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Bayesian Network revealing evidence-based strategies to enhance the performance of building envelope openings subject to wind-driven rain

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ABSTRACT

Severe storms and tropical cyclones bring destructive winds and heavy rain. While building structural performance has significantly improved in the last few decades due to higher regulatory requirements, some non-structural elements, such as windows, external doors, roof coverings and attachments such as guttering, fascia and eaves, remain subject to minor failure, causing loss of amenity and damage to structural building components over time. Enhancing the performance of buildings has become imperative to mitigating the impacts of tropical cyclones and storm events. Damage investigations conducted after tropical cyclones and severe storms have consistently revealed that windows and external glazed doors are affected by wind-driven rain, causing leakage into the cavity and interior of the building. This research study focuses on repeated water ingress through windows and external glazed doors. Wind-driven rain can penetrate undamaged windows and external doors, gaps around the window seals or doors, and waterproofing elements, thereby allowing water to enter buildings. A qualitative expert interview research approach was applied to identify several factors affecting the performance of openings (windows and external glazed doors). Subsequently, a Bayesian Network model was developed according to the determined parameters and expert workshops. The Bayesian Network scenario analysis enabled the researchers to identify the best combination of management interventions to enhance the performance of openings to water ingress from tropical cyclones and severe storms. The study findings provide evidence-based support for industry and government authorities to develop effective strategies for enhancing the performance of openings subject to wind-driven rain from tropical cyclones and severe storms.

1. Introduction

1.1. Tropical cyclones and severe storm events

Many countries have a long history of natural hazards. The devastating effects of severe storms and tropical cyclones, which are also called typhoons or hurricanes, underscore the vulnerability of some non-structural building elements in several building types in many nations' coastal areas. Damage costs associated with severe storm events globally exceed trillions of dollars each year and extreme weather-related disasters will increase due to climate change. These natural hazards still present challenges to overcome since they continue to significantly impact local communities, the construction industry, the insurance industry and governments. Strengthening the resilience and performance of buildings is critical for achieving a well-functioning society, particularly during and post extreme weather events. Water ingress through poorly designed and/or installed windows and external glazed doors in buildings remains an ongoing problem causing internal leakage and subsequent damage [1,2]. Water damage associated with each individual storm event may not be excessive but repeated serviceability damage has a cumulative cost impact and often causes more severe long-term issues with a building (e.g. mould, termite infestation, etc.). Results from a qualitative interview and a probabilistic approach from this study, identified and linked the factors that can potentially enhance the performance of openings that are

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Table 1
Research stages, methods, activities and objectives.

Research stage	Research methods	Research activities	Research activity objectives
First	Qualitative expert interview, thematic analysis research	Phone interviews and workshops with experts	To identify the factors affecting the performance of windows and external glazed doors and whether the performance is affected in events such as storms
Second	Bayesian Network design and scenario analysis	Conceptual model developed through consultation with experts	To synthesise previous knowledge into a system to provide a BN structure
		BN structure and operationalisation	To convert the conceptual model into a BN structure
		Parameter learning	To populate conditional probability tables (CPTs) and marginal probability tables (MDPs) to determine the current condition of the performance of openings
		Sensitivity analysis and scenario testing and analysis	To identify potential management interventions under different scenarios

Table 2
Results from the thematic analysis.

Category	Issues and factors raised by industry and government
Adequacy of Australian Standards and its adequate knowledge and training	• Despite a water penetration test under the Australian Standards, 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 [56] cause water ingress, moisture and building damage • Poor knowledge and level of skills of many designers, builders, installers and certifiers in waterproofing practices and openings installation
Installation quality assurance and control regime	• Installation work quality documentation is completed with limited information. Poor detailed design specifications in general for waterproofing • Contracts with limited scope specification or clear rules in relation to the contractor's responsibilitiesduring the construction process regarding qualitycontrol
Inspection regime	• 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 relatedwaterproofing statement required on the currentQueensland Form 16 • Missing supervision during installation and in the inspection process
Liability and recourse	• Self-regulation does not work • Building certifiers rely on Queensland Form 16 • Poor accreditation of installation workmanship • Builders should be more responsible for checking thequality of the building's construction • Builders and tradesmen 'cutting corners'

subject to the entrance of wind driven rain from tropical cyclones and severe storms in the North of Queensland.

Tropical cyclones produce strong winds, heavy rain fall, large waves and flooding. The heavy rainfall that accompanies tropical cyclones covers hundreds of square kilometres and may be experienced over many days [3]. They are divided into five categories. Based on the Australian Cyclone Severity Scale, Category 1 is a weaker tropical cyclone with gusts lower than 125 km/h and minimal house damage; while Category 5 are the strongest, with wind gusts exceeding 280 km/h. Tropical cyclones rated higher than category 3 are called severe tropical cyclones [4]. In the USA, the Saffir-Simpson wind scale classifies the intensity of hurricanes (which is the same natural phenomenon as a tropical cyclone) [5]. Severe storms produces gusts of 90 km/h or more with peak wind gusts exceeding 160 km/h in the most damaging storms [6]. According to Middlemann [7]; "severe storms are atmospheric disturbances generally described by strong and hazardous winds, commonly associated with heavy rain, snow, hail, ice and/or lightning and thunder". Ciavola and Coco [8] state that "a degree of confusion surrounding the use of the term storm is evident and surprisingly no overarching definition presently exists to assist in their identification". The greatest impacts of severe storms are generally the result of large hail, destructive winds and heavy rainfall and its paid insurance claims are greater than those for tropical cyclones, [7].

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 (AU$74.14 billion; 1 US$ = 1.4286 AU$ in May 2019), Hurricane Maria (2017) at US$30.7 billion (AU$43.85 billion), Hurricane Irma (2017) at US$25.6 billion (AU$36.57 billion), Hurricane Harvey (2017) at US$20.4 billion (AU$29.14 billion) and Hurricane Sandy (2012) at US$20.4 billion (AU$29.14 billion) [9]. Hurricane Andrew (1992) was a major influence for building code regarding wind design and was also one of the costliest to date in the USA. Construction that failed to meet the code due to poor enforcement and poor quality workmanship were responsible for approximately 25% of the insurance losses (about US$4 billion) (AU$5.71 billion) [10].

