scenario analysis

<table>
<thead>
<tr>
<th>Scenario Analysis</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opening standards + standards knowledge and training + construction documentation</td>
<td>66.60%</td>
</tr>
<tr>
<td>Opening standards + standards knowledge and training</td>
<td>61.70%</td>
</tr>
<tr>
<td>Opening standards + construction documentation</td>
<td>53.30%</td>
</tr>
<tr>
<td>Opening standards</td>
<td>52.00%</td>
</tr>
<tr>
<td>Standards knowledge and training + construction documentation</td>
<td>44.70%</td>
</tr>
<tr>
<td>Standards knowledge and training</td>
<td>41.10%</td>
</tr>
<tr>
<td>Construction documentation</td>
<td>35.20%</td>
</tr>
<tr>
<td>Inspection effectiveness</td>
<td>35.00%</td>
</tr>
<tr>
<td>Inspection certificate document</td>
<td>34.50%</td>
</tr>
<tr>
<td>Contract documentation</td>
<td>34.20%</td>
</tr>
<tr>
<td>Contractor’s performance review</td>
<td>32.20%</td>
</tr>
</tbody>
</table>
6.6 Summary

The first research stage encompassed a qualitative research. A participatory modelling was chosen and included workshops and phone interviews. The target respondents included the construction Industry and construction Government sector, and its associated professionals with knowledge and work experience of windows and external glazed doors in tropical cyclone-prone regions of Queensland. The data collection ran from November 2017 to March 2018, reaching a total of 39 participants. In order to comprehensively interpret the solicited data, thematic analysis (Trangkanont et al., 2018, Wipulanusat et al., 2019) of the transcribed data was undertaken to extract findings in a systematic and thorough manner. The qualitative analysis resulted in a broad comprehension of the communication between the building ‘openings’ supply chain, role of each involved professional, barriers, best-practices, as well in some recommendations.

The results derived from the BN study demonstrated the model's ability to accurately quantify the current acceptable performance and how the probability of the acceptable performance varies under different scenarios. The high impact factors in the BN model were illustrated using a sensitivity analysis. Moreover, scenario analyses provided the capacity for deeper understanding of the acceptable performance behaviour. The results corroborate that tackling the right nodes, performance of openings standards in addition to standards knowledge & training and construction documentation will effectively increase the performance of openings subject to wind driven rain. The BN model provided to the construction industry as well as government with various scenarios for decision options. Thus, providing a more rational decision making on the management practices to focus when looking at openings subject to wind-driven rain.
Chapter 7: Conclusion

7.1 Introduction
This chapter concludes the thesis with a summary of the research main contributions. The discussion presented in this chapter has built upon the previous chapters. It details the conclusions; it addresses the study’s contributions and limitations as well as the recommended future research directions. In Section 7.1 a brief review of the study. Section 7.2 recapitulates the objectives of the study and presents the outcomes. This is followed by Section 7.3, which presents the theoretical and practical contributions made by this study. Section 7.6 discusses the limitations of the study. Directions for future research is in Section 7.7. Finally, Section 7.8, gives a closure which ends the thesis discourse.

7.2 Overview
Structural damage resulting from severe storms, cyclones and hurricanes, has been significantly reduced in advanced economies in the last fifty years due to much higher building standards and certification. However, repeated minor to moderate damage resulting from serviceability failures from non-structural elements of windows and external glazed doors have not been sufficiently actioned since they do not lead to structural failure and loss of life. Improving the performance of openings subject to wind-driven rain water ingress is important for reducing the repeated occurrence of water-related damage in regions subject to tropical cyclones and severe storms. However, deriving an effective but feasibly implemented strategy to improve the performance of openings is challenging, as there a number of interconnected causal factors leading to defects. The hybrid combination of research methods including expert interviews, thematic analysis and probability theory with graph theory used in BNs, enabled this study to identify workable strategic pathways to improve the performance of openings to water ingress. Precisely, the BN model that was formulated from this novel method aided this study to explore the interrelationship between causal factors in the network, revealing a number of scenarios and the one and only that would be the most effective to derive the desired improvements in performance.

In total, 55 participants from the construction industry and government experts, in an interesting mix of roles with many years of working experience, provided reliable
results to the study. The main conclusion of this research is that openings performance would be best enhanced when a combination of management strategies was implemented.

Despite from the catastrophe of Tropical Cyclone Tracy devastating Darwin, the hereafter, provided a significant improvement in the construction process based on mitigations measures provided from the Australian Building Code with a focus on structural elements, as previously discussed. The non-structural elements should be focused, especially windows and external glazed doors should, based on the herein research results. An envelope that is not adequately resilient to wind-driven rain cannot be handed over to homeowners as it will incur preventable repeated repair or heightened insurance premium costs over the life cycle of that building asset. The proposed changes should be comprised into the construction industry and serviceability standards, and when enforced, will likely change the way houses and buildings are constructed.

7.3 Research objectives and outcomes
This study had three research objectives: (1) identification and understanding of the key factors, in current practices, that affects the performance of windows and external glazed doors subject to wind-driven rain water ingress during severe storms and tropical cyclones; (2) development of a performance prediction model; (3) estimate the current performance of openings and developing a range of scenarios, that could potentially lead to greater performance of openings.

7.3.1 Objective 1
“To identify the key factors, in current practices, that affects the performance of windows and external glazed doors to wind-driven rainwater ingress during tropical cyclones and investigate if the failure occurs during severe storms”

The literature pertinent of failures of non-structural elements, including windows and external glazed doors in Chapter 2, provided the categorisation of the failure modes based on surveyed buildings from tropical Cyclone Debbie (2017), Yasi (2011) and an Insurance Council of Australia report (Section 2.4.1 and Appendix A). The failure modes provided an indication that only a broad understanding of the current practices could provide a deep and clear understanding of the current scenario. A data collection method and thematic analysis was undertaken with a total of 39 participants with
several experts from the construction industry and government. As a result, four salient themes emerged and were namely: standards, installation quality regime, inspection regime and liability and recourse. Each theme was then unfolded in several sub-factors as described in Chapter 4. These empirically determined factors and sub-factors, were the essential ingredient for developing the BN model to estimate the performance of windows and external glazed doors described below.

7.3.2 Objective 2
“
To develop an openings’ wind-driven water ingress performance prediction model using a BN modelling approach”

Utilising the results from the primary stage, a conceptual model was performed forming the basis for the BN structure. The conceptual model provided the variables and its interdependencies and included different groups, like standards, training, policies and management, and liability, under covered in Chapter 4. The conceptual model consisted of 12 variables: (1) Opening standards; (2) Standards knowledge & training; (3) Inspection certificate document; (4) Construction documentation; (5) Contract documentation; (6) Inspection effectiveness; (7) Contractor’s performance review; (8) Product’s performance; (9) Monitoring & inspection practice; (10) Liability evidence; (11) Quality Assurance and Control; and one outcome factor: (12) Performance. For each variable, two states were specified. From that, the conceptual model was converted into a BN structure and next, validated with three Academic experts in BN.

7.3.3 Objective 3
“Use BN scenario analysis to identify the most appropriate management interventions that could lead to a higher performance of openings subject to wind-driven rainwater ingress during tropical cyclones and severe storms, providing decision makers with a simple communication and support for better targeting and prioritization of investments”

To estimate the performance of openings in the validated BN structure, the CPTs and MDPs were populated based on beliefs of experts’ knowledge with large experience on the theme to ensure reliable results. The participants working experience ranged between 15 and 45 years. To populate the CPTs and MDPs, a workshop, phone interviews and a face-to-face meeting were the employed strategy which reached a total of 16 participants. The input provided by the experts, as prior probabilities, led to
a likelihood for an initial Acceptable Performance of 32.2% endorsed as the current condition for windows and external glazed doors subject to wind-driven rain arriving form tropical cyclones and severe storms. Following, a sensitivity analysis, a form of quantitative evaluation of the model, ranked the variables in order of their importance relative to the outcome. The three variables that are most influential on the outcome, an Acceptable Performance are: (1) Product’s performance; (2) Quality Assurance and Control; and (3) Opening Standards (Chapter 5). Next, 11 scenarios were evaluated to identify which variables could effectively raise the initial Acceptable Performance of 32.2%. The best result provided between the 11 scenarios was a combination of three management practices powering the Acceptable Performance to 66.60%. As a result, the effort should be concentrated on: Openings Standards, Standards Knowledge and Training and Construction Documentation, those practices occur long before the construction of the building (Openings Standards and Standards Knowledge and Training) and at the early stages of the construction process (Construction Documentation). Emphasizing the three practices together, the less likely that windows and door openings will experience serviceability failure during their lifetime.

7.5 Contributions to Research
This thesis made original contributions for the performance of windows and external glazed doors subject to wind-driven rain based on management practices and standards, from both theoretical and practical perspectives.

