Protocols for Mitigating Cladding Risk Support Package

D.04 – Risk Benefits

Version 2

Date: 13 March 2024

Aboriginal acknowledgement

Cladding Safety Victoria respectfully acknowledges the Traditional Owners and custodians of the land and water upon which we rely. We pay our respects to their Elders past, present and emerging. We recognise and value the ongoing contribution of Aboriginal people and communities to Victorian life. We embrace the spirit of reconciliation, working towards equality of outcomes and an equal voice.

Application of Minister's Guideline 15

These documents contain information, advice and support issued by CSV pursuant to Minister's Guideline 15 - Remediation Work Proposals for Mitigating Cladding Risk for Buildings Containing Combustible External Cladding. Municipal building surveyors and private building surveyors must have regard to the information, advice and support contained in these documents when fulfilling their functions under the Act and the Regulations in connection with Combustible External Cladding on buildings:

a) which are classified as Class 2 or Class 3 by the National Construction Code or contain any component which is classified as Class 2 or Class 3;

b) for which the work for the construction of the building was completed or an occupancy permit or certificate of final inspection was issued before 1 February 2021; and

c) which have Combustible External Cladding.

For the purposes of MG-15, Combustible External Cladding means:

a) aluminium composite panels (ACP) with a polymer core which is installed as external cladding, lining or attachments as part of an external wall system; and

b) expanded polystyrene (EPS) products used in an external insulation and finish (rendered) wall system.

Disclaimer

These documents have been prepared by experts across fire engineering, fire safety, building surveying and architectural fields. These documents demonstrate CSV's methodology for developing Remediation Work Proposals which are intended to address risks associated with Combustible External Cladding on Class 2 and Class 3 buildings in Victoria. These technical documents are complex and should only be applied by persons who understand how the entire series might apply to any particular building. Apartment owners may wish to contact CSV or their Municipal Building Surveyor to discuss how these principles have been or will be applied to their building.

CSV reserves the right to modify the content of these documents as may be reasonably necessary. Please ensure that you are using the most up to date version of these documents.

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Abbreviations

Term	Meaning
2H	2 Horizontally connected
2V	2 Vertically connected
ACP-PE	Aluminium Composite Panel with a Polyethylene core
ASE	Alarm Signalling Equipment
BN	Bayesian Network
BOWS	Building Occupant Warning System
CBD	Central Business District
CPD	Conditional Probability Distribution
CRMF	Cladding Risk Mitigation Framework
CSV	Cladding Safety Victoria
dB	decibel/s
EPS	Expanded Polystyrene
FDS	Fire Dynamics Simulator
MMHC	Maximum Minimum Hill Climbing
pgmpy	Python Library for Probabilistic Graphical models
PMCR	Protocols for Mitigating Cladding Risk
SOU	Sole Occupancy Unit as defined in the National Construction Code

1 Introduction

Combustible cladding on the building facade changes the compartmentation design, increasing risk to buildings by providing additional fuel loads and pathways to spread fire between compartments.

This document will provide insight into the method applied to determine the risk benefits of rectification solutions (i.e., interventions) used in the Protocols for Mitigating Cladding Risk (PMCR).

This document refers to the highest risk combustible cladding types, aluminium composite panels with a polyethylene core (ACP-PE) and expanded polystyrene (EPS). There are 15 interventions associated with the fire hazards and consequences as presented in the threat barrier analysis diagram (Figure 1).