In Australia, the Insurance Council of Australia (ICA) estimates the loss value for natural hazards: tropical cyclones damage examples include Tropical Cyclone Debbie (2017), AU$1.7 billion (US$1.19 billion; 1 AU$ = 0.70 US$ in May 2019), Tropical Cyclone Yasi (2011), AU$1.4 billion (US$0.98 billion) and the Perth storms (2010), AU$1.3 billion (US$0.91 billion). In Australia, the greatest economic loss from a single tropical cyclone was caused by Cyclone Tracy in December 1974, which caused more than AU$5 billion (US$ 3.7 billion) in insured losses [11]. Up to 60% of the houses and buildings were destroyed, 65 lives were lost due to building failure, only 6% of the houses and buildings were classified as intact after the event. Cyclone Tracy had a significant influence on causing changes to the Australian Building Code (a performance-based regulatory system), in the development of the Australian Standards and in building regulations, as well as in a number of design manuals for housing; the storm impacted building construction throughout Australia from the 1980s, during which issues with structural elements were the main types of building failure. By that time, the performance of houses and small buildings was not fully structurally engineered compared to larger buildings [12]. Nowadays, structural elements failures are hardly mentioned during tropical cyclones investigations as a result of the introduction of new regulations that are providing higher performance against tropical cyclones and severe storms.

Building codes are used widely as a tool to regulate buildings' design and construction [13]. The USA's Multi-hazard Mitigation Council of the National Institute of Building Sciences verified, through a cost-benefit analysis, that every public US$1 (1.4286 AU$) spent on mitigation strategies, such as in particular exceeding codes, would save to individuals, states and communities an average of US$4 (5.71 AU$), with specific scenarios increasing that estimate to US$16 (22.86 AU$); thus proving that mitigation policies are a cost-effective strategy to deal with extreme events [14,15].

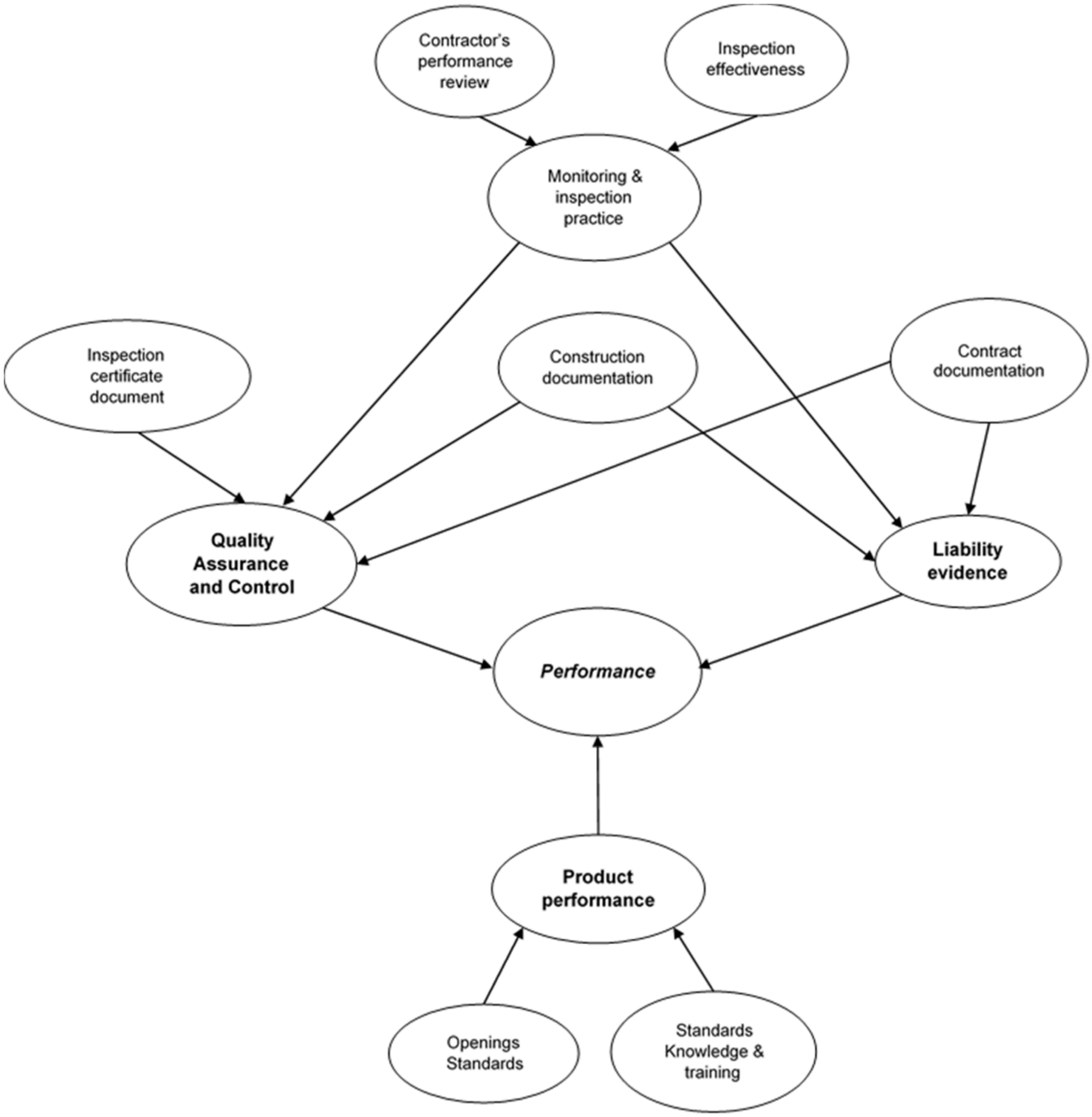

Fig. 1. Conceptual model of the factors influencing the performance of openings.

1.2. Non-structural elements

According to Flores-Colen and de Brito [16] buildings can fail due to faulty design, construction, maintenance, materials and use. Researchers have attempted to identify the stages in which general buildings' defects arise. Design issues contribute to 50%–60% of building defects [17,18] and 60% of these defects would have been preventable with a superior design [17]. Josephson and Hammarlund [19] examined building defects and found that 45% originated on site, 20% related to materials and machines, and 32% originated in the earlier phases of development (including design). As stated by Forcada et al. [20]; poor workmanship, poor supervision, limited skills or experience, and lack of motivation, have been highlighted in the literature as the immediate cause of building defects, when, in fact, the causes have been attributed to organisational practices. In line with Jingmond and Ågren [21] arguments, it is important to modify project management procedures to minimize the impact of building defects, and this is likely to be more effective than increased training or other changes in the construction site routine.