7.5.1 Theoretical Contributions
The scientific contribution of this study consists of adopting an integrated and holistic view of the performance of windows and external glazed doors subject to wind-driven rain based on management practices and standards, from both theoretical and practical perspectives. This study proposed a novel model to identify and understand the current factors affecting the performance of openings and, to estimate the performance and explore relationships between variables in different scenarios by using a BN model approach. Thus, the main theoretical contribution entails the development of an efficient model to estimate the performance of non-structural elements in many different natural hazards in a causal analysis reasoning process. The main advantage of BN is that it can deal with uncertainty and attain better levels of performance and accuracy than those obtained with classical linear models.
7.5.2 Practical Contributions

From the practical perspective, this study provided benefits for the construction industry and government firstly and also for the insurance industry and homeowners as the developed model provides support on decision making onto the performance of windows and external glazed doors subject to wind driven rain exposed to severe storms and tropical cyclones. The study also includes practical recommendations for a quality assurance process for best results when delivering openings to homeowners.

Looking over the BN approach, the practical contribution is that openings performance would be best increased when a combination of three practices is focused as in the current condition, windows and external glazed doors will continue to be failing during periods of tropical cyclones and severe storms. As structural failures during storms and cyclones are now less current as from the 1980s due to more stringent building codes, non-structural elements continue to suffer serviceability failures, ultimately increasing insurance premiums as well as governments spending on unnecessary repairs. Windows and external glazed doors must be properly built and inspected for quality prior to handover to the homeowner. The more significance that is placed on the early stages of the process such as improved openings standards, standards knowledge and training and construction documentation, the less likely that windows and external glazed doors will experience serviceability failure during their lifetime. For this reason, it is clear that the government and construction industry cannot solve the windows and external doors failures independently. The herein suggested changes should be incorporated into the construction industry and serviceability standards, and when enforced, will likely change the way houses and buildings are constructed.

7.6 Study Limitations

- The lack of numerical data on failure rates restricted the study on the choice of the quantitative method. Hence this study was limited to the use of the Bayesian Network approach.

- The qualitative and quantitative method applied would benefit from a larger sampler size, especially in terms of regional location which could have included participants from the Northern Territory and Western Australia, states that annually suffers from severe storms and tropical cyclones.
• The elicitation process for the BN model was held with 16 participants, thus increasing the population to increase data base with a series of workshops should be undertaken. This approach would provide more curacy on the estimated performance.

• Limited economic data access restricted this use as it would be highly beneficial to provide a cost-beneficial analysis to decision makers allied to the thematic analysis results and BN model.

7.7 Future Research Directions
Future research should investigate practices, policies, standards, enforcement, and liability regimes to other non-structural elements exposed to a range of natural hazards (i.e. storms, fires, floods, etc.), applying similar methodology from this study in order to enhance the performance of others non-structural building elements from the building envelope. As demonstrated herein, scenario analysis techniques such as BNs, can provide evidence-based results that can help decision-makers to improve practices, policies, standards, enforcement, and liability regimes.

7.8 Closure
The current study makes a fundamental contribution to the field of water ingress from non-structural elements during natural hazards such as tropical cyclones and severe storms in formulating a method for estimating the performance of windows and external glazed doors subject to wind-driven rain from a management view. It investigated the relationships between current management practices and their influence on the performance of windows and external glazed doors. To achieve the study objectives a qualitative interview method comprising phone interviews and workshops involving several participants from the construction industry and government was conducted. Semi-structured questions were developed based on the literature review and applied during data collection. Through thematic analysis, four major themes emerged: Standards, Inspection regime, Installation quality assurance and control regime and Liability and recourse. Recommendations were provided by interviewees resulting in a quality assurance process designed for the use of governments and industry projects with improvements in common basis management practices related to documentation, inspection liability assignment and installation training for building windows and doors, especially in locations where severe winds are frequent in Australia).
Moving forward to the qualitative method, the results from the data collection, underpinned the study to establish the conceptual model leading to the development of the BN structure. The elicitation process organised to estimate probabilities counted with a workshop, phone interviews and a face-to-face meeting resulting in the current Acceptable Performance of 32.2%. This study shed additional light to improve the current Acceptable Performance by providing 11 scenarios regarding best combinations of management practices and standards to raise the current Acceptable Performance. The main contribution of this study is that: concurrently improving and implementing “Opening standards” and “Standards knowledge & training” and “Construction documentation” openings will raise the performance level to 66.6%.

In addition, this study proved to be reliable providing practical contribution to academics, construction industry and government. Specifically, to academics, by offering a detailed process of qualitative data collection and a model depicting pathways that explain the mechanism to estimate the performance of non-structural elements subject to natural hazards. To the construction industry and government, to better understand the dynamic interactions of variables affecting the performance of windows and external glazed doors, it also has the potential to assist the construction industry and governments to actively manage those variables making changes into the way windows and external glazed doors are constructed, increasing its performance. As well as a quality assurance process related to improving the quality assurance process to prevent wind driven rainwater ingress through windows and external glazed doors was recommended.

Finally, the dissertation closes with a number of future research directions, sowing a lay out for other researchers willing to enhance and extend the current findings of this research study.
References


IBHS 2009. Hurricane Ike, nature’s force vs. structural strength. IBHS Tampa, FL.


Suncorp 2018. Wind-driven rain drives damage costs.