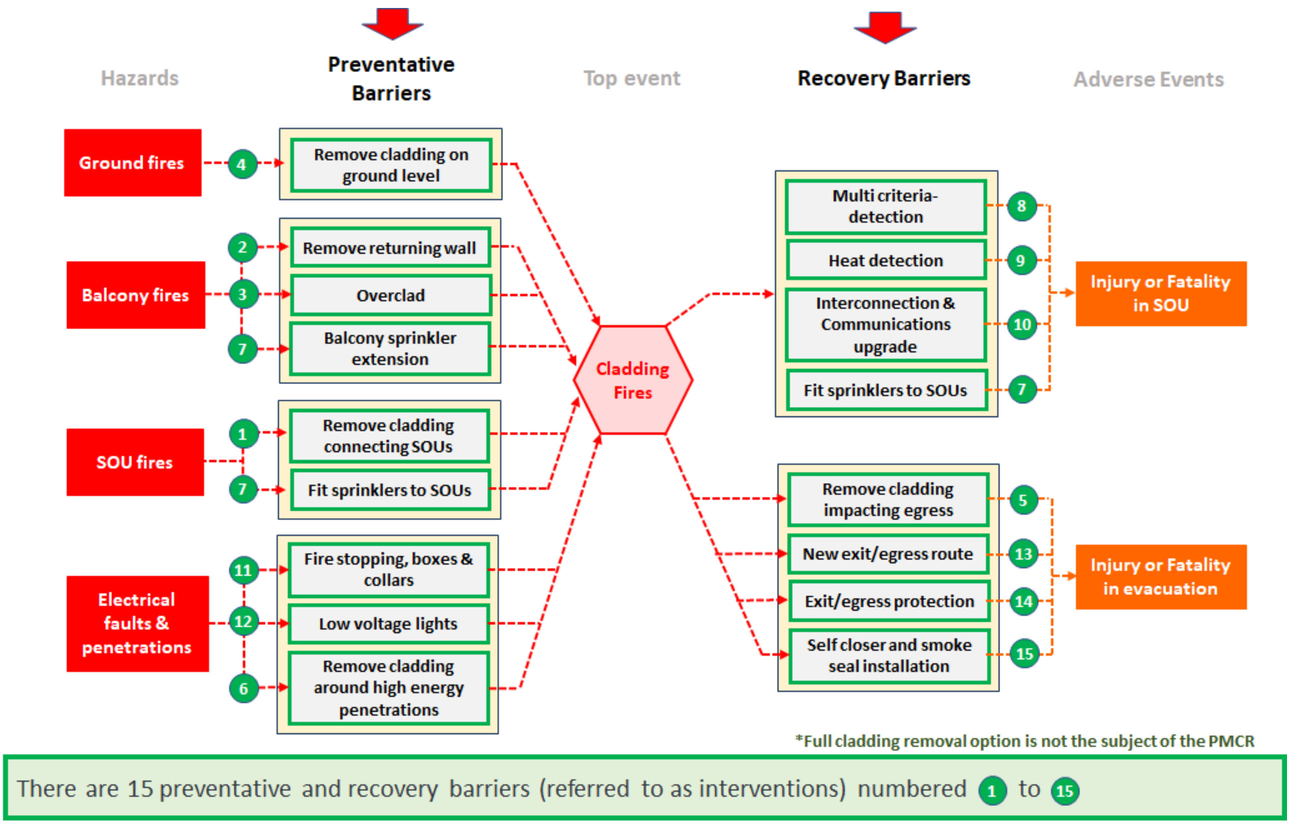


Figure 1: Threat barrier analysis

This document forms a set of five support packages that provide supporting evidence behind the design of the PMCR. This document attempts to answer the following research question technically:

Research Question 1	To determine when an acceptable risk reduction outcome has been reached via the implementation of one or several applied intervention solution(s).

2 Method to determine risk benefits of interventions in the PMCR

The "Cladding Risk Mitigation Framework" sets out the risk-based approach for buildings with combustible external cladding (referred to as "target building" hereafter) in the elevated risk rating category to:

"Undertake targeted removal of Combustible External Cladding either alone or in combination with the application of alternative, cost effective risk reduction interventions to achieve, at a minimum, an Acceptable Cladding Risk rating without, where possible, the need to remove all Combustible External Cladding."

The "Acceptable Cladding Risk" is defined as either achieving "Low Cladding Risk" or similar to/less than the fire risk of the same building if that building has no combustible cladding.

The "Low Cladding Risk" rating is defined as the risk of fire spread across the combustible external cladding of ≤ 1 SOUs for non-sprinkler-protected SOUs or ≤ 2 SOUs for sprinkler-protected SOUs.

The method in this section has been developed as a comparative tool that benchmarks the target building with proposed interventions against the "Acceptable Cladding Risk" criteria set out in the "Cladding Risk Mitigation Framework". A probabilistic approach has been used to develop this comparative tool following PD 7974-7:2019 [1].

The "IF-SCAN method" establishes a triaging approach to identify different 'Elevated' rated cladding clusters (referred to as "cluster" hereafter), which consists of two or three SOUs connected via combustible external cladding. In this document, the target building will be assessed on a cluster basis.

$$\sum_{k \in K} p(k)L(k)$$

While the increasing power of computation has enabled risk analysis, the limited computational capability with available fire simulations (including Fire Dynamics Simulation) is a challenge to be used directly in fire risk analysis. One solution to overcome this limitation is to use models such as Bayesian Network (BN). A BN approach for building fire simulation was proposed by Cheng et al [2] and has been frequently cited. Other variants of network-based probabilistic methods have also been explored by Kacem et al [3]. BN has also been used where transitions are between building fire, occupant and rescue services' states (such as "Human awake", “In house firefighting” and “Fire growth/flashover”) and where these states are not spatially explicit [4,5]. The spatially explicit (fire propagation focused) and the state-of-entities focussed work is relevant in our context. The parameterisation/validation of a BN is a challenging task and requires assimilation of subject matter expertise, lab/field experimental data, modelling, and data assimilation. Naval vessel fire spread probabilities [3] have complex physical and time dependencies and their parameterisation involved data analysis, modelling and physical experimentation. Previous work [4-7] utilise data, expert elicitation, and fire science findings in various combinations in order to parameterise their BN models. Based on this review, BN approaches will be utilised to yield a computational method which is sufficiently accurate for computing building fire fatality risk under different interventions and relative to cladding fire risks.

With the aim of evaluating the risk-benefit of applying interventions compared to the benchmark set out in the Cladding Risk Mitigation Framework, the method is applied to each cluster typology, which could be a cluster of two non-sprinkler protected SOUs or three sprinkler-protected SOUs. The cluster typology forms a library that allows the end-users to apply the pre-calculated value to the target cluster directly. The flow diagram of applying this method for each cluster typology is presented in Figure 2.

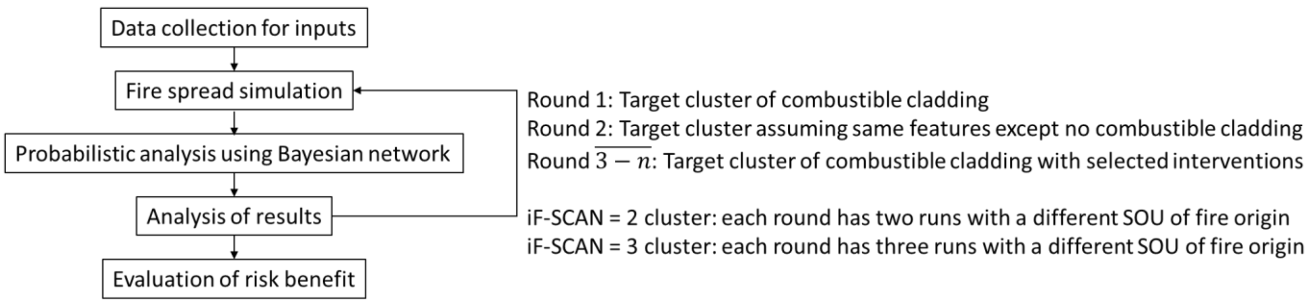


Figure 2: Flow diagram of risk evaluation method (with n being the number of sets of interventions considered for the cluster to achieve the required risk reduction)

The expected risk for an SOU can be computed relative to a finite set of K by way of the simple formula:

$$\sum_{k\in K} r(k)L(k) = \sum_{k\in K} f(k)p(k)L(k)$$

in which *r(k)* is the rate of occurrence of outcome *k* per unit time. The rate of occurrence r(k) is decomposed into an ignition rate component $f(k)$ and a conditional probability $p(k)$ of escalation of this ignition into outcome *k*; and *L(k)* is the loss associated with the set *k* covering an enumeration of ignition possibilities and outcomes of these ignitions for the cluster.