A solid structural system and building envelope (compound of the external doors, windows, soffits and roof systems, external wall coverings) performance are critical to prevent harm and minimising damage to a building and are especially critical for buildings exposed to high wind events. Solid design, materials, installation, maintenance and repair result in a favourable performance of a building. The performance of the building can be lowered due to a defect in any of these five elements; an improved design is considered the key to achieve a superior performance. A better design solution can compensate for some of the inadequacies of the building materials and/or its installation, by embedding some secondary waterproofing barriers. However, a poor design solution will still be inadequate for repelling water ingress, regardless of the quality of materials and installation workmanship. These findings are based on field investigations of houses hit by Hurricanes Hugo, Andrew, Iniki, Charley, Ivan, Katrina and others [22].

The Cyclone Testing Station (CTS) of James Cook University in Australia, conducted investigations of building damage from Tropical Cyclone Debbie (2017), Tropical Cyclone Yasi (2011), Tropical Cyclone Larry (2006) and Tropical Cyclone Olwyn (2015) and identified

Table 3
Model variables, states and their description used in constructing the conceptual model and subsequently BN structure.

Variable	Variable states	Description
1. Opening Standards	1.Adequate 2.Inadequate	The resistance to water penetration (under static wind load) test requirement for windows and external glazed doors (AS 2047–2014 and AS/NZS 4420.1)
2. Standards knowledge training	1.Adequate 2.Inadequate	Level of skills and knowledge in several scales (designers, builders and installers) in (design, installation and waterproofing practices)
3. Inspection certificate document	1.Adequate 2.Inadequate	Level of information provided on Form 16 (Qld document)
4. Construction documentation	1.Adequate 2.Inadequate	Level of design specification
5. Contract documentation	1.Adequate 2.Inadequate	Level of project scope in relation to the quality control during the construction
6. Inspection effectiveness	1.Effective 2.Ineffective	Level of inspection provided for windows and external glazed doors and its waterproofing
7. Contractor's performance review	1.Monitored 2.Not monitored	Record of the quality of construction provided by contractors
8. Product's performance	1.High 2.Low	Level of product performance based on Openings Standards and Standards knowledge & training
9. Monitoring & inspection practice	1.Effective 2.Ineffective	Level of Monitoring & inspection practice based on Inspection effectiveness and Contractor's performance review (relates to the inspection provided by certifiers using only Form 16 (Inspection effectiveness) and the quality of the construction provided by contractors (contractor's performance review)
10. Liability evidence	1.Satisfactory 2.Unsatisfactory	Level of liability evidence based on Construction documentation, Contract documentation and Monitoring & inspection effectiveness (liability assignment to the openings supply chain for issues related to water ingress from the openings)
11. Quality Assurance and Control	1.Adequate 2.Inadequate	Level of quality assurance and control based on Inspection certificate document, Construction documentation, Contract documentation and Monitoring & inspection practice
12. Performance	1.Acceptable 2.Needs improvement	Performance of windows and external doors rely in three pillars: Product's performance and its variables, Quality Assurance and Control and its variables and Liability evidence and its variables

Table 4
Prior probabilities of Parent nodes from parameter learning.

Parent nodes (variables)	Prior probabilities in each given state	
Opening Standards	Adequate (14.2%)	Inadequate (85.8%)
Standards knowledge and training	Adequate (33.3%)	Inadequate (66.7%)
Inspection certificate document	Adequate (33.8%)	Inadequate (66.3%)
Construction documentation	Adequate (38.7%)	Inadequate (61.3%)
Contract documentation	Adequate (38.3%)	Inadequate (61.7%)
Inspection effectiveness	Effective (30.4%)	Ineffective (69.6%)
Contractor's performance review	Monitored (31.7%)	Not monitored (68.3%)

a reduction in structural damage as a result of the improvement of the Building Code and the introduction of the Australian Standards in the early 1980s. 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 [23–26]. Minimum standards for the construction of buildings are provided on the National Construction Code (NCC), which is a performance-based code [27].

Wind and rain can 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. In addition, windows and external doors may be sucked out of the house if they have not been properly installed, due to fault or unsatisfactory fixing of the frames to the house structure [23–26]. The problem of the ingress of wind-driven rain is common and occurs through exterior doors, between the door and its frame, the frame and the wall as well as the threshold and the door; for windows, the failures were caused by inappropriate connection of the window frame to the wall, according to field investigations on houses hit by Hurricanes Hugo, Andrew, Iniki, Charley, Ivan, Katrina and others in the USA [10].

Specific mitigation measures for homeowners to prevent water intrusion include installing a plastic sheet sill extension on the inside face of the window [28] or the use of storm shutters on the exterior face of the window, though shutters will likely not significantly decrease the wind-driven rain demand on the glazed assembly [28,29]. In addition, a range of industry guidelines with information related to the selection of openings and installation [30,31] addressed to homeowners and the construction industry is available.

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 [22]. During the construction of the building, appropriate quality control (e.g., inspection by the contractor's personnel) and appropriate quality control (e.g., inspection by third parties) should be provided based on a specified, detailed design [22]. For quality control, the inspection of the windows and doors includes checking the attachment of the windows and doors to ensure there is enough wall-framing nails/screws [29]. Larger windows should receive more inspection than smaller ones. The inspection of roof coverings and windows is generally more important than for most wall coverings, since roofing and glazing are more susceptible to wind, creating considerable water damage when these elements fail [22].

An assessment in Canada of various window types exposed to wind and rain was undertaken by RDH Building Engineering Limited [32] to determine the water ingress paths in the building and the causal factors associated with the water ingress paths. The objective was to establish strategies for addressing water ingress as a performance issue, because previous studies identified that issues in fabrication, installation and maintenance were considered main contributors to moisture problems in buildings. Industry sectors participated in the project to help identify causal factors and as input for the validation of the results. It was found that the most positive opportunities related to the manufacturing sector and building design sector. Recommendations provided to the manufacturing sector addressed the need to increase quality control and, for the designers, the need to provide special attention to the window to wall interface, as those details had historically been a responsibility of the general contractor and the trades. Builders should focus more on the quality of installation, and greater trade training should be made available and possibly mandated. In Johnston and Reid [33]; research about buildings' defects advised that water ingress-related defects often manifest after the first major rain event's impacts, are observable to residents and usually require immediate action. However, concealed defects, usually behind a wall or other structure, are often difficult or even impossible to detect when undertaking a building audit post-construction.