## Appendix A

Building failure modes, root causes and mitigation strategies

<table>
<thead>
<tr>
<th>Building elements</th>
<th>Failure Modes</th>
<th>Damage through components</th>
<th>Root Cause</th>
<th>Suggestions: Design / Specification / Check list / Options for mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windows</td>
<td>Material / design</td>
<td>louvres</td>
<td>Water ingress through louvre windows, in some houses. Some houses with louvered window with did not have water ingress.</td>
<td></td>
</tr>
</tbody>
</table>
|                   | Material / design | open gaps between sashes, frames and through seals | 1. water ingress through undamaged windows  
2. worn or damaged window seals  
3. wind-driven rain passed through building envelope at openings such as windows and doors (even if closed), around flashings, through linings.   
A high differential pressure between the inside and the outside of the building is established in strong winds. This differential pressure can force water through gaps and spaces that it would otherwise not penetrate. The air flow around and over a building in an extreme wind event can drag water upwards over the building envelope. The movement in a direction opposite to its normal movement means some flashings that channel downward-moving water away from the envelope, may direct the upward-moving water into the building. |
|                   | Material / design | weep holes, gaps and around seals | Water ingress through undamaged doors (glass sliding door, under swinging doors and bi-fold doors)  
Failure of element |
|                   |               |                             | Flap-type seals are more effective in water penetration than mohair seals on sliding doors  
1. Windows are not tested to resist the water ingress. The pressure for the test should be the same level of the structural design, so whenever a severe storm is followed by rain, most likely water will get inside.  
2. Make sure the balcony floor is not in the same level as the balcony window with at least one step up. |
<p>|                   |               |                             | Weep holes must be covered by external rubber or an external baffle that concealed the wee holes and also, for doors, a step to |</p>
<table>
<thead>
<tr>
<th>Building elements</th>
<th>Failure Modes</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Doors</td>
<td>Material / design</td>
<td>weep holes, gaps and around seals</td>
<td>The report was not able to describe the windows that have performed well of the ones that have let water into the building. Weep holes are designed in windows and sliding glass doors to allow condensation and minor leakage around seals to pass from the inside to the outside of the building. In high winds, the driven rain passes through the weep holes and through other gaps in the building envelope. The windows without significant water ingress had weep holes that were covered by external rubber strips. (i.e. bi-fold and swinging windows and doors with gaps installed without a sill) water ingress - small amounts and large volumes of rainwater damage to vulnerable elements like plasterboard wall linings and ceilings, floor coverings; and personal belongings.</td>
<td>prevent wind driven rain to go inside. Better design for windows and doors related to sill (some houses with this type of window/doors worked right) 1. Make sure there balcony floor is not in the same level as the balcony door, with at least one step up.</td>
</tr>
<tr>
<td>Doors</td>
<td>Material / design</td>
<td>sash and tracks in aluminum sliding glass door, aluminum swinging glass door and timber sliding glass door</td>
<td>1. Failure of the sash (sash bent, door laminated glass did not brake), high internal pressure into the house, causing wind and water ingress into the building. 2. Sliding door panels disengaged from their tracks. 2.1 Because of the failure of the sash. 2.2 Because of differential air pressure. 3. The timber sliding glass doors came out causing water ingress, the sash come out of the frame because of the rail and rollers deformation.</td>
<td>1. There were some cases were the door have not failed because the hinges were more robust and there were twice as many hinges compared to the door that have failed 2. Wind ratings are required for windows and glass doors but not required for non-glazed entrance doors. The consequences of failure of entrance doors were similar to those of failure of glass doors.</td>
</tr>
<tr>
<td>Doors</td>
<td>Material / design</td>
<td>free bolts in aluminum bi-fold door</td>
<td>Free bolts caused the break of the hinges causing water ingress allowing door repeatedly swing.</td>
<td></td>
</tr>
<tr>
<td>Building elements</td>
<td>Failure Modes</td>
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<td>Root Cause</td>
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</table>
| Doors             | Material / design | hinges and latches in timber bi-fold door | Failure of latches and bolts in the entrance door causing wind and water ingress  
1. Because of wind forces on the doors.  
2. Wind ratings are required for windows and glass doors but not required for non-glazed entrance doors. The consequences of failure of entrance doors were similar to those of failure of glass doors. | |
| Doors             | Material / design | latches and bolts in entrance timber double swinging door | Doors lock fail, not able to withstand the wind pressure causing wind and water ingress  
1. The failures of doors were from inadequate lock and/or drop bolts which were not able to withstand the wind pressure allowing the doors to be pushed open. The door and window failures then caused pressure and wind driven rain to exacerbate internal damage. Houses constructed in vulnerable locations exposed coastal locations or site on hills  
2. The failure of the door lock, because of the wind to the wall generated large internal pressure which contribute to the failure of the entire roof. This house had metal screens over the windows, but still was exposed to internal pressures from dominant openings because of the failure of the door lock. | |
| Doors             | Material / design | door lock in the entrance door | | |
| Doors             | Material / design | temperate glass in the door with | Temperate glass fragmented because of wind pressure causing wind and water ingress. | |
| Roof              | Material / design | soffit, gutter, fascia, gable linings | Loss of partial or total components causing wind and water ingress  
these loss, allows pressurisation of roof space and wind driven rain to enter.  
Poor performance is due to a combination of connection capacity. | 1. Poor performance is due to a combination of connection capacity. Soffits made from adequately fastened resilient materials, such as steel sheeting or composite materials, resist successfully wind pressures. |
<table>
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</thead>
</table>
| Roof             | Material / design | roof structure            | Loss of roof over the outrigger, causing damage to the flashing at the top of the windward wall consequent water ingress to the building, possible inadequate design. | 2. Better sizing of flashing and gutters.  
1. Missing or damaged or inadequate or poorly fixing of flashings, gutters and soffit linings  
2. Flashings not fixed to the barge, flashings fastened with pop rivets allowed water ingress causing damage to vulnerable elements like plasterboard wall linings and ceilings; floor coverings; and personal belongings.  
3. Water ingress under flashings, through tie down connections rainwater inside the building trough under flashings, causing damage to or collapse of ceilings, flashings are made to protect the entrance of rainwater into the building that come in descendant direction. At the time there is cyclone, fierce winds with changing directions will be happening. The rainwater will too be projected into the roof in an ascendant direction.  
Gutter: rainwater driven under the roof sheeting and into the ceiling space due to gutters damage/lost/blocking |
| Roof             | Material / design | rubber boot and sealant in vent pipes | Rubber boot and sealant deteriorated allowing water to enter into ceiling space and incorrect location. | 1. Better sizing of flashing and gutters.  
2. Flashings fastened with pop rivets generally have removed from buildings, flashings fastened with screws worked well.  
3. Attention to skillion roofs that require apron flashings, or roofs with complex designs that require additional flashings on many roof edges  
4. Gutters: Design, box gutters should have the overflow at the opposite end to the normal outflow into the downpipe. This will provide drainage at both ends of the box gutter. Each end should have a spillway overflow so the overflows can’t be blocked by detritus. The back edge of eaves gutters should be higher than the front so that they |
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<td></td>
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<td>1. damage or lost - gutter attached to fascia with clips or fixing that not have the capacity to resist the wind forces for 2. blocked - by the considerable volume of broken trees and plant debris that are part of the current of air throughout the cyclones 3. box gutters usually only have a drain at one end. Strong winds can drive water pooled in the gutter to the opposite end to the drain where it piles up and overflows into the ceiling space.</td>
<td>overflow to the outside of the building rather than into the eaves and ceiling space.</td>
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</tr>
<tr>
<td>Building elements</td>
<td>Failure Modes</td>
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<tr>
<td>Bad installation / material / design</td>
<td>air conditioning units / aerials, fascia or, gable ventilators, sarking and soffit lining, louvres or ventilators louvres and connections</td>
<td>1. Failure or loss of the components causing damage to timber, steel or concrete structure such as lining infiltration with consequent water ingress due to the fixing into the roof. 2. Rusting or blocked guttering (e.g. vegetation). 3. Water penetration in: cladding (facade); through tie down connections between roof structure and walls; sarking under shingles roof that were able to redirect water that has overflowed the valley gutters and flashings into the eaves gutters.</td>
<td>1. Regardless of the cladding material, roof complexity adds to the potential for water ingress. Valley gutters, box gutters and parapets, all require additional flashings and therefore more potential locations for water to be driven into the roof space 2. Care is needed in detailing of the sarking into the gutters if water entry into the building is to be avoided. However, in some cases where the tiles had been lifted or broken, the sarking was also damaged and this allowed water to penetrate the building. 3. Soffit linings and eaves linings are in regions of the buildings that are very affected by interior pressure or suction. Plasterboard ceilings if water ingress becomes heavy and the strength will be reduced so the ceiling might collapse. Usually that soffit can be under an outdoor area. 4. Eaves must be designed for protection from rain and wind in semi-open areas 5. When designing a roof with louvre, make sure using water resilient linings, to be used next of louvres (areas of potential water ingress). 6. Make sure the gutters are correctly designed to not be blocked for instance with vegetation blocking the way 7. Make sure aerials and air conditioning units are fixed not fixed at the roof 8. Better detail the connections between roof structure and walls 9. Better detail the connections between veranda beams and posts.</td>
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<tr>
<td>Building elements</td>
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<tr>
<td>Bad installation / material/ design</td>
<td>gable, eaves, ridge vent</td>
<td>Missing or damaged or inadequate fixing because of the strong wind caused small and large volumes of rainwater, sometimes causing ceiling damage.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bad installation / material/ design</td>
<td>through the frame to wall window fixing / window frame</td>
<td>Window frame separated from the building house providing water ingress 1. did not have the appropriate frame to wall fixings for the window resulted in the window and frame being &quot;blown&quot; into the house. The door and window failures then caused pressure and wind driven rain to exacerbate internal damage. Houses constructed in vulnerable locations exposed coastal locations or site on hills 2. possible the frame was bad anchored to the building fabric and so separated from the building causing a large opening allowing wind pressure that contributed to the failure.</td>
<td>1. window/door frame must be securely anchored to the building fabric to ensure that the building envelope is secure. Design must be according to the required higher pressures 2. Mitigation: the use of robust window shutters will offer some level of protection to window as well.</td>
<td></td>
</tr>
<tr>
<td>Bad installation / material/ design</td>
<td>connections in door frame</td>
<td>Door frame separated from the building, causing water ingress because of inadequate connections between the timber frame and the timber house.</td>
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</tr>
<tr>
<td>Bad installation / material/ design</td>
<td>hip &amp; ridge tile</td>
<td>Failure modes of the tiles were loss of ridge capping (both apex and hip tiles), loss of tiles near gable ends, and cut tiles associated with hips. On most houses that had lost ridge capping, no mechanical fixings such as clips or screws on the ridge tiles were observed. The dislodgement of the ridge or other tiles generally led to additional damage to the tile roof and to adjacent structures through wind-borne debris. 1. due to high local pressures 2. material deteriorated because of age around hip and ridge tiles may reduce the strength possibly contributing to the damage Caused wind and water ingress</td>
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<tr>
<td>Building elements</td>
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<tr>
<td>Bad installation / material / design</td>
<td>brick cladding</td>
<td>Failure of brick veneer away from the structural masonry wall, possible causes of failure: Lack of brick ties and/or masonry reinforcement in a brick/masonry veneer wall.</td>
<td></td>
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</tr>
<tr>
<td>Bad installation / material / design</td>
<td>fixing</td>
<td>Doors failed due to not adequate fixing into the building, only one side of the frame was secure fixing and because of the wind the doors failed. The high internal pressure was caused by the loss of the door frame.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bad installation / material / design</td>
<td>solar hot water, photovoltaic panels, skylights, aerials, vents</td>
<td>Many of those items had no wind damage and no damage to the roof, in some of them mounting brackets between roof and item failed. When it failed, the report could not provide enough evidence if it was from items fixed to the roof itself or to the roof structure. Inadequate fixing to the roof caused loss of the aerials/vents causing water ingress contributing to damage the ceiling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design / bad installation</td>
<td>light gauge steel framing</td>
<td>Wall failure because of the discontinuous studs, perhaps a not very good design or bad installation</td>
<td>better specification/design related to light gauge steel Panels above the studs cannot be disconnected</td>
<td></td>
</tr>
<tr>
<td>Bad installation / material</td>
<td>fixing</td>
<td>Strong wind Not adequate fixing into the building made the windows fail, the frame of the window was stapled into the building frame. Probably the staples were located temporarily, and a proper fixing would be done later The high internal pressure was caused by the loss of the window frame on the windward wall.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Building elements</td>
<td>Failure Modes</td>
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</tbody>
</table>
| Bad installation | batten-to-rafter / truss connections | Partially loss of the roof, inadequate / poor connection / loss of function initiated by the fastener corrosion enabling rain water entering the building | 1. Make sure the batten-to-rafter connections are specified correctly on the design (nails, screws, straps)  
2. Roof inspections should be undertaken to detect partial failure of batten to rafter connections. The inspection must be performed on all buildings that have experienced high winds even if they appear to be undamaged.  
3. Where there has been deterioration of connections or member, this should be detected during inspections and replaced. |
<p>| Bad installation | vents | Inadequate fixing to the roof caused water ingress contributing to damage the ceiling | |
| Bad installation | tiled roof | Because of the strong wind, the tile damaged caused loss of the ridge cap, possible cause unlined eaves | |
| Bad installation | cladding | Cladding disconnected from purlins or battens causing damage near edges of walls or roofs and roof not installed conform specifications, flashings damaged possibly contribute to the damage | |
| Bad installation | metal roof tiles | Loss of metal roof tiles, tiles not installed correctly, did not penetrate enough to the tile | |
| Bad installation | Pierce-fixed metal | Loss of the roof, battens stayed attached, roof not installed conform specifications, flashings damaged possibly contribute to the damage | |
| Material | roof vents | Whirly bird vent deformed and, in some cases, contributed to water ingress into the ceiling because of the strong wind | |</p>
<table>
<thead>
<tr>
<th>Building elements</th>
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<th>Suggestions: Design / Specification / Check list / Options for mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>punctured cladding</td>
<td>Caused water ingress, make sure balconies/patios have drainage points</td>
<td>Regardless of the cladding material, roof complexity adds to the potential for water ingress. Valley gutters, box gutters and parapets, all require additional flashings and therefore more potential locations for water to be driven into the roof space</td>
<td></td>
</tr>
<tr>
<td>Design</td>
<td>veranda</td>
<td>Loss of veranda, fail between connections with veranda beams and posts or walls (fail observed in timber, steel and concrete) Buildings in exposed locations are submitted to high wind speed and so pressure; large verandas have higher loads beams straps and bolts nailed incorrectly to the veranda beam (probably inadequate design specification)</td>
<td>Check for sizing of the veranda/balcony. In case of material is steel implement a good checking of the tack weld</td>
<td></td>
</tr>
</tbody>
</table>
## Appendix B