The expected risk for a cluster is the sum of the expected risk of individual SOUs in the cluster. For a defined cluster, $f(k)$ and *L(k)* are fixed. The presence of either combustible cladding or interventions changes the conditional $p(k)$ which is determined from BN. The cladding risk premium of a cluster is, then, calculated as follows:

$$C_R^C = \frac{\sum_{i=1}^{N}\sum_{j=1}^{N} f_{ij}p_{ij}L_{ij}\big|_{Round\ 1}}{\sum_{i=1}^{N}\sum_{j=1}^{N} f_{ij}p_{ij}L_{ij}\big|_{Round\ 2}} - 1 = \frac{\sum_{i=1}^{N}\sum_{j=1}^{N} p_{ij}\big|_{Round\ 1}}{\sum_{i=1}^{N}\sum_{j=1}^{N} p_{ij}\big|_{Round\ 2}} - 1$$

in which N is the number of SOUs in the cluster while i and j are the indices for SOU j in the case that fire ignition initiated in SOU i. Round 1 is with the cluster as is with combustible cladding, and Round 2 is the benchmark as defined in the Cladding Risk Mitigation Framework (i.e. the same cluster as if no combustible cladding is presented).

The expected risk-benefit index of the selected set of interventions for the cluster and each SOU is calculated as:

$$B_R^C = \frac{\sum_{i=1}^{N}\sum_{j=1}^{N} p_{ij}\big|_{Round\ \overline{3-n}}}{\sum_{i=1}^{N}\sum_{j=1}^{N} p_{ij}\big|_{Round\ 2}} - 1$$

$$B_R^{SOU_i} = \frac{\sum_{j=1}^{N} p_{ij}\big|_{Round\ \overline{3-n}}}{\sum_{j=1}^{N} p_{ij}\big|_{Round\ 2}} - 1$$

in which *n* is the number of different sets of interventions selected for the cluster. The risk-benefit index should have a negative value if the selected interventions are effective in reducing the cladding risk to a level lower than the benchmark. As the model does not allow risk trade-offs between SOUs, i.e. individual SOU is required to obtain an equal or reduced risk compared to the benchmark, sets of interventions are tested until both B_R^C and $B_R^{SOU_i}$ must not return a positive number.

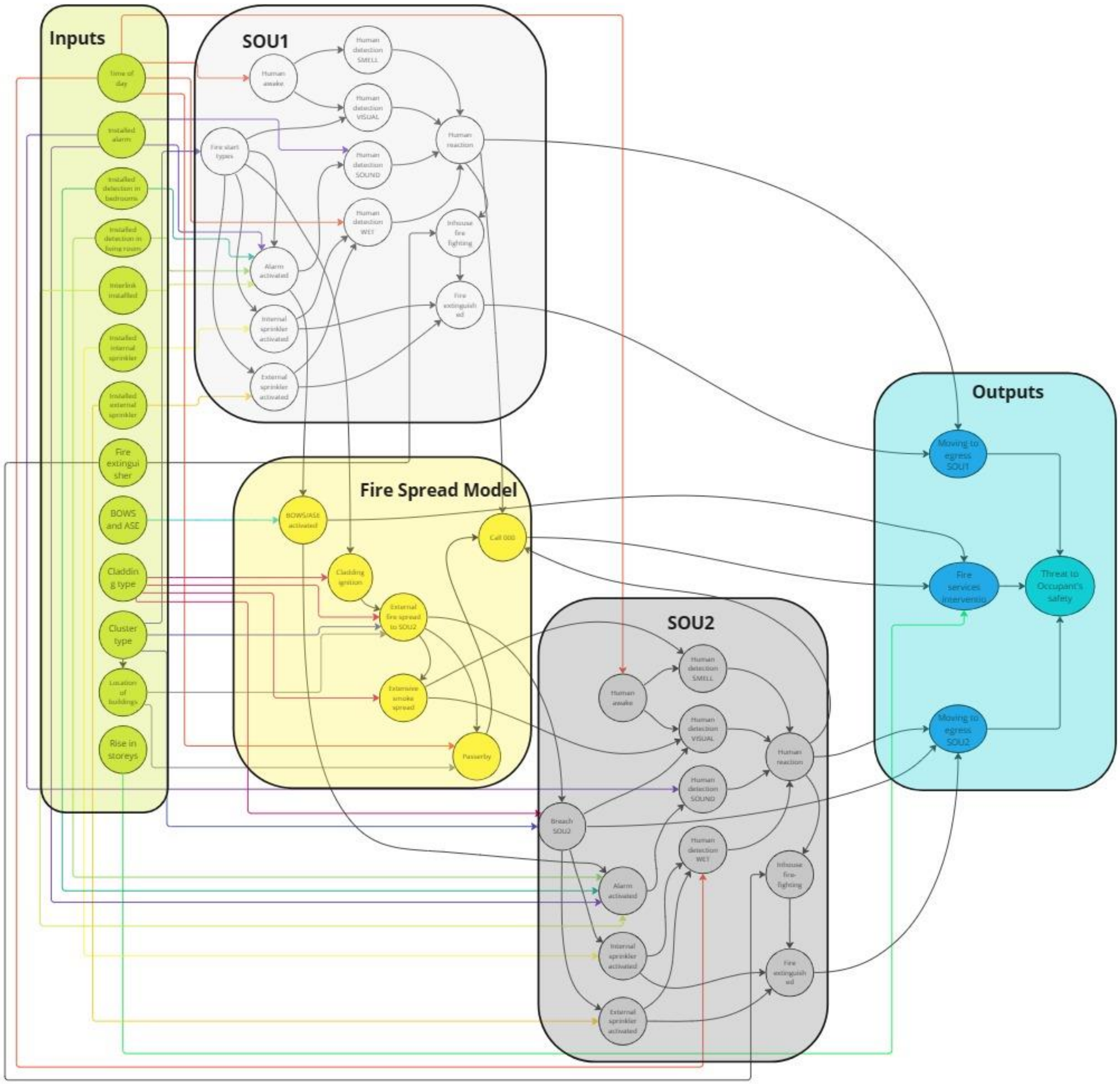
3 Bayesian Network (BN) model for fire risk of a cladding cluster

The Bayesian Network (BN) model has been developed with two primary components: a graphical network and a probability table [4]. The graphical model shows the structures representing the probabilistic dependence of events in the cluster, while the probability table will define the joint distribution of these events.