Ginger [3] has suggested that water ingress into a building is associated with non-structural elements when heavy rain occurs with wind speeds exceeding 108 km/h. Laboratory research at the University of Florida has investigated the performance of residential window-wall systems with regards to water penetration rates based on

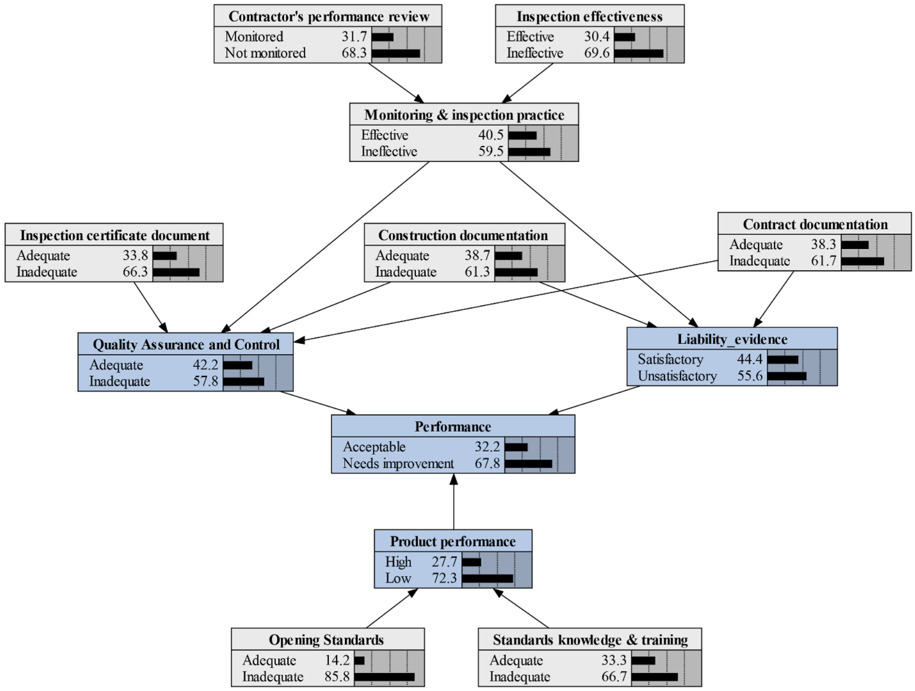

Fig. 2. Bayesian Network model - Current condition.

Table 5

Sensitivity of 'Performance' to influencing variables.

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

time-varying wind loads scenarios developed through wind tunnel experiments and has indicated that realistic driving-rain (under cyclonic winds and rain) scenarios should be implemented to accurately test the test water penetration resistance of the window-wall interface and this, may be a critical omission in the American Standard, since more than two-thirds of the window-wall specimens leaked at the interface [34]. The Australian water penetration resistance test is a method for determining the resistance to water penetration under static wind load (water sprayed uniformly and continuously [35]. Although this standard provides wind pressures and rainfall rates that are complied with, these pressures are not adequate to prevent water ingress during cyclonic events [28].

1.3. Research gap and objectives

The above review of the literature has critically summarised 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. Specifically, this study conducted a scientific investigation of the factors affecting the performance of windows and external glazed doors during tropical cyclones and severe storms allowing water ingress into the building which cause minor or moderate damage. This issue has been generating repeated repair and consequent cost impact. The target population to conduct the scientific investigation, was the openings supply chain, as the study also sought to unveil, understand and unpack interdependencies between the openings supply chain which have diverse interests to possibly identify best practices to enhance the performance of building envelope openings. As described, windows and external glazed doors will leak if not designed and installed in a quality manner. Elimination of all water ingress is not likely possible; however, unnecessary water ingress during severe events should be eliminated. The aim of this paper was to address this research gap. As part of the research approach, a qualitative interview data collection method was adopted to increase the theoretical and practical understanding of management practices with relevant industry groups and government. From that, a probabilistic modelling approach using a Bayesian Network (BN) was used to identify the most effective management practices that can increase the performance of openings. BN uses probability theory for quantifying uncertainty, which allows reasonably straightforward communication of model uncertainties to stakeholders and collaborators [36]; as a consequence for this research work BN can be used to support in better targeting and prioritising investments and decision making for building openings performance. 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.

The objectives of this research project are as follows:

1) To identify the key factors that affect 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 using a BN modelling approach;
3) Use BN 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,