<table>
<thead>
<tr>
<th>Group (Code)</th>
<th>Insights from interviewees</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CATEGORY: Standards</strong></td>
<td></td>
</tr>
<tr>
<td>M1</td>
<td>Manufacturer 1 does training with employees for their own installations. With contractors, there are site visits but are rare. However, estimated roughly the same quality in the final installed product. Education is a key too.</td>
</tr>
<tr>
<td>G</td>
<td>Tradies are cutting corners, they should know. Northern Qld less qualified people.</td>
</tr>
<tr>
<td>BC1</td>
<td>We require an improvement to training and licencing (QBCC). Key issues toward water ingress are poor construction. Improve the licencing aspect from QBCC. Include another inspection for windows wouldn't help. What is necessary is a better trade’s education system which is terrible.</td>
</tr>
<tr>
<td>BC3</td>
<td>Skills are satisfactory. AWA provide installation information online.</td>
</tr>
<tr>
<td>BC4</td>
<td>Generally good work. Many resources are found online if required.</td>
</tr>
<tr>
<td>BC5</td>
<td>Skills and labour are satisfactory for the region.</td>
</tr>
<tr>
<td>BC6</td>
<td>The training and skills are there. Key issues are cutting corners to save money. Referring to glazing where no inspection can be made, relying on form 16. Not enough liability on installers.</td>
</tr>
<tr>
<td>BC7</td>
<td>Professional installation of waterproofing and flashings.</td>
</tr>
<tr>
<td>BC8</td>
<td>In tropical regions the skills and labour are better as higher quality builds are required. Rely on Form 16 as assurance of high-quality install.</td>
</tr>
<tr>
<td>BC9</td>
<td>Incorrect materials being used (Roofing: wrong size screws/corrosion resistant elements. Glazing: manufacturers provide incorrect materials).</td>
</tr>
<tr>
<td>BC9</td>
<td>Labour and skills are to a high standard in North QLD. There is an online workplace that most trades use to share/help information.</td>
</tr>
<tr>
<td>BC10</td>
<td>Skills and labour are satisfactory for the region.</td>
</tr>
<tr>
<td>BC11</td>
<td>Skills and labour are to a high standard in North QLD.</td>
</tr>
<tr>
<td>I/B1</td>
<td>Insufficient training of carpenters to install windows/doors. Has met carpenters onsite that have never installed before.</td>
</tr>
<tr>
<td>I/B1</td>
<td>Carpenters should know what is required. Have seen substandard windows used to cut costs.</td>
</tr>
<tr>
<td>I/B2</td>
<td>Insufficient training for apprentice carpenters, AWA should provide some training.</td>
</tr>
<tr>
<td>I/B3</td>
<td>Insufficient training for carpenters, experience is key to a quality install.</td>
</tr>
<tr>
<td>I/B3</td>
<td>General knowledge of the construction industry leads to knowing how to correctly waterproof flashings.</td>
</tr>
<tr>
<td>I/B4</td>
<td>Further training is required.</td>
</tr>
<tr>
<td>I/B5</td>
<td>Further training is required.</td>
</tr>
<tr>
<td>I/B7</td>
<td>Skills are lacking in some areas</td>
</tr>
<tr>
<td>I/B8</td>
<td>Skills are lacking, provide better training</td>
</tr>
<tr>
<td>I/B9</td>
<td>Use specialised trades for best results. Some better than others.</td>
</tr>
<tr>
<td>I/B10</td>
<td>Better training for new workers should be implemented.</td>
</tr>
<tr>
<td>M1</td>
<td>Test pressure insufficient to cyclone winds. Test pressure insufficient to cyclone winds. Test rig was builded in order to create a high dynamic range pressure to several types of window to test the water penetration resistance.</td>
</tr>
<tr>
<td>IA</td>
<td>Test pressure insufficient to cyclone winds.</td>
</tr>
<tr>
<td>A2</td>
<td>Test pressure insufficient to cyclone winds.</td>
</tr>
<tr>
<td>I/B1</td>
<td>Blocked weepholes, Windows/Doors cannot handle the force of high category cyclones. Substandard window design for the area.</td>
</tr>
<tr>
<td>I/B3</td>
<td>Cyclonic wind driven rain will make any window/door/roof leak to an extent. Storm shutters can stop 90%</td>
</tr>
<tr>
<td>-----</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>M1</td>
<td>Products attends standards that are made for minimum requirements</td>
</tr>
<tr>
<td>G</td>
<td>The standard is made to meet the minimum requirements, so the products meet the minimum required by the standard</td>
</tr>
<tr>
<td>BC10</td>
<td>Most windows and doors allow for water ingress during extreme wind driven rain. Improvement to Australian Standards windows/door design is required.</td>
</tr>
<tr>
<td>BC11</td>
<td>Failing Australian Standards relating to tropical climates</td>
</tr>
<tr>
<td>BC12</td>
<td>Rework of AUS Standards</td>
</tr>
<tr>
<td>I/B10</td>
<td>Cannot stop water ingress from wind facing windows and doors in a cyclone</td>
</tr>
<tr>
<td>G</td>
<td>Every year</td>
</tr>
<tr>
<td>CC1</td>
<td>Every year</td>
</tr>
<tr>
<td>M1</td>
<td>Every 2 years</td>
</tr>
<tr>
<td>IA</td>
<td>Every cyclone and high wind event</td>
</tr>
<tr>
<td>BC1</td>
<td>Water ingress is a common issue during cyclonic events</td>
</tr>
<tr>
<td>BC3</td>
<td>After an extreme weather event there is a spike in water ingress related maintenance. Usually minor repairs (carpet, gyprock)</td>
</tr>
<tr>
<td>BC4</td>
<td>After severe storm events there are many maintenance teams out there to repair and dry damages related to water ingress</td>
</tr>
<tr>
<td>BC6</td>
<td>Always a large influx of insurance claims after an extreme weather event. Cannot make a building entirely waterproof. We need to make manufactures test glazing post install and make builders responsible for a high standard of install</td>
</tr>
<tr>
<td>BC8</td>
<td>After severe storm events notice a spike in water ingress</td>
</tr>
<tr>
<td>BC9</td>
<td>Water ingress is very common after an extreme weather event</td>
</tr>
<tr>
<td>BC10</td>
<td>A lot of repair and maintenance is required after an extreme weather event in North QLD</td>
</tr>
<tr>
<td>BC11</td>
<td>After severe storm events there is a spike in water ingress</td>
</tr>
<tr>
<td>BC12</td>
<td>After severe storm events there is a spike in water ingress</td>
</tr>
<tr>
<td>I/B5</td>
<td>Most buildings will leak in an extreme cyclonic event (about every 3 years). Regular maintenance required every 3 years (cleaning sills to avoid blockage) (cleaning gutters)</td>
</tr>
<tr>
<td>I/B6</td>
<td>Always have issues with water ingress caused by cyclonic weather. Cannot prevent water ingress in these situations. Care must be taken in own home (put towels etc around windows)</td>
</tr>
<tr>
<td>I/B9</td>
<td>Every structure will leak to some degree in a cyclone. Nothing is completely waterproof</td>
</tr>
<tr>
<td>I/B10</td>
<td>Extreme weather every 3-5 years therefore structures require sufficient maintenance in this period</td>
</tr>
</tbody>
</table>

**Group (Code)** | **Insights from interviewees**
--- | ---
**CATEGORY: Inspection Regime** |  
**M1** | Private certifier does not check, they just get the form 16  
Form 16 could have extra questions about if fixing requirements are met  
An extended Form 16 would not be too time consuming as long as there is enough training and personal integrity for QDHPW supervisors  
Form 16 essentially declares that the product has been installed as per Form 15 (design).  
Not clear who should signed the Forms, apparently even QBCC that have made the Forms are not sure |
Today superintendents inspect documents. Self-regulation is bad, needs to be policed.