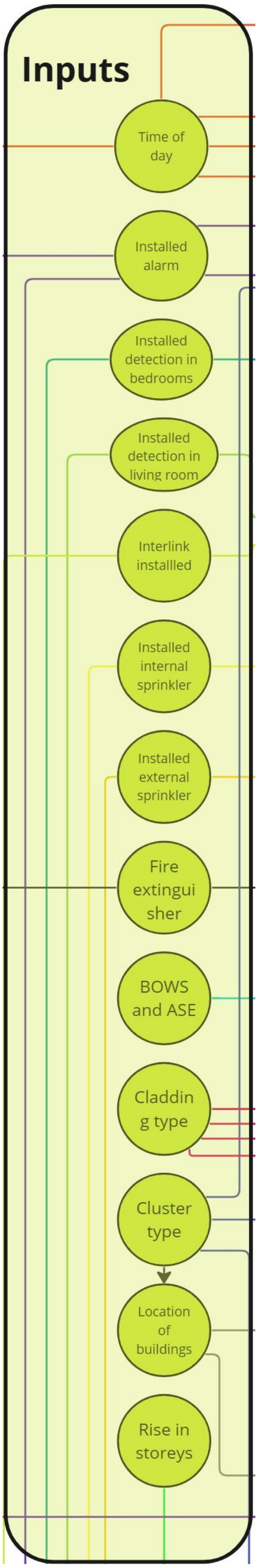
3.1 Graphical network

The graphical network has been designed to combine three different models: fire spread, human reaction and active fire protection operation. This combined approach will allow for the independence of different models.

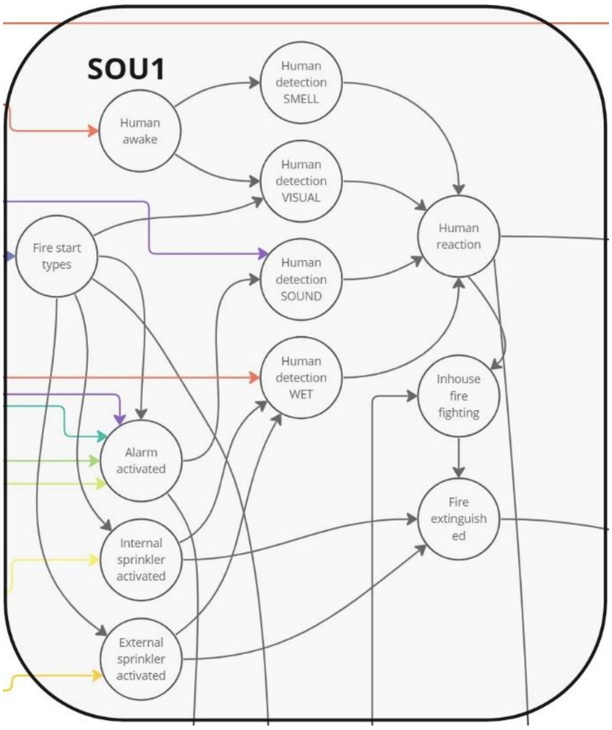
As this assessment method is developed for elevated risk category which includes a cluster of 2 non-sprinkler protected SOUs (case 1 – IFSCAN = 2 non-sprinkler protected) or a cluster of 3 sprinkler-protected SOUs (case 2 – IF-SCAN = 3 sprinkler protected), a graphical network is designed for each case. Figure 3 shows the graphical network of the first case, an additional set of nodes representing the third SOU is added for case 2.



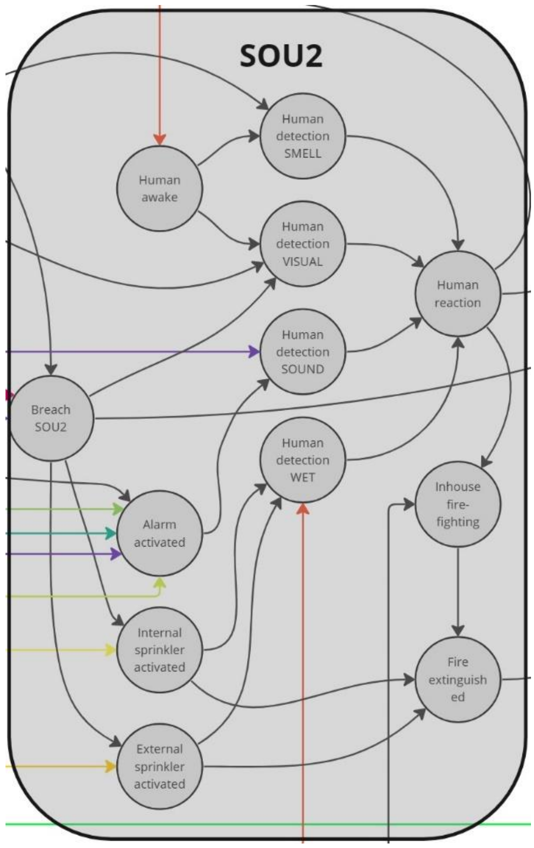
(a) Overall Graphical Bayesian Network for IF-SCAN = 2 cluster