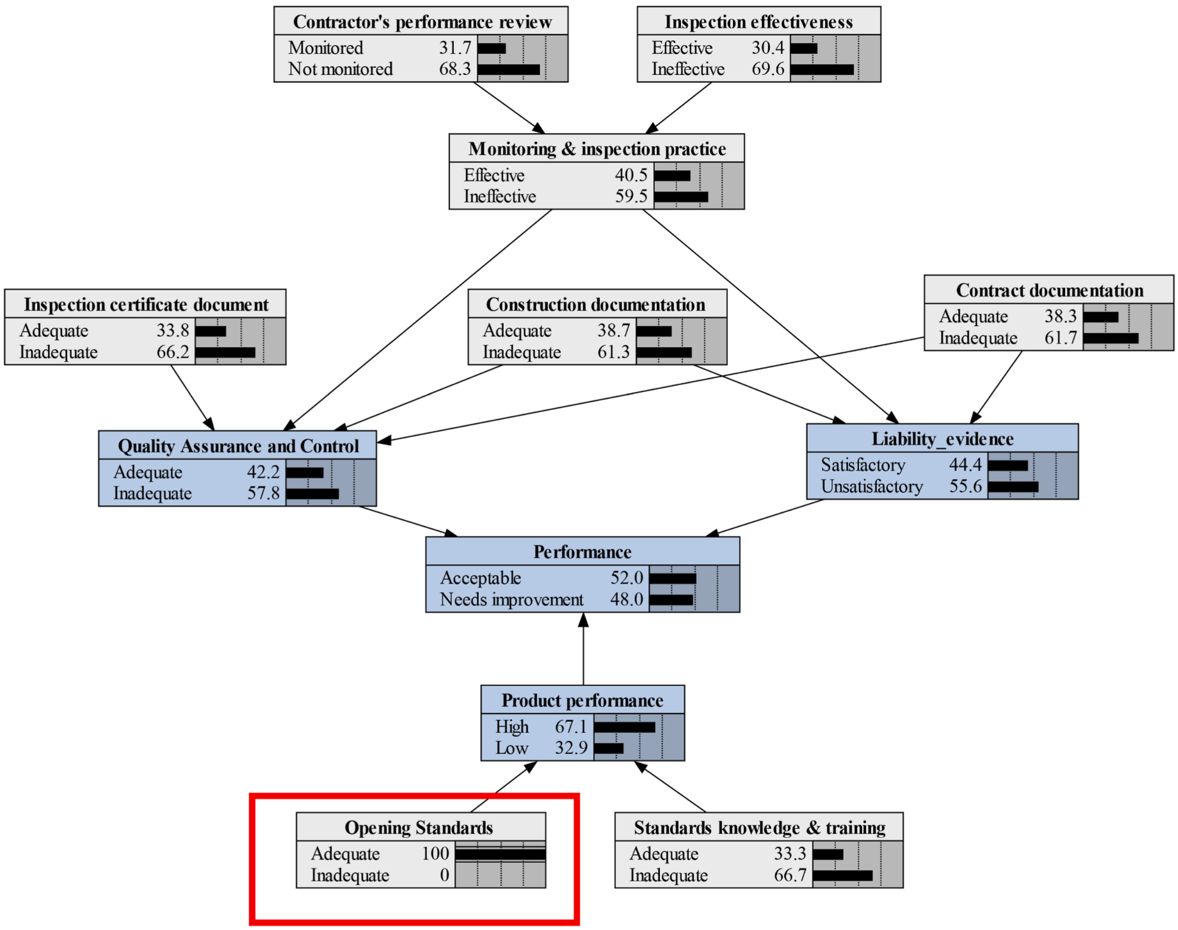

Fig. 3. Bayesian Network model - Openings performance level prediction when the 'Openings Standard' node is changed to "100% Adequate' (i.e. Scenario 1).

helping decision making with a straightforward communication and support for better targeting and prioritization of investments.

The paper is organised into five sections. Section 2 describes the research method and activities employed, including, qualitative data collection and analysis, followed by the Bayesian Network (BN) model development procedure. The study results are presented in Section 3 and a discussion in Section 4. Finally, Section 5 provides concluding remarks and the main contribution of this paper.

2. Methods and activities

The northern part of the state of Queensland in Australia was selected as the case study location, as storms and tropical cyclones (categories 1 and 2) occur anytime of the year and tropical cyclones (categories 3, 4 and 5) generally occur between November and April. A mixed-method research approach was adopted to achieve the research project objectives. The study started with a series of qualitative interviews with industry and Government participants who had knowledge and work experience with windows and external glazed doors in tropical cyclone-prone regions. Subsequently, a BN model was conceptualised and developed based on the qualitative research results and subsequent workshops. The BN was used to identify the most effective management practices that can increase the performance of openings. Table 1 summarises the main research stages, methods, activities and objectives undertaken in this research project.

2.1. Stage 1: qualitative data collection and analysis

The first research stage encompassed a qualitative research. A participatory modelling approach [37] was chosen and included workshops and phone interviews. It was anticipated that industry knowledge would help to identify the factors affecting the performance of windows and external glazed doors during tropical cyclones, 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. 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, as described in Section 1.2. While government agencies and major window manufacturers were actively targeted to participate in the study, a number of smaller builders, installers and inspectors were contacted after business directory searches and requested to participate in this study. The data collection ran from November 2017 to March 2018, reaching a total of 39 participants through both phone interviews (27) and workshops (12). This approach was applied to gain industry knowledge on current management practices in relation to the design, manufacturing, installation, certification and inspection processes of windows and doors in residential buildings. The phone interviews participants were industry practitioners including installers and builders, building certifiers, manufacturers, construction managers and architects based on the Gold Coast, Townsville and Cairns. These professionals were the most familiar with the issues and factors affecting the performance of openings during tropical cyclones and severe storms. Three workshops were facilitated, with the following participants and locations: 1) a large Brisbane-based aluminium windows

Table 6
Scenarios (1–11) with state and variable descriptions.

Scenarios	Variable	State
1	Opening standards	100% Adequate
2	Standards knowledge and training	100% Adequate
3	Construction documentation	100% Adequate
4	Inspection effectiveness	100% Adequate
5	Inspection certificate document	100% Adequate
6	Contract documentation	100% Effective
7	Contractor's performance review	100% Monitored
8	Opening standards + Standards knowledge and training + Construction documentation	100% Adequate +100% Adequate +100% Adequate
9	Opening standards + Standards knowledge and training	100% Adequate +100% Adequate
10	Opening standards + Construction documentation	100% Adequate +100% Adequate
11	Standards knowledge and training + Construction documentation	100% Adequate +100% Adequate

and doors company; 2) staff from the Queensland Department of Housing and Public Works (building and asset services) and from a larger building contractor in Townsville; and 3) James Cook University's CTS researchers, from Townsville. The 2-h workshop in Brisbane involved the themes of standards, documents, quality procedures, design, manufacturing and the installation process. The 3-h workshop in Townsville focused on understanding the design, construction and inspection stages. The 2-h workshop with the specialist CTS researchers was conducted on the afternoon of the same day as the workshop with Queensland Department of Housing and Public Works staff in Townsville and included an open discussion about window and waterproofing testing procedures and the adequacy of Australian Standards for achieving adequate serviceability standards. Following data collection, workshop transcriptions were analysed maintaining anonymity.

Structured questions were used to prompt discussion; questions focused on the following topics:

- Confirmation whether wind-driven rain through openings is an issue that causes minor or moderate damage and consequent repairs (i.e., internal linings);
- Identification of the causes of water penetration in building envelope, windows and doors; and
- Perceptions of the functions and effectiveness across the entire supply chain for openings, including industry knowledge and skills, installation process, waterproofing, related documents, inspection, products and level of design specification.

In the final part of phone interviews and workshops, open-ended questions were asked on the respondents' opinions, best-practice experiences and suggestions to prevent, minimize and inspect openings. When necessary, follow-up contacts were made with interviewees to clarify responses. Responses were recorded and later transcribed.

In order to comprehensively interpret the solicited data, thematic analysis [38,39] of the transcribed data was undertaken to extract findings in a systematic and thorough manner. 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. 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.

2.2. Stage 2: Bayesian Network model

2.2.1. Bayesian Networks: introduction

Bayesian Networks (BN) are probabilistic, graphical models representing a number of variables (nodes) and their conditional interdependencies that conceptualise a directed acyclic graphic (DAG). BN use probabilistic concepts to enable learning and reasoning process [40]. The nodes in a DAG are linked by arrows that represent the dependent relationship between them. The values of the nodes are defined in terms of different states. Parent nodes are the nodes that directly affect another node, and the ones affected are named child nodes. The strength of the relationships between linked nodes is defined in a Conditional Probability Tables (CPTs) that are attached to each node [36]. For nodes without parent nodes, instead of a CPT a marginal probability distribution (MPD) is linked to the node and also represented in a discretised tabular format. Parameter learning is the process of using data (from empirical datasets or expert judgment) to learn the distributions of the CPTs and MDPs [41]. The behaviour of the model can then be tested by applying different scenarios. The effect of the scenario can be examined by its effect on other nodes through the propagation of probabilities as BN rely on Bayes' theorem to propagate information between nodes [42]. Chen and Pollino [36] have stated that the rapid propagation of information through the BN is one of its major advantages; as a consequence, they can be used to quickly assess how decisions and observed conditions at one node will affect the entire system. BN enable reasoning under uncertainty, which can be critical for decision-making [40].