**G**

Current Form 15/16 leave minimal liability when certifier signs off. IDEAS to include at Form16:
- Photo of flashings and install
- Type of fixings and spacing.
- Type of products used

**BC1**

Form 15/16 is only documentation. Information can be found on the glazing manufactures website.

**BC2**

Buildings certifiers only check structural elements, not windows. For windows, the form 15 must be filled for the engineer/designer for the window specification and the manufacturer for the installation. The form 16 must filled by the engineer inspector or building inspector for the foundation and footing slabs.

**BC3**

Inspection checklist: Anchoring @ 300mm centres, Sealing (mastic), Glass specification, Form 15/16.

Flashings cannot be inspected after install. Typical install follows NCC (National Construction Code) and Australian Standards (2188 Glazing). Form 15 from manufacture (glass thickness) derived from glazing standards, where windows are designed for wind driven water.

**BC4**

Final inspection (only check glass classification and form 15/16) No improvement required.

**BC6**

The training and skills are there. Key issues are cutting corners to save money. Referring to glazing where no inspection can be made, relying on form 16. Not enough liability on installers.

Inspection checklist: Anchoring, mastic, glass specification, frame design, Form 15/16. Not enough responsibility.

Only looking for Form 15/16. (This is not enough in his opinion). Key issues: Sub contractors and Installers have no responsibility to install to a high standard. (They focus on being quick and the minimal use of waterproofing products).

**BC8**

In tropical regions the skills and labour are better as higher quality builds are required. Rely on Form 16 as assurance of high-quality install.

Improve the licencing aspect from QBCC.

**BC9**

Check sticker on glazing C1, C2, C3 cyclone rated (thicker glass, required to have heavy duty seals etc.) Rely on Form 15/16. Improvement could be for the builder to supply effective waterproofing statement (this would enforce the testing of the waterproofing of the structure).

**BC10**

Form 15/16 provides necessary information. Check seals and glass rating.

**BC11**

Has not worked with HPW. Basically, have a failing system in tropical regions were certifiers rely on the design from manufactures (Australian Standards currently not sufficient). Also rely on installation were if not done properly it will fail. Key to reduce water ingress is maximise eve/awning coverage.

No official check list. Check anchors. Rely on installers to provide correct install to Australian Standards. Rely on manufacturers to provide correct design as per Australian Standards.

**BC12**

Check anchoring and mastic. Flashing and sub sills cannot be seen. Rely on Form 16.

**I/B1**

No inspections. Form 16 is provided (by licenced person under QBCC).

**I/B2**

Knows of AWA but never bothered to look. Assumes that manufactures provide correct windows. Provides form 16 after install.

**I/B3**

No inspections. Form 15, 16 is provided by the Manufacturer.

**I/B5**

Form 15/16, not enough responsibility for professional install.

**I/B7**


**I/B8**

Form 16 is provided to certifier.
**Group (Code)** | **Insights from interviewees**
---|---
M1 | **CATEGORY: Installation quality documentation**
Private certifier does not check, they just get the form 16
Form 16 could have extra question about if fixing requirements are met
An extended Form 16 would not be too time consuming as long as there is enough training and personal integrity for QDHPW supervisors
Form 16 essentially declares that the product has been installed as per Form 15 (design)
Form 16 is about installation, no requirements for the installer indicating what details (screws, seals, etc)
Not clear who should signed the Form 16
G | Current Form 15/16 leave minimal liability when certifier signs off
Data from maintenance events are inserted in the system in a generic way
- IDEAS to include at Form 16:
  - Photo of flashings and install
  - Type of fixings and spacing.
  - Type of products used
BC1 | Form 15/16 is only documentation. Information can be found on the glazing manufactures website
BC2 | Buildings certifiers only check structural elements, not windows. For windows, the form 15 must be filled for the engineer/designer for the window specification and the manufacturer for the installation. The form 16 must filled by the engineer inspector or building inspector for the foundation and footing slabs
BC3 | Inspection checklist: Anchoring @ 300mm centres, Sealing (mastic), Glass specification, Form 15/16
Flashings cannot be inspected after install, Typical install follows NCC (National Construction Code) and Australian Standards (2188 Glazing). Form 15 from manufacture (glass thickness) derived from glazing standards, where windows are designed for wind driven water.
BC4 | Final inspection (only check glass classification and form 15’16) No improvement required
BC6 | The training and skills are there. Key issues are cutting corners to save money. Referring to glazing where no inspection can be made, relying on form 16. Not enough liability on installers
Inspection checklist: Anchoring, mastic, glass specification, frame design, Form 15/16. Not enough responsibility
Improve the focus of liability on builders to guarantee the waterproofing to the building envelope is installed to a high standard (by providing a personal guarantee rather than form 15/16)
Only looking for Form 15/16. (This is not enough in his opinion). Key issues: Sub contractors and Installers have no responsibility to install to a high standard. (They focus on being quick and the minimal use of waterproofing products)
Improve the focus of liability on builders to guarantee the waterproofing to the building envelope is installed to a high standard (by providing a personal guarantee rather than form 15/16)
BC8 | In tropical regions the skills and labour are better as higher quality builds are required. Rely on Form 16 as assurance of high-quality install
Form 15/16 is only documentation from manufacturer and installer. (Usually Manufacturer 1 provides both)
BC9 | Check sticker on glazing C1, C2, C3 cyclone rated (thicker glass, required to have heavy duty seals etc.) Rely on Form 15/16. Improvement could be for the builder to supply
| **BC10** | Form 15/16 provides necessary information. Check seals and glass rating |
| **BC11** | Has not worked with HPW. Basically, have a failing system in tropical regions were certifiers rely on the design from manufactures (Aus Standards currently not sufficient). Also rely on installation were if not done properly it will fail. Key to reduce water ingress is maximise eve/awning coverage. |
| **BC12** | Check anchoring and mastic. Flashing and sub sills cannot be seen. Rely on Form 16. Form 15/16 provides assurance that AUS Standards have been adhered to. |

| **I/B1** | No inspections, Form 16 is provided (by licenced person under QBCC). |
| **I/B2** | Knows of AWA but never bothered to look. Assumes that manufactures provide correct windows. Provides form 16 after install. |
| **I/B3** | No inspections, Form 15, 16 is provided by the Manufacturer. |
| **I/B5** | Form 15/16, not enough responsibility for professional install. |
| **I/B6** | Form 15/16 is provided by the Manufacturer. |
| **I/B7** | Form 15/16 is provided by the Manufacturer. |
| **I/B8** | Form 16 is provided to certifier. |
| **I/B10** | Form 15 and 16. |

| **M1** | Form 16 is about installation, no requirements for the installer indicating what details (screws, seals, etc) need to be done. |
| **M2** | Most of the plans don’t come with specification they have to ask the builder or the architect or the engineer. Form 16 is about installation, no requirements for the installer indicating what details (screws, seals, etc) need to be done. |

| **G** | Design standards are lacking. |
| **G** | Provide design specs for all windows including all flashings for the tender process. |
| **G** | Increase scope definition of projects. |
| **G** | Clearly specify design for key elements (roof/window/door/flushing/gutter/fixings/etc). |
| **G** | Provide detail designs from engineer/architects instead of “Refer to Australian Standard”. |

| **CC1** | The concluded design is approved by Certifiers that are given to Builders according to certain requires and rules for the design of Social Housing, poor requires and rules. |
| **BC3** | Has done work for HPW before. Additional required specifications should be provided to the builder throughout the tendering process. |
| **BC9** | Incorrect materials being used (Roofing: wrong size screws/corrosion resistant elements. Glazing: manufacturers provide incorrect materials. |
| **BC11** | Manufacturer 1 supply and install provide most effective waterproofing system at the moment however having minimal eve/awning coverage creates problems. |
| **I/B1** | Manufacturers do not provide a window/door installation guide/check list. Would like to see information from manufacture relating to installation guide/standards attached to the window (sticker or small booklet), not just online. |
| **I/B8** | Biggest issues are brick veneer. Block construction is much better. Provide waterproofing membrane and sub sill as best practice. Provide better training to apprentice carpenters. |
| **M1** | Private certifier does not check, they just get the form 16. An extended Form 16 would not be too time consuming as long as there is enough training and personal integrity for QDHPW supervisors. |
| **M1** | Outside windows installers are paid on fixed price, not quality. |