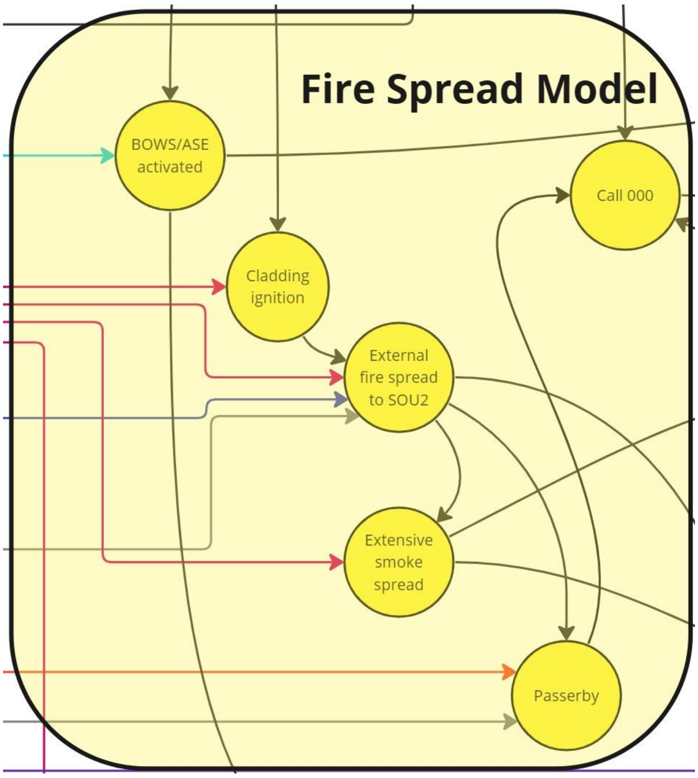
(a) Inputs



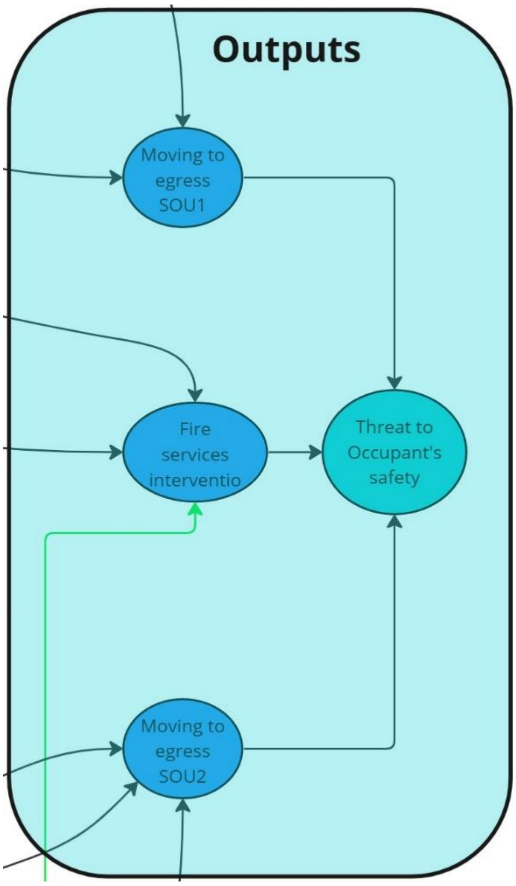
(c) SOU1



(d) SOU2



(e) Fire spread model



(f) Outputs

Figure 3: Graphical network of IF-SCAN = 2 cluster

As highlighted in Figure 3, there are five main "blocks of nodes" for an IF-SCAN = 2 cluster:

- Inputs: This block includes all nodes that will define different characteristics of the cluster and the inclusion of interventions into the analysis.
- SOU1: This block includes nodes that represent the human interaction of occupants in SOU1 with the fire, the operational status of active fire protection systems, and the ignition of combustible cladding that belongs to this SOU. It is assumed that fire starts from SOU1 in the cluster. The level of risk in different SOUs in a cluster could be different owing to its geometry (i.e., the upper SOU in a vertical cluster has generally higher risk than the lower one). In such cases, the network will run multiple times with different SOUs of fire origin in each run to cover different scenarios.
- Fire spread model: This block includes nodes that represent the spread of fire from SOU1 via combustible cladding to SOU2 and other parameters that do not belong to a particular SOU in the cluster, including the status of BOWS/ASE or the presence of a passerby and call to emergency services via telephone. The fire spread model is developed to generate probabilistic data of fire spread via combustible cladding for that cluster based on cluster characteristics (including the type of cladding and geometry of cladding in the cluster) and the wind profile of the location where the target building is allocated. The wind profile from the weather station at Essendon Airport was used as it was one of two automatic weather stations that are closest to the majority of buildings with combustible claddings. This method is similar to the model used in Support Package 2, and further details of the method could be found in that supporting package's document.

- SOU2: This block is similar to the SOU1 block, except for the “Fire start type” node, which is replaced by the Breach SOU2 node. This node represents the status of fire spread via combustible cladding to enter SOU2 via an opening.
- Outputs: This block includes the nodes of egress status in SOU1/2, the intervention of fire services, which contributes towards the overall “threat to occupants’ safety”.

The detailed description of each node within these blocks is included in the following sections.

Inputs

The first part of the network is the inputs. The nodes which are dependent on the cluster, location and general environment have been selected as inputs of the network. The following list briefly describes the network's input nodes, the possible values that can be selected for these nodes, and the rationale behind the chosen values.

1. **Time of day** [states: day, night]: This node describes the time when a fire occurs. This time has been divided into two categories, i.e. day and night. The time of day at the occurrence of fire influences both the human reaction and the fire protection operation.
2. **Location of buildings** [states: high density, low density]: This node represents the population density in the area of fire. The population density can be broadly divided into two parts, i.e., the Central Business District (CBD) which is generally quite highly populated, and the suburban regions where the population density is relatively much lower. The two possible values for this node are hence ‘high density’ and ‘low density’, respectively.
3. **Installed internal sprinkler** [states: yes, no]: A sprinkler system plays an important role in fire control and extinguishing. A sprinkler system may be installed internally within an SOU or externally within a building. The presence of a sprinkler system within an SOU is predetermined. Here, we will consider the possibility of any one of the two common sprinkler types used in Victoria, Australia, i.e., FPAA 101D, FPAA 101H or AS 2118. Therefore, this node can have one of two possible values, i.e., either an internal sprinkler is installed, which is represented by state ‘yes’, or it is not installed, which is represented by state ‘no’.
4. **Installed external sprinkler** [states: yes, no]: The presence of an external sprinkler system installed to the balconies of the SOUs being considered are characterised through this input node. The types of external sprinklers considered are FPAA 101D, FPAA 101H and AS 2118. Similar to node 3, the presence of an external sprinkler system is depicted by a ‘yes’ state for this node and the absence is depicted by a ‘no’ state.
5. **Installed alarm** [states: in bedroom, in SOU, in common area, no]: This node represents the presence of an alarm in the building with the SOUs that are being considered. There are four possible states for this node, which are dependent on the presence of an alarm as well as the location within the building where the alarm has been installed. When there is no alarm installed, the ‘no’ state is selected. In the case of presence of an alarm, the state is chosen according to the location of the alarm, such that the state ‘in bedroom’ represents an alarm installed within the main bedroom of the SOU or an equivalent design requirement of achieving $75\ dB$ at the bedhead from the building’s alarm system. The state ‘in SOU’ represents an alarm within the SOU where no physical alarm is installed within the bedroom nor is there a requirement for $75\ dB$ at the bedhead. The state ‘in common area’ represents the presence of an installed alarm within the buildings common area.