Bayesian Networks can provide adequate accuracy also with missing or few data as long as the model structure is well defined [43]. Also, different sources of data can be integrated, or where numerical data are not available, probabilities based on expert knowledge can be provided to the model [43]. Bayesian Networks also represent a suitable decision support tool for decision-makers, as the costs and risks associated with different management strategies can easily be assessed [43]. The causal graphic structure representation allows for understanding by stakeholders and non-technical users [36]. BNs however also have a few limitations. Morgan et al. [44] have stated that it may be challenging to convert experts' opinions into probability distributions, especially when dealing with large CPTs. As a consequence, it is imperative to keep the BN simple in order to restrict the number of conditioning factors, when relying mainly on expert input. However, Charniak [45] considers experts' opinions as often reliable. Finally, feedback loops are not easily supported in BNs [46].

Real-life problems can be addressed by BNs, and for this reason, they have become widely accepted as intuitively appealing probabilistic models [47]. They have established themselves in a wide variety of domains, including ecology, engineering and medicine [48–50]. In engineering, domains where BNs have been used vary from hurricane damage [51] to coastal hazards [52], extreme events impacts on water systems [53], road accidents [49], safety risk analysis in construction projects [54], evaluation of building design [48] and of best policies for increased retrofitting uptake of public buildings [55].

2.2.2. Bayesian Network: model development

The construction of a BN involves the following three steps:

1. Conceptual model development: identification of the variables (nodes) and its states related to the research study;
2. Conversion of the conceptual model into a BN DAG structure; and
3. Parameter learning, based on the BN structure, completed through either, or a combination of, historical data, expert data, or outputs of other models.

Once developed and validated based on expert judgment, a BN can be used for the following purposes: sensitivity analysis to identify the

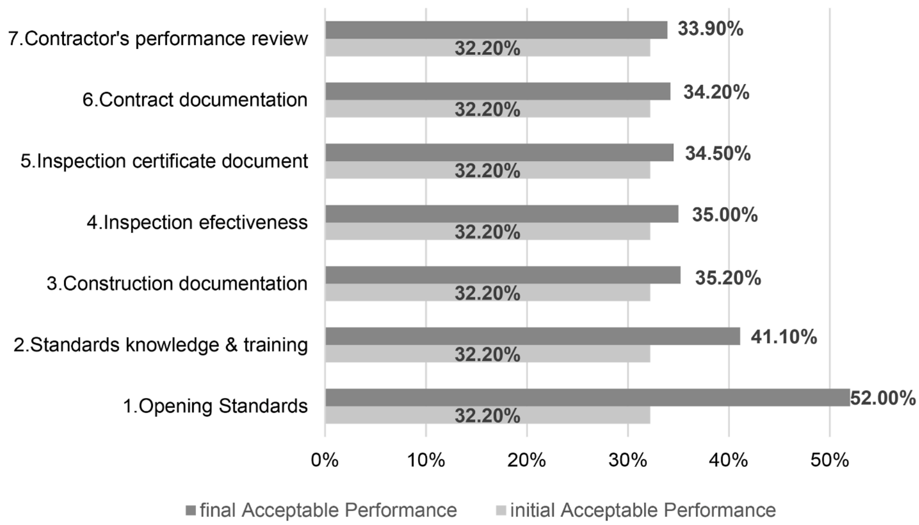

Fig. 4. Calculated probability of "Acceptable" Performance for scenarios 1 to 7 (only individual BN nodes being changed) compared to initial prior probability for Acceptable Performance.

most impactful inputs for the target node; and scenarios testing and analysis based on sensitivity analysis [41,49].

The first activity for this research study under the BN stage was to synthesise the existing knowledge into a conceptual model of the system. The main purpose was to identify the most important system components and their connections, providing the basis of the BN structure. As a first step, all the main factors affecting the performance of openings were listed, followed by the identification and definition of each input variable and the definition of the states for each variable (node). Two states were defined per node, which are considered relatively small and therefore easier to populate. The conceptual model was completed by the research team following an extensive review of the existing literature and consultation with experts.

The conceptual model was subsequently converted into a BN network structure created in Netica (by Norsys Software Corp. – Bayes Net Software). Once the BN network was formed, parameter learning was conducted. The parameter learning was conducted through a workshop, phone interviews and a face-to-face meeting. A total of ten experts from industry and governments in different fields attended the workshop in Brisbane, Australia. Five experts from government and industry participated through follow-up phone interviews, and a face-to-face meeting with one industry expert was conducted, thus reaching a total of 16 participants in this stage of the research. 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. During the elicitation process, questions such as, "*What is the probability that variable **A** (e.g., liability evidence) takes the state **X** (e.g., satisfactory) given information **Y** (e.g., the monitoring and inspection practice is effective, the contract documentation is adequate, and the construction documentation is adequate)?*", based on the BN structure model were asked. A sensitivity analysis was then conducted to identify which factors have more important policy or management values in analysing the openings' performance. Then, various scenarios were tested; BNs provide a simple way of testing scenario, by updating 'new evidence' into one of the two states for one or more input nodes, hence updating the entire network and consequently, the target node with a new outcome prediction probability.

3. Results

3.1. Qualitative thematic analysis

Wind and rainwater ingress through openings were frequently mentioned during the investigation stage, confirming the existence of failure, which occurs during tropical cyclones and severe storms, acknowledged as a significant cause of claims and repairs in northern Queensland. Four salient themes emerged from the thematic analysis, which was based on 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. Table 2 presents the issues and factors raised by industry and government that have been used to understand what currently affects the performance of openings from a holistic view. The findings revealed some key recommendations to improve the current practices based on the participants' collaboration as well as the authors' initiative. These nine recommendations related to the following critical aspects: (1) construction documentation – drawings and specifications; (2) contract documentation; (3) preparation and installation procedure; (4) auditing check list; (5) installation quality form; (6) openings certificate; (7) auditing check grading; (8) design standards; and (9) knowledge transfer and education. These practical recommendations are detailed in a publicly available industry report completed by the authors [57].