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<p>| G | Self-regulation is bad, needs to be policed |
| Other manufactures no training; anyway, if one contractor does a bad job, they will probably not get the next tender. So they are somehow forced to do a good job |
| BC1 | Form 15/16 is only documentation. Information can be found on the glazing manufacturers website. |
| Has seen incorrect glazing installed |
| BC3 | Incorrect windows and doors being used in tropical region |
| Flashings cannot be inspected after install, Typical install follows NCC (National Construction Code) and Australian Standards (2188 Glazing). Form 15 from manufacture (glass thickness) derived from glazing standards, where windows are designed for wind driven water. |
| BC4 | Have seen incorrect glass provided from manufacturer |
| BC6 | Always a large influx of insurance claims after an extreme weather event. Cannot make a building entirely waterproof. We need to make manufactures test glazing post install and make builders responsible for a high standard of install |
| Incorrect windows and doors being used. Incorrect roofing and gutter being used. Poor construction. Can be mitigated by focusing liability on the builder (personal guarantee) |
| The training and skills are there. Key issues are cutting corners to save money. Referring to glazing where no inspection can be made, relying on form 16. Not enough liability on installers |
| Inspection checklist: Anchoring, mastic, glass specification, frame design, Form 15/16. Not enough responsibility |
| Improve the focus of liability on builders to guarantee the waterproofing to the building envelope is installed to a high standard (by providing a personal guarantee rather than form 15/16) |
| Only looking for Form 15/16. (This is not enough in his opinion). Key issues: Subcontractors and installers have no responsibility to install to a high standard. (They focus on being quick and the minimal use of waterproofing products) |
| BC8 | In tropical regions the skills and labour are better as higher quality builds are required. Rely on Form 16 as assurance of high-quality install |
| BC11 | Has not worked with HPW. Basically, have a failing system in tropical regions were certifiers rely on the design from manufactures (Australian Standards currently not sufficient). Also rely on installation were if not done properly it will fail. Key to reduce water ingress is maximise eve/awning coverage |
| No official check list. Check anchors. Rely on installers to provide correct install to Australian Standards. Rely on manufacturers to provide correct design as per Australian Standards |
| BC12 | Check anchoring and mastic. Flashing and sub sills cannot be seen. Rely on Form 16 |
| I/B2 | Knows of AWA but never bothered to look. Assumes that manufactures provide correct windows. Provides form 16 after install |
| I/B3 | No inspections, Form 15, 16 is provided by the Manufacturer |
| General knowledge of the construction industry leads to knowing how to correctly waterproof flashings |
| I/B4 | Builder should check/monitor install process. Depends on type of build, timber frame can be checked before cladding is installed |
| I/B5 | Form 15/16, not enough responsibility for professional install |
| I/B8 | Form 16 is provided to certifier |</p>
<table>
<thead>
<tr>
<th>Group (Code)</th>
<th>Insights from interviewees</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>M1</strong></td>
<td>Private certifier does not check, they just get the form 16</td>
</tr>
<tr>
<td></td>
<td>Self-regulation is bad, needs to be policed</td>
</tr>
<tr>
<td></td>
<td>An extended Form 16 would not be too time consuming as long as there is enough training and personal integrity for QDHPW supervisor</td>
</tr>
<tr>
<td><strong>G</strong></td>
<td>Current Form 15/16 leave minimal liability when certifier signs off</td>
</tr>
<tr>
<td><strong>BC1</strong></td>
<td>Form 15/16 is only documentation. Information can be found on the glazing manufactures website</td>
</tr>
<tr>
<td><strong>BC2</strong></td>
<td>Incorrect windows and doors being used in tropical region</td>
</tr>
<tr>
<td></td>
<td>Flashings cannot be inspected after install. Typical install follows NCC (National Construction Code) and Australian Standards (2188 Glazing). Form 15 from manufacture (glass thickness) derived from glazing standards, where windows are designed for wind driven water</td>
</tr>
<tr>
<td><strong>BC4</strong></td>
<td>Have seen incorrect glass provided from manufacturer</td>
</tr>
<tr>
<td><strong>BC6</strong></td>
<td>Inspection checklist: Anchoring, mastic, glass specification, frame design, Form 15/16. Not enough responsibility</td>
</tr>
<tr>
<td></td>
<td>Improve the focus of liability on builders to guarantee the waterproofing to the building envelope is installed to a high standard (by providing a personal guarantee rather than form 15/16)</td>
</tr>
<tr>
<td></td>
<td>Only looking for Form 15/16. (This is not enough in his opinion). Key issues: Sub contractors and Installers have no responsibility to install to a high standard. (They focus on being quick and the minimal use of waterproofing products)</td>
</tr>
<tr>
<td><strong>BC8</strong></td>
<td>In tropical regions the skills and labour are better as higher quality builds are required. Rely on Form 16 as assurance of high-quality install</td>
</tr>
<tr>
<td><strong>BC9</strong></td>
<td>Check sticker on glazing C1, C2, C3 cyclone rated (thicker glass, required to have heavy duty seals etc.) Rely on Form 15/16. Improvement could be for the builder to supply effective waterproofing statement (this would enforce the testing of the waterproofing of the structure)</td>
</tr>
<tr>
<td><strong>BC11</strong></td>
<td>Has not worked with HPW. Basically, have a failing system in tropical regions were certifiers rely on the design from manufactures (Australian Standards currently not sufficient). Also rely on installation were if not done properly it will fail. Key to reduce water ingress is maximise eave/awning coverage</td>
</tr>
<tr>
<td><strong>BC12</strong></td>
<td>Check anchoring and mastic. Flashing and sub sills cannot be seen. Rely on Form 16</td>
</tr>
<tr>
<td><strong>I/B8</strong></td>
<td>Form 16 is provided to certifier</td>
</tr>
</tbody>
</table>
BAYESIAN NETWORK

CONDITIONAL PROBABILITY TABLES (CPT’s)
### Bayesian Network variables description

**CPT’s**

<table>
<thead>
<tr>
<th>Parents Node</th>
<th>Current practices</th>
<th>Recommendation/Improvement/CPT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 Opening Standards</td>
<td>The 'openings' standard for Australia is the AS 2047 – 2014. The water penetration resistance test is described in the AS/NZS 4420.1:2016 and occurs under static wind load (water sprayed uniformly and continuously over the exterior face) when in fact the static pressure water penetration tests are inadequate for characterising cyclonic events and most windows would have some form of water penetration during cyclone conditions. The Cyclone Testing Station (CTS) is conducting tests to replicate high dynamic range (HDR) pressure consistent with cyclonic pressure. Their preliminary findings indicate that static pressure water penetration tests are inadequate for characterising cyclonic events and most windows would have some form of water penetration during cyclone conditions.</td>
<td>The CTS may propose new requirements for AS 2047-2014 and AS/NZS 4420.1:2016.</td>
</tr>
<tr>
<td>1 Standards knowledge &amp; training</td>
<td>The Australian Window Association (AWA) provides industry training to improve familiarisation with relevant windows and glazed doors installation. The Australian Institute of Waterproofing (AIW) provides industry training to improve familiarisation with waterproofing systems. While there are courses and online materials available, installers in regional northern Queensland still provide poor quality and low level of inspection of work related to the preparation of the window/door opening.</td>
<td>Better knowledge transfer and education Better dissemination of best-practice</td>
</tr>
</tbody>
</table>
|   | How much % do you attribute the current scenario as Adequate or Inadequate? | 1. Generally, it was identified that incorporating design details for each wall opening. Aspects to specify for windows and glazed door openings: A typical waterproofing system detail should include specifications for the substrate, sub-sill, waterproofing membrane system, head, side angles and watertight seal.  
2. There is a need to improve documentation providing more detailed requirements within the tender documents that indicate the level of detail required from the contractor when providing their construction design documentation. This recommendation suggests that for “Design and Construction” arrangements, either:  
   • That process be limited to projects where detailed documentation is not required, or  
   • The building contractor be required to provide fully detailed construction documentation and specifications for the documentation stage and for as-constructed records on handover of the project. For “Construction Only” projects, the recommendation is that:  
     • DHPW should ensure that fully detailed construction documentation and specifications are provided in the documentation stage and,  
     • The builder is required to provide as-constructed records on handover of the project. This documentation should include detailed design |
|---|---|---|
| 2 | Construction documentation | 1. Research identified a low level of design and specifications. Do you consider that design for wall opening is adequate or inadequate? How much % would you attribute to Adequate and Inadequate?  
2. DHPW procures Social housing through two main procurement models, “Construction only” and “Design and construction”. The differing nature of each method has an effect on the outcome for resilience of the completed wall openings. Research on the current design specifications/details for Social Housing projects indicated that the move towards “Design and Construct” procurement for public housing in government departments, has resulted in poorer quality design and as-constructed information being produced by contractors. |
<table>
<thead>
<tr>
<th></th>
<th><strong>3 Inspection certificate document</strong></th>
<th><strong>4 Contract documentation</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Form 16 is the Qld document used for Building Certifiers/Superintendents to inspect windows and external glazed doors. Research indicates that this document is often not completed or completed with limited information (i.e. statement saying that works according to AS). Do you consider the document Adequate or Inadequate? How much% would you attribute to Adequate and Inadequate?</td>
<td>Research has indicated that the contract documentation should be more specific. Do you consider appropriate have a combined procedure? Adequate or Inadequate. How much %?</td>
</tr>
<tr>
<td></td>
<td>The recommended quality assurance process in Figure 1, for quality documents, should include steps 4, 5 and 6. 4.AC 5.IQF 6.OC</td>
<td>Tendering process should specify the addition of the recommended quality assurance process that will be included in the contract documentation. Contract documentation should outline the quality assurance process for the preparation and installation of windows and external glazed doors in an effort to increase quality and direct liability in the construction phase. Contract documentation to cover the remaining recommendations: <strong>Recommendation 1</strong> Construction documentation <strong>Recommendation 2</strong> Contract documentation</td>
</tr>
</tbody>
</table>
### Recommendation 3: Preparation and installation procedure