6. **Installed detection in bedroom** [states: smoke, thermal, both, no]: This node depicts the presence and type of detector in the bedroom adjacent to cladding of the SOU. Similar to the sprinklers and alarm, the presence of a detector within bedroom is predetermined, and is therefore treated as an input node. When there is a detector installed in bedroom, the state of this node portrays the type of detector. The state 'smoke' is chosen in the case of a smoke detector. The state 'thermal' is chosen when the detector in bedroom is of thermal type. The state 'both' represents the presence of a detector capable of detecting both smoke and heat, which may be a single detector with both capabilities or a combination of two separate single type detectors. The state 'no' is chosen when there is no detector installed within the bedroom of the SOU.

7. **Installed detection in living room** [states: smoke, thermal, both, no]: The presence and type of a detector in the living area of SOU is depicted through this node. Similar to node 6, the absence of detector is represented through the 'no' state, whereas the presence of detector is depicted through its type, such as 'smoke' for smoke detector, 'thermal' for a heat detector and 'both' for a combination of smoke and heat detection within the living room.

8. **Interlink installed** [states: smoke and heat within SOU, smoke within SOU and heat within the building, no]: This node represents if the detectors within SOU and/or the building are interlinked or not. If there is an interlink between the smoke and heat detection within the SOU, we select the first state. The second state represents the interlink of smoke within the SOU and heat building-wide, whereas the third state depicts when there is no interlink installed.

9. **BOWS and ASE** [states: BOWS and ASE installed, BOWS only, no]: This node depicts if the cluster has BOWS and/or ASE installed. The presence of both is depicted through the first state, the presence of BOWS only is depicted through the second state, whereas the third state represents when there is no BOWS or ASE installed.

10. **Cluster type** [states: 2H balcony, 2H no balcony, 2V balcony, 2V no balcony]: This is the main input node for the designed network. It represents the size and shape of the cluster. In the case study, we consider four states. The first state, i.e., '2H balcony' depicts the case with 2 SOUs, which are connected horizontally, and there is a balcony present. The second state, i.e., '2H no balcony' depicts the horizontal cluster without balcony. The vertical cluster is represented by states 3 and 4 with '2V balcony' representing the case with balcony and '2V no balcony' representing the case with no balcony. An illustration of these states are presented in Figure 4 as part of the case study in section 5.

11. **Cladding type** [states: EPS, ACP, none]: This input root node represents the type of cladding present in the cluster. The state 'EPS' represents the expanded polystyrene cladding. The state 'ACP' represents the aluminium composite panel with a polyethylene core (ACP-PE) cladding as described in section 1. The third state, 'none,' represents the case with no cladding in the cluster.

12. **Rise in storeys** [states: 4 and below, 5 and above]: This input node depicts the height of the building with the cluster being considered. The first state represents a building with 4 and less storeys, while the second state represents taller building with 5 or more storeys.

13. **In-house firefighting equipment** [states: yes, no]: This input node illustrates the presence of fire extinguisher in the cluster, which is the most common firefighting equipment in residential buildings. The state 'yes' depicts the presence of a fire extinguisher, and the state 'no' depicts the absence.

SOU nodes

This sub-section presents details of the nodes that lead to the possibility of human reaction for fire control and/or moving to egress.

The nodes included in this part of the network are all ‘chance’ nodes. Chance nodes are nodes that depend on at least one other node, thus making the probability of these nodes dependent on the previous nodes of the network.

For the case 1 cluster with 2 SOUs, the nodes within this part of the network can be further be divided into two parts, i.e., the nodes for SOU1 and the nodes for SOU2 within the cluster. The SOU name has been included as part of the node name, where applicable, to clarify the difference in dependence of the similar nodes for SOU1 and SOU2. The SOU name has not been included in Figure 3, however, the SOU1 nodes are depicted in white color while SOU2 nodes are shown in grey color.

Some nodes, however, are only present for the SOU1 since it is the origin of the fire, and SOU2 is only affected if the fire spreads out of SOU1.

14. **Fire start type** [states: flaming outdoor, flaming indoor]: This node represents the type of fire at the start. Since the origin of fire is in SOU1, this node is only considered in SOU1. Smoldering fires have not been considered here. The two states of this node are, therefore for flaming fires, namely ‘flaming outdoor’ and ‘flaming indoor’ fires, where indoor and outdoor represent the location of fire start. This node is dependent on the cluster type.

15. **Alarm activated in SOU1** [states: yes, no]: This node represents the activation of alarm within SOU1. It has various dependencies, such as the fire start type, installed alarm, installed detection within the bedroom as well as living room, and interlink. All these dependencies act as parent nodes and influence the state of the node.

16. **Internal sprinkler activated in SOU1** [states: yes, no]: This node represents the activation of internal sprinkler in SOU1, if installed. It, therefore, depends on whether an internal sprinkler has been installed, as well as the fire start type.

17. **External sprinkler activated in SOU1** [states: yes, no]: This node illustrates the activation of external sprinkler in SOU1, if it is installed. Similar to node 16, it depends on the presence of external sprinkler, as well as the fire start type.