3.1.1. 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. These two issues are further analysed below.

(1) Adequacy of Australian Standards - All windows and external glazed doors must satisfy performance criteria according to *AS 2047 – 2014 Windows and external glazed doors in buildings* [58] and satisfy the water penetration test *AS/NZS 4420.1:2016 Windows and external glazed, timber and composite doors - Method*

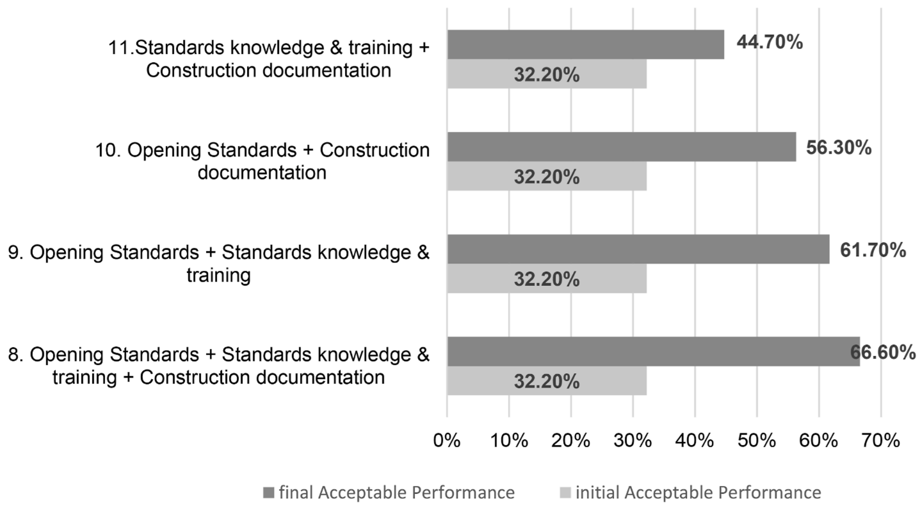

Fig. 5. Probability of "Acceptable" Performance for scenarios 8 to 11 (i.e. concurrent change to 2 or more BN nodes).

of test, Part 1: Test sequence, sampling and test methods and *AS/NZS 4284:2008 Testing of building facades* [59,60]. 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 [61]. Even though the interviewees were aware of the existence of the standards, it was clear that there seem to be shortfalls. The water penetration resistance test does not provide adequate pressure (under static wind load) to prevent water ingress during cyclonic events [28,62]. This standard should be strengthened against wind-driven rain damage. Ginger [3] mentioned that a higher test pressure, using a dynamic pressure, similar to a tropical cyclone could improve the performance of openings.

(2) Adequate knowledge and training - 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* [56]. 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 [33]. Tyrell [63] 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 learning and communication. For example, the Australian Window Association (AWA) provides free online training through 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, the primary users are professionals involved in the construction of buildings, including architects, builders, engineers, and certifiers [33].

3.1.2. Installation quality assurance and control regime

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 [64]. Smith [61] 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 will enforce a higher set of expectations from contractors. Determining responsibilities through clear legal contract terms and conditions could ensure that all stakeholders undertake their duties carefully.

3.1.3. Inspection regime

The inspection regime category focused on the challenges with windows inspections. As the data collection only involved participants from Queensland, *Form 16* was mentioned as the document used to certify window and door installation. *Form 16* is an inspection certificate which certifies that an aspect of building work complies with the approved plans and relevant standards and codes [65]. The Building Act 1975 determines that the certificate of inspection must state in detail the extent to which the inspector has, in carrying out the inspection, relied on tests, specifications, rules, standards, and codes of practice [66]. This information is supposed to be followed by inspectors who however have often failed to do so; interviewees mentioned for instance that: '*no inspection is provided, relying on Form 16,*' or '*forms are issued saying that things are okay when they have not inspected*

Table 7
Scenarios ranking.

Ranking	Scenarios		Final acceptable performance	Improvement from default performance
1	8	Opening standards + Standards knowledge and training + Construction documentation	66.6%	+106.83%
2	9	Opening standards + Standards knowledge and training	61.7%	+91.61%
3	10	Opening standards + Construction documentation	56.3%	+74.84%
4	1	Opening standards	52.0%	+61.49%
5	11	Standards knowledge and training + Construction documentation	44.7%	+38.82%
6	2	Standards knowledge and training	41.1%	+27.64%
7	3	Construction documentation	35.2%	+9.32%
8	4	Inspection effectiveness	35.0%	+8.70%
9	5	Inspection certificate document	34.5%	+7.14%
10	6	Contract documentation	34.2%	+6.21%
11	7	Contractor's performance review	33.9%	+5.28%

themselves basically because it is not their role to check windows and doors'. 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*'.

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 [67]. 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 [68].

3.1.4. Liability and recourse

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 main 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 all identified as factors contributing to defective building work.

This category aims to promote the importance of responsibility assignment. 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.

3.2. Bayesian Network outputs

The qualitative results provided the basis for the conceptual model (Fig. 1), that in turn formed the basis for the BN structure. The variables included in the conceptual model were associated with different categories, such as standards, training, policies and management and liability. More specifically, the performance of openings relies on three pillars according to the model:

(1) 'Product performance', composed by the variables labelled Openings standards and Standards knowledge & training;
(2) 'Quality Assurance and Control' which refers to the level of information required on the openings inspection certificate document, Form 16 (variable: Inspection certificate document); to the level of design specification (variable: Construction documentation); to the level of detail on the project scope in relation to the quality control during the construction (variable: Contract documentation) and to Monitoring & inspection practice which refers to the inspection provided by certifiers, recorded as inefficient or non-existent, (variable: Inspection effectiveness) and the quality of construction provided by contractors (variable: Contractor's performance review)
(3) 'Liability evidence', which refers to the responsibility assignment to the openings supply chain for issues related to water ingress from the openings (composed by the variables Construction documentation, Contract documentation and Monitoring and inspection practice.

Table 3 lists the variables affecting the openings performance, which were determined during the conceptual model development stage of the research. Assigning two states to each variable was the first step towards converting the conceptual model into a BN model. The conversion was facilitated by the fact that the conceptual model was already a DAG, i.e. no feedback loops (not supported by BN) were identified and conceptualised.

3.2.1. Parameter learning - current condition

The parameter learning provided the following prior probabilities for each state of each parent node which reflect the expert input provided by the stakeholders during the workshop, phone interviews, and a face-to-face meeting (Table 4).

The prior probabilities were included in the BN model (Fig. 2) and the Bayes' theorem of probability theory, using the software Netica, propagate the information between nodes providing 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 (see Section 3.1 for the results of the qualitative thematic analysis).