### Recommendation 4: Windows and external glazed doors installation quality form (IQF)

### Recommendation 5: Auditing check list (AC)

### Recommendation 6: Openings certificate (OC)

### Recommendation 7: Auditing check grade (AC grade)

The recommended quality assurance process in Figure 1.

![Schematic quality assurance process during design and construction of openings](image)

**Fig. 1 Schematic quality assurance process during design and construction of openings**

<table>
<thead>
<tr>
<th>5</th>
<th><strong>Contractors performance</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No current practices were identified. Do you consider that “Contractors performance” is Monitored or Not monitored? How much % would you attribute to Monitored and Not monitored?</td>
</tr>
</tbody>
</table>

**Recommendation 7: AC grade -** The AC will be used as well to provide a grade to the work provided by the primary contractor for windows and external glazed doors. During the AC, all openings inspected must have 100% of the check list as “Satisfactory” to provide a “Satisfactory” result. The grade highlights the importance of providing a satisfactory installation to mitigate the potential for water ingress. Where tenderers have a poor record of providing quality construction, they will receive...
It is recommended to implement the AC and the IQF for different activities during the construction process and the results can be used as quality indicators of the as built construction and used in subsequent tendering. This information can be used to provide an indication of the overall quality of future work.

| 6 | **Inspection effectiveness** | Research indicated that inspection of windows and glazed door installations is not viewed as a critically milestone for residential building construction, so it is often not carefully inspected. There is no appropriate timing to inspect the preparation stage (waterproofing system) to finally, the opening installation. They are not often checked independently. Resulting in little in-depth inspection of windows and poor-quality documentation provided by installers. When preventable water ingress occurs after high wind events, there is little chance to link failure modes to liable parties. How much % would you say Inspection effectiveness is Effective or Ineffective? | The Quality assurance process recommended is (Figure 1):

**Recommendation 5** - The Auditing checklist (AC) is designed to be completed during the inspection of windows or external glazed doors by superintendents. The AC has two objectives:
1. Is to check if the external openings have been installed adequately;
2. Is to place a degree of responsibility and liability on contractors and superintendents by emphasising the importance of windows and external glazed doors to the building envelope.

The AC is to be completed by the superintendent, accompanied by the supervisor responsible for the activity. The AC is to be completed in two stages of the construction phase; upon completion of the opening membrane and flashing system and on completion of the glazing installation. The number of windows and external glazed doors to be checked on site will be a minimum of 25%. These are to be identified by a unique identification tag or sticker to prevent double checks on the same openings. **Recommendation 4** - The primary contractor’s... |
responsibility is to complete the Installation quality form (IQF) and provide this to the superintendent. The IQF must include photographic documentation of each completed stage of the installation providing visual evidence to the superintendent that the openings were satisfactorily installed by the primary contractor according to the preparation and installation procedure. The number of windows and external glazed doors to be documented is a minimum of 25%. This will ensure sufficient variations of openings are documented. An indicator (tag or sticker) must be allocated once the opening has been documented. The IQF must be held by the primary contractor, then signed and approved together with the superintendent. The objective is to ensure that both parties are taking responsibility for the installation. The first objective of the IQF is to check if the external openings were installed satisfactorily. The second objective of the IQF is to raise liability and responsibility for contractors/builders in placing sufficient attention to windows and external glazed doors as a building element that is significantly important to the building envelope.

**Recommendation 6** - Once the AC and IQF have been completed, the superintendent is able to provide the Openings Certificate (OC) to the contractor. The AC and IQF together will have documented 50% of the openings of the project. The aim of the OC is similar to that of the AC and the IQF in that it documents responsibility for the information provided from both the contractor and
superintendent. In Form 16 in Qld, the AC, IQF and OC should be added in item “4 Description of component/s certified”. The first part of Form 16, “1 Indicate the type of certificate”, refers to “Aspects of building work”, Windows and external glazed doors satisfactorily installed.

<table>
<thead>
<tr>
<th>Child Nodes</th>
<th>Description</th>
<th>CPT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Product’s performance</td>
<td>Product’s performance receives influence, directly and independently by Opening Standards and Knowledge of Standards. How much % do you attribute as being High or Low to the Products performance?</td>
<td>Populate the CPT. Go to page 14.</td>
</tr>
<tr>
<td>2 Monitoring &amp; Inspection practice</td>
<td>Monitoring &amp; Inspection practice is influenced by Inspection effectiveness and Contractors performance. This variable has influences in the variable Quality regime.</td>
<td>Populate the CPT. Go to page 14.</td>
</tr>
<tr>
<td>3 Liability evidence</td>
<td>Liability evidence means the importance of responsibility assignment for issues related to water ingress. It is influenced directly and independently from “Preparation &amp; installation procedure” and “Monitoring &amp; inspection practice”.</td>
<td>Populate the CPT. Go to page 15.</td>
</tr>
<tr>
<td>5 Performance</td>
<td>Bayes nets usefulness - may be used in any walk of life where modelling an uncertain reality is involved (and hence probabilities are present). In this specific case, we are</td>
<td>Populate the CPT. Go to page 17.</td>
</tr>
</tbody>
</table>
using BN as a decision net, in order since to make intelligent, justifiable and quantifiable the current situation: Acceptable or Needs improvement and in making use of different scenarios, maximize the chances of an Acceptable outcome.
Conditional Probability Table (CPT)

Please provide:

1. Your roll in your organization:

2. Years of experience:

How to populate the Parent’s Nodes tables and CPT’s:

1. Supply the table or CPT with quantifiable values, based on your judgment/experience. These numbers will be used to run the Bayes net to see what the most likely future outcomes will be for the Life Cycle & Serviceability &Resilience.

2. In the CPT the sum MUST be 100%, e.g. 10% + 90%.

3. In **GREEN** best scenario and in **RED** worst scenario

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<td>1. Product performance</td>
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<td>2. Standards Knowledge &amp; training</td>
<td>2. Monitoring &amp; inspection practice</td>
</tr>
<tr>
<td>3. Construction documentation</td>
<td>3. Liability evidence</td>
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<td>5. Contract documentation</td>
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<td>6. Contractor’s performance</td>
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<td>7. Inspection effectiveness</td>
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#### 2. Standards Knowledge & training

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#### 3. Construction documentation

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#### 4. Inspection certificate document

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CPT's

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### 5. Performance

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Appendix D
Specification for the design phase

The following eight recommendations and specifications should be considered for the design phase.

1. Durability and compatible sealants;
2. Preparing the substrate;
3. Preparing the opening with appropriate membrane system;
4. Curing;
5. Head, side angle flashing, sub-sill and dam ends;
6. Flashings, drip moulds, storm moulds and trims;
7. Fasteners; and
8. Consideration for storm shutters.

1. **Durability and compatible sealants**

The quality of the sealant material can often determine the durability of the window or door installation over a period of time. Without durable materials, any construction project leaves itself open to short and long-term resilience issues. With this in mind, a poor-quality sealant has the potential to be the sole cause of leakage of water through windows and doors.

The recommendation is the use of a polyurethane-based sealant. This must be used with a compatible primer and the substrate must be free from dust, grease and loose material. This will ensure the cleanliness and increase durability and adhesive bonding between the sealant and substrate. The technical datasheet must be reviewed to ensure the overall performance of the waterproofing system, ensuring the approved primer and sealant is used for a watertight seal.

2. **Preparing the substrate**

The substrate specification must be detailed to include appropriate falls of no less than 15 degrees as suggested by the Australian Window Association (AWA) to ensure the free flow of water drainage toward the exterior of the structure, with the exception of residual water remaining due to surface tension. The design must also include a
perimeter water stop. Examples of designed substrates are provided in Figure 1 and Figure 2.