18. **Human awake in SOU1** [states: yes, no]: This node represents if the human in SOU1 is awake or not. The state ‘no’ incorporates the probability of human present and asleep as well as the chance that there is no human present in the SOU at the time of fire. This node, therefore, depends on the time of day input node.

19. **Human detection of sound in SOU1** [states: yes, no]: This node illustrates the human’s ability and therefore probability to detect fire through the sense of sound. The node will have a ‘no’ state in cases when the human is not present in the SOU, as well as the human’s inability to detect sound due to some disability. But most importantly, this node depends on the activation of the alarm in the SOU1, which would be the only source of sound in case of a fire. Therefore, we have only considered the direct dependence on nodes 5 and 15.

20. **Human detection visual in SOU1** [states: yes, no]: This node depicts the human’s ability to detect fire by seeing it. This node, therefore, heavily depends on the human being awake. Moreover, it depends on the fire start type as well as cladding ignition, which is explained in node 38.

21. **Human detection smell in SOU1** [states: yes, no]: This node represents the human’s ability to detect fire through their sense of smell. We assume that the human’s ability to detect fire smell is heavily dependent on their consciousness, therefore, the detection of fire through smell is dependent on human being awake. Moreover, it is dependent on whether the cladding has been ignited, which is represented by node 38.

22. **Human detection wet in SOU1** [states: yes, no]: This node portrays the human's ability to detect fire through their sense of feeling, i.e., feeling the water. Therefore, this node depends on the activation of an internal or external sprinkler head, as well as the time of day. The dependence on time of day is selected due to the consciousness of human as well as their presence within the SOU1, which are all dependent on the time of day.

23. **Human reaction in SOU1** [states: yes, no]: The ability of a human within an SOU to react to a fire depends on the human being able to detect the fire. Therefore, this node depends on nodes 19 through 22.

24. **In-house firefighting in SOU1** [states: yes, no]: This node has a 'yes' state when the human tries to fight the fire as a result of human reaction within SOU1. We have considered that most occupants are not trained to fight a fire, therefore the only way they can fight a fire within the SOU is if there is a fire extinguisher available.

25. **Fire extinguished in SOU1** [states: yes, no]: This node depicts if the fire is extinguished within SOU1. This could happen as a result of effective in-house firefighting, or the effectiveness of internal and/or external sprinklers. The more parent nodes are positive (have a 'yes' state), the more chance of the fire being extinguished within the SOU1.

26. **Breach SOU2** [states: breach internal, breach external, no]: This node represents if the fire has breached SOU2, whether internally or externally. It depends on the external fire spread to SOU2, as well as the cluster type.

27. **Alarm activated in SOU2** [states: yes, no]: This node represents the activation of alarm for SOU2, and depends on various factors and alarm types being installed. In particular, it depends on the presence (if installed) of ASE and/or BOWS, alarm, interlink, and detectors in bedroom and living room of SOU2, as well as the breach of SOU2.

28. **Internal sprinkler activated in SOU1** [states: yes, no]: Similar to node 16 for SOU1, this node represents the activation of internal sprinkler for SOU2. This node depends on whether the SOU2 has an internal sprinkler installed and if the SOU2 has been breached, as represented by node 26.

29. **External sprinkler activated in SOU1** [states: yes, no]: This node is SOU2 equivalent to node 17 for SOU1. This node represents the activation of an external sprinkler in SOU2, depending on the installation of an external sprinkler, as well as the breach of SOU2 (node 26).

30. **Human awake SOU2** [states: yes, no]: This SOU2 node is similar to the SOU1 node 18. It represents the state of consciousness of the occupant for SOU2. This node depends on the time of day as there is a greater chance of human being awake during the day as compared to night time.

31. **Human detection sound in SOU2** [states: yes, no]: This node depicts the ability of human to detect fire through sound in SOU2. It is the counterpart of node 19 for SOU1. This node depends on whether there is an alarm installed in the building, as well as the activation of alarm within the SOU2.

32. **Human detection visual in SOU2** [states: yes, no]: This node is the counterpart of node 20 for SOU2, and represents the ability of human detection of fire through visual cues. This node depends on whether the fire has breached into SOU2, the external fire spread to SOU2 (which is a fire spread node – node 39), as well as the occupant of SOU2 being awake (node 30).

33. **Human detection smell in SOU2** [states: yes, no]: This node, which is the SOU2 counterpart of node 21 for SOU1, represents the detection of fire by the occupant of SOU2 through the sense of smell. It depends on the extensive smoke spread (fire spread node – node 40) and the human in SOU2 being awake (node 30).

34. **Human detection wet in SOU2** [states: yes, no]: This node, which is the SOU2 equivalent of node 22 for SOU1, represents the detection of fire by the human in SOU2 through detection of 'wet', i.e., through activation of the external or internal sprinkler. This node also depends on the time of day.

35. **Human reaction in SOU2** [states: yes, no]: This node depicts the ability for human in SOU2 to react to fire, as a result of detecting fire through the use of their senses, as described by nodes 31 to 34. This is a parallel node of node 23 (for SOU1).

36. **In-house firefighting in SOU2** [states: yes, no]: This node represents the in-house firefighting within SOU2. It is the SOU2 counterpart for node 24 in SOU1. The states of this node are dependent on the human reaction in SOU2, as well as the presence of fire extinguisher (input node – node 13).

37. **Fire extinguished in SOU2** [states: yes, no]: This is the final node for SOU2, which is the counterpart of node 25 in SOU1. This node depends on the activation of internal and external sprinklers within SOU2, as well as the in-house firefighting within SOU2.

Fire spread nodes

38. **Cladding Ignition** [states: yes, no]: This node has a state of 'yes' if the cladding is ignited as a result of the fire in SOU1. This node depends on the fire start type, the cladding type, as well as the fire being extinguished within SOU1 as a result of human reaction and fire fighting.

39. **External fire spread to SOU2** [states: yes, no]: This is the first node for SOU2, which depicts the fire spread to SOU2. This node depends on the building location, cluster type, as well as the cladding type and ignition. This is the fundamental node that connects the fire from SOU1 to SOU2. The probability of external fire spread is generated by integrating the wind geospatial data into FDS models of the cluster. Each cluster topology will have its own probabilistic FDS model. As the network assumes that fire starts from SOU1, each cluster typology will be simulated multiple times with fire starting at different SOUs.