3.2.2. Sensitivity analysis

To evaluate the quantitative performance of the model, a sensitivity analysis was performed, as described in Section 2.2, to identify the variables that are most influential on openings' Performance. As displayed in Table 5, it can be seen that 'Product performance' (Mutual Information = 0.16), based on the influence of Openings standards and Standards knowledge and training, exerts the greatest influence on the model when considering Performance, followed by 'Quality Assurance and Control' (Mutual Information = 0.03) influenced by Inspection certificate document, Construction documentation, Contract documentation and Monitoring and inspection practice, and 'Opening standards' (Mutual Information = 0.02), meaning how applicable the serviceability test requirement for windows and external glazed doors is for characterising storms and cyclonic events.

3.2.3. Scenario analysis

The constructed BN model investigated all possible management interventions that can lead to increasing the performance of openings by using scenario analysis. BNs allow an assessment of the changes in outcome probabilities, associated with changes in intervention actions (in the states parameters). By inputting a 100% for a given state for a variable (intervention action), the impacts on the target node (and other nodes) can be predicted (Fig. 3). For the scenario analysis, initially, the seven parent nodes were tested individually, creating seven scenarios (1–7; Table 6) to predict the impact on the target node Performance. Based on the top three results from scenarios 1 to 7, four other scenarios (8–11) were tested (Table 6).

In Netica, the BN model was set to 100% for one of the two states (see Table 3 for the variables states), according to each scenario proposed in Table 6. Fig. 3 illustrates the variable "Openings Standards" inputting the probability 100% to the state "Adequate", hypothetically implementing a resistance water penetration test for windows and external glazed doors with a heightened performance to better characterise the dynamic pressure fluctuations that realistically occur with storms and cyclonic events. A change in this node/state increases the Performance from an 'Acceptable' 32.2% (i.e. current condition to business as usual) to 52% (i.e. an increase of 19.8%).

As another example, for the node Standards knowledge and training, if hypothetically the skills and qualifications issues could be significantly improved (i.e. inputting the probability to 100% to the state Adequate) the target node Performance changes to 'Acceptable' 41.10%. For scenarios 2 to 11, the same exercise described above was conducted in order to verify the new probability on the target node Performance. Fig. 4 outlines the results for the first 7 scenarios (Table 6).

The BN node that derived the second highest 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 highest change 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.

The top three performance improvement strategies shown in Fig. 4 were then used to create four new combined scenarios (i.e. Scenarios 8 to 11, Table 6). The results of those scenarios are shown in Fig. 5. Scenario 8 concurrently, enhanced the '*Opening standards*', '*Standards knowledge and training*' and '*Construction documentation*' BN nodes and led to an increase in the *Performance* level from the initial Acceptable 32.2%–66.6%. Scenario 9 was the second best with concurrent changes to the BN nodes '*Opening standards*' and '*Standards knowledge and training*' improved the *Performance* to 61.7% acceptable. The overall ranking of the 11 examined individual and combined scenarios is presented in Table 7.

4. Discussion

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 are still high and have not been sufficiently actioned since they do not lead to structural failure and loss of life. Providing a higher performance for building envelope openings to wind-driven rainwater ingress is important for reducing the repeated occurrence of water-related damage in regions subject to tropical storms. However, deriving an effective strategy to improve the performance of openings is challenging, as there are 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 the researchers to identify workable strategic pathways to improve the performance of openings to water ingress during tropical cyclones and severe storms. Specifically, the derived BN that was formulated from this novel method aided the researchers to explore the interrelationship between causal factors in the network, in order to reveal what combination of factors (i.e. scenarios) would be the most effective to derive the desired improvements in the openings performance during tropical cyclones and severe storms.

5. Conclusions, recommendations and future research directions

5.1. Study conclusions

Under the current conditions, it is most likely that windows and external glazed doors will continue failing in terms of serviceability standards during periods of tropical cyclones and severe storms. Due to the lack of empirical data on failure rates, qualitative research was conducted with the objective of investigate the factors and understanding the reasons for windows and external glazed doors fails during tropical cyclones and severe storms. A Bayesian Network model was developed relying on the factors raised in the qualitative phase and was populated by industry experts. The main conclusion of this research is that openings performance would be best enhanced when a combination of management strategies was implemented. Due to the high rates of serviceability failure in regions prone to extreme storm events and cyclones, a failure to address the herein recommended management strategies will likely result in a high repair cost over a building's life cycle due to repeated water ingress. While structural failures during storms and cyclones are now less prevalent in recent years due to more stringent building codes, non-structural elements continue to suffer serviceability failures, ultimately increasing insurance premiums. In certain tropical regions, severe storms and cyclones are common and might become stronger and more frequent due to changing climate; enhanced performance of non-structural elements in such regions should be made a priority.

5.2. Study recommendations for industry

Windows and external glazed doors must be properly built and inspected for quality prior to handover. The most effective management intervention, that can increase the performance of openings subject to wind-driven rain from tropical cyclones and severe storms were identified as: *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). Improving the three practices together, will substantially reduce the likelihood that windows and door openings will experience serviceability failure during their lifespans. The Australian Government should take the lead at a national level in establishing an action plan and performance goals along with incentives for the construction industry to adopt and implement them. The Australian Government has an emergency response in place, coordinating and paying for post-disaster rebuilding. The government should now consider providing incentives to the construction industry in the prevention (e.g. better qualification and education with a strong focus on the specific standards) and control measures instead of reactively providing disaster financial aid after catastrophic events. The improved process established in the 1980s after Tropical Cyclone Tracy that devastated Darwin provided a significant contribution to the Australian Building Code with a focus on structural elements, as previously discussed. A focus on the non-structural elements such as windows and external glazed doors should now be considered based on the herein research results. The herein suggested changes should be incorporated into the construction industry and serviceability standards, and when enforced, will likely change for the better the way houses and buildings are constructed.

5.3. Future research directions

This study has uncovered that building serviceability issues are under-researched. Future research should focus on the building envelope's non-structural elements that are exposed to a range of natural hazards (i.e. storms, fires, floods, etc.) in order to enhance the performance of the building as a whole. As demonstrated herein, scenario analysis technique such as BN can provide evidence-based results that can help decision-makers to improve practices, policies, standards, enforcement, and liability regimes even limited numerical data is available. Future work could extend the BN model to consider, for instance climate change impacts. A cost benefit analysis would be highly beneficial to justify the study conclusions as it was not possible due to the limited economic data access.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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