Figure 1 Example of physically cut rebate with appropriate fall of no less than 15 degrees (Source: AWA)

Figure 2 Example of precast sloping sill (Building Science Corporation)

3. *Preparing the opening with appropriate membrane system*
The membrane preparation must follow _AS 4654.2.2012 waterproofing membranes for external above ground use Part 2 Design and installation_, item 2.5.3.1. Whereby the preparation of the opening for fully-bonded or liquid-applied membranes shall result in the surface of the substrate being smooth, without protrusions, voids or formwork distortions, clean, dry, and free from dust and contamination. Design specifications must include a note stating liquid waterproofing system should extend to a minimum length of 200 mm beyond the opening and must be continuous.

4. **Curing**

The importance of curing components of a membrane system is highlighted in _AS 4654.2.2012, Section 2.6.2_. Manufacturer’s specifications must be consulted in relation to curing times of products. Further work should not be commenced until the membrane is cured. Premature covering of the membrane may prevent it from curing and may lead to its degradation. Due to varying curing times, intervals between applied membrane coatings must be considered. Design specifications must include a note highlighting the importance of curing when designing the structure and the necessity of the verification of the manufacturer’s datasheet for further details of the product.

5. **Head, side angle flashing, sub-sill and dam ends**

Appropriate designed sub-sill incorporating dam ends installed with head and side angle flashings to allow for the free flow of water without any obstructions.

6. **Flashings, drip moulds, storm moulds and trims**

Ensure an appropriate design of external flashings, drip moulds, storm moulds and trims. The importance of this is to be highlighted where surface runoff of water down the side of the structure can enter a window or door below. Design of these must be provided by the window and door manufacturer or architect.

7. **Fasteners**

Corrosion resistant fasteners must be used in accordance with engineer's specifications. Fasteners must be over and under-sealed to prevent moisture penetrating the opening and causing a failure of the membrane system. It is important
to provide a water-tight seal and allow for appropriate clearances for thermal expansion and free-flowing drainage.

8. **Consideration for storm shutters**

It is recommended to implement storm shutters for social housing projects in exposed cyclonic regions of Australia. Storm shutters will deflect flying debris and will reduce the quantity and pressure of wind-driven water being directed laterally toward the window. This will effectively reduce the likelihood of water ingress into the structure.
Appendix E
Preparation and installation procedure Stage 1 and Stage 2

Stage 1 – Openings preparation

1. Ensure all primer, waterproofing membrane and sealants are compatible before installation.

2. Prepare the substrate in accordance with AS 4654.2 and Australian Window Association to provide appropriate fall as per design (minimum 15 degrees as per AWA).

3. Ensure opening is clean, dry and free from debris before the application of any primer, membrane and sealant.

4. Provide a continuous water-stop throughout the perimeter of the opening (rebate and/or fixed angle).

5. Prepare opening with appropriate primer and waterproofing membrane system in accordance with AS 4654.2 (waterproofing membranes for external use). Multiple layers of membrane should be applied to ensure membrane is free from any holes or gaps that will allow water to penetrate the substrate. The waterproofing membrane must extend a minimum of 200 mm past the opening.

6. Components of membrane systems shall be cured as per manufacturer specifications. Intervals between applied membrane coatings should be taken into account due to varying curing times.

7. Install appropriate specified sub-sill, angled metal dam ends, head drip moulds and side angles that are required before the window frame is installed. In Appendix D, Figure 1 gives an example of a sub-sill incorporating metal dam ends. It should be noted that the head-sill, side angle and flashings must be directed to flow into the sub-sill without any obstructions. The back and end dams provide additional water-stop; this ensures that any inadvertent water entry via the frame is directed to flow out the front of the sub-sill due to the force of gravity.
8. Ensure approved primer and sealant is used for a water-tight seal. Ensure appropriate corrosion resistant fasteners are used as per specified wind load or engineer's specifications. Fasteners must be over and under-sealed to prevent moisture penetrating the opening. Ensure a water-tight seal and allow appropriate clearances for thermal expansion and free flowing drainage.

**Stage 2 – Openings installation**

1. Ensure the correct window and door specifications for the terrain category and height of the building.

2. Ensure weep holes are free from debris and are free flowing.

3. Install window and door and frame to the opening as per manufactures specifications.

4. Ensure appropriate specified flashings, mouldings and trims are installed to ensure the prevention of water ingress.

5. Storm shutters and awnings are to be installed as per manufactures specifications.
**Appendix F**

**AC - Auditing Checklist**

Use this checklist to help identify potential water ingress risks that may be caused by an insufficient waterproofing membrane and flashing system. This inspection is to be carried out after the opening has been prepared for the installation of the window or door.

<table>
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<th>MEMBRANE &amp; FLASHING SYSTEM</th>
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<tbody>
<tr>
<td>1. Adhesion of waterproofing membrane</td>
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<td></td>
</tr>
<tr>
<td>2. Waterproofing membrane termination</td>
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<td></td>
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<tr>
<td>3. Sealants, over sealing &amp; adhesion</td>
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<tr>
<td>4. Minimum falls in substrate</td>
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<td>5. Continuous water stop</td>
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<td>6. Sub head &amp; sub sill</td>
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<td>7. Dam ends</td>
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<td>8. Appropriate drip moulds &amp; flashing</td>
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<tr>
<td>9. Fasteners</td>
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</tbody>
</table>

**Further Information Provided Below:**

1. Check waterproofing is free from protrusions & voids. Check adhesion with sealants & substrate.
2. Check waterproofing membrane cover (minimum 180mm).
3. Check adhesion with waterproofing membrane and substrate. Ensure the over sealing of fasteners.
4. Check fall are in accordance with AS 4654.2.2012 (minimum 1:100).
5. Check water stop provided (Rebated and/or fixed metal angle).
6. Check sub sill up & down turn flashing heights and sealant are sufficient.
7. Ensure dam ends have sufficient sealing and allow for drainage.
8. Ensure the flow of water down he building is directed away from openings below.
9. Check the amount & fasteners used are appropriate for the region.

**Further Comments:**
4. Description of components certified
Clearly describe the extent of work covered by this certificate, e.g. all structural aspects of the steel roof beams.

6. Basis of certification
Detail the basis for giving the certificate and the extent to which tests, specifications, rules, standards, codes of practice and other publications, were relied upon.

8. Building certifier, competent person or QBCC licensee details
A competent person must be assessed as competent before carrying out the inspection.

7. Building certifier reference number and development approval number

Building certifier reference number
Development approval number

8. Building certifier, competent person or QBCC licensee details
A competent person must be assessed as competent before carrying out the inspection.

Name (in full)

Company name if applicable
Contact person

Phone no. (business hours)
Mobile no.
Fax no.

Email address

Postal address
Postcode

Licence class
Licence number

Date approval to inspect received from building certifier

9. Signature of building certifier, competent person or QBCC licensee
Note: A building certifier must sign this form for temporary swimming pool fencing under section 4 of Schedule 1 of QCC MP 3.4.

Signature
Date

The Building Act 1975 is administered by the Department of Housing and Public Works
Appendix H

**IQF – Installation quality form**

Use this checklist to help identify potential water ingress risks that may be caused by an insufficient waterproofing system. This inspection is to be carried out after the opening has been prepared for the installation of the window or door.

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<td>Project: ..................................................</td>
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<td>Building Contractor</td>
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<table>
<thead>
<tr>
<th>MEMBRANE &amp; FLASHING SYSTEM</th>
<th>YES</th>
<th>NO</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Compatible primer, membrane &amp; sealants</td>
<td>☐</td>
<td>☐</td>
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<td>2. Minimum falls in substrate</td>
<td>☐</td>
<td>☐</td>
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<td>3. Continuous water stop</td>
<td>☐</td>
<td>☐</td>
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<tr>
<td>4. Application of membrane system as per AS 4654.2</td>
<td>☐</td>
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<td>5. Curing of primer, membrane &amp; sealants</td>
<td>☐</td>
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<td>6. Sub head, side/jamb flashing &amp; sub sill</td>
<td>☐</td>
<td>☐</td>
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<td>7. Primed &amp; sealed fasteners &amp; dam ends</td>
<td>☐</td>
<td>☐</td>
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<td>8. Appropriate drip moulds</td>
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<td>9. Photo documentation of the membrane &amp; flashing system. Inspection and acceptance testing as per AS 4654.2</td>
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**Further information provided below:**

1. Ensure the compatibility of all products used on the substrate (Consult the material technical data sheet).
2. Ensure falls are in accordance with AS 4654.2 2012 (minimum 1:100).
3. Ensure a continuous water stop around all sides of the opening.
4. Ensure appropriate primer and membrane system installed on a clean surface. Multiple layers of membrane being without protrusions or voids. Membrane minimum cover 180mm.
5. Ensure curing or membrane and sealants as per manufactures specifications.
6. Ensure sub sill flashing heights and sealant are sufficient. Ensure an unobstructed flow of water from head to sill.
7. Ensure dam ends are incorporated with head and side flashings to ensure the unobstructed flow of water. Ensure sufficient priming & sealing and allow for drainage.
8. Ensure drip moulds are installed to direct the flow of water away from openings.
9. Provide photo documentation of the membrane & flashing system.

**Comments:**