40. **Extensive smoke spread** [states: yes, no]: If the fire spreads to SOU2, there is a chance that there might be smoke spread to SOU2 as well. This node, therefore, depends on the external fire spread to SOU2, as well as the cladding type.

41. **BOWS/ASE activated** [states: yes, no]: This node represents the activation of BOWS and ASE from SOU1. This node is directly related to node 9, which depicts whether BOWS is installed or both BOWS and ASE have been installed. If there is no BOWS or ASE installed, this node will have a 'no' state. It also depends on the activation of alarm within SOU1, as it is directly responsible for activating BOWS and/or ASE, if present.

42. **Passerby** [states: yes, no]: This node depicts the presence of a passerby outside the SOU. This is because the passerby may be able to influence the response from fire services. There is a higher possibility of a passerby being present and noticing a fire in densely populated areas such as the CBD. Therefore, this node has a direct dependence on the location of buildings, as well as the fire spread outside the SOU1 to SOU2, and the time of day as there is a lesser chance of a passerby being present at nighttime as compared with daytime.

43. **Call 000** [states: yes, no]: This node represents whether there is a call made to fire services as a result of the fire. This call may be initiated by a passerby or as a result of human reaction within SOU1 and/or SOU2.

Output nodes

44. **Fire services intervention** [states: yes, no]: This node shows whether there is an intervention by the fire services in order to extinguish the fire. This intervention could be the result of a 000 call, the activation of ASE and/or BOWS, and the height of the building, i.e., the rise in storeys.

45. **Moving to egress – SOU1** [states: yes, no]: This node depicts the SOU1 occupant safety or the ability of the occupants to move towards safety. This node directly depends on human reaction, as well as whether the fire within SOU1 was extinguished.

46. **Moving to egress – SOU2** [states: yes, no]: In case of effective human reaction and/or the successful intervention of fire services, the state of this node, which represents the ability of human (occupant) in SOU2 to move towards egress, has a state of 'yes'.

47. **Threat to occupants' safety** [states: yes, no]: This is the ultimate output node of the network, which represents the threat to the safety of occupants within SOU1 and SOU2. This node is directly dependent on the intervention by fire services, as well as the occupants from SOU1 and SOU2 moving towards egress. The probability of this node represents the final probability outcome for various types of clusters.

3.2 Probability table

This subsection illustrates the details of the probability tables for various nodes. The probability table for a node represents the dependence of the particular node on its parent nodes, if present, i.e., the probability density for a node is actually the conditional probability, given its parent nodes. The probability density for each node is considered to be discrete. Therefore, the probability tables for some nodes are too long and complex to be included here. There is, however, included a summary of the details regarding probability tables for nodes, including the type of node (root nodes are parentless, while nodes dependent on parent nodes are termed as chance nodes), the number of states, the number of parent nodes (if present), as well as the number of permutations within the probability table. The details have been presented in the table below.

Node no.	Node name	Node type	No. of parent nodes	No. of states	No. of permutations in prob. table
1	Time of day	root	0	2	2
2	Location of buildings	root	0	2	2
3	Installed internal sprinkler	root	0	2	2
4	Installed external sprinkler	root	0	2	2
5	Installed alarm	root	0	3	3
6	Installed detection in bedrooms	root	0	4	4
7	Installed detection in living room	root	0	4	4
8	Interlink installed	root	0	3	3

Node no.	Node name	Node type	No. of parent nodes	No. of states	No. of permutations in prob. table
9	BOWS and ASE	root	0	3	3
10	Cluster type	root	0	4	4
11	Cladding type	root	0	3	3
12	Rise in storeys	root	0	2	2
13	In-house fire equipment	root	0	2	2
14	Fire start type	chance	1	2	8
15	Alarm activated in SOU1	chance	5	2	768
16	Internal sprinkler activated in SOU1	chance	2	2	8
17	External sprinkler activated in SOU1	chance	2	2	8
18	Human awake in SOU1	chance	1	2	4
19	Human detection SOUND in SOU1	chance	2	2	16
20	Human detection VISUAL in SOU1	chance	2	2	8
21	Human detection SMELL in SOU1	chance	1	2	4
22	Human detection WET in SOU1	chance	3	2	16
23	Human reaction in SOU1	chance	4	2	32
24	In-house firefighting in SOU1	chance	2	2	8
25	Fire extinguished in SOU1	chance	3	2	16
26	Cladding ignition	chance	3	2	24
27	Breach SOU2	chance	3	3	72
28	Alarm activated in SOU2	chance	6	2	2,304

Node no.	Node name	Node type	No. of parent nodes	No. of states	No. of permutations in prob. table
29	Internal sprinkler activated SOU2	chance	2	2	12
30	External sprinkler activated SOU2	chance	2	2	12
31	Human awake SOU2	chance	1	2	4
32	Human detection SOUND SOU2	chance	2	2	16
33	Human detection VISUAL SOU2	chance	3	2	24
34	Human detection SMELL SOU2	chance	2	2	8
35	Human detection WET SOU2	chance	3	2	16
36	Human reaction SOU2	chance	4	2	32
37	In-house firefighting SOU2	chance	2	2	8
38	Fire extinguished SOU2	chance	3	2	16
39	External fire spread to SOU2	chance	4	2	96
40	Extensive smoke spread	chance	2	2	12
41	BOWS/ASE activated	chance	2	2	12
42	Passerby	chance	3	2	16
43	Call 000	chance	3	2	16
44	Fire services intervention	chance	3	2	16
45	Moving to egress SOU1	chance	2	2	8
46	Moving to egress SOU2	chance	3	2	24
47	Threat to occupants' safety	chance	3	2	16

4 Implementation of the Bayesian Network (BN)

The Bayesian Network (BN) depicted in Figure 3 requires the use of probabilistic data for each possible input node combination to be implemented. In order to conduct such analysis, data from expert judgement was collected within CSV, and used for risk benefit analysis. The network was then implemented using Python in Jupyter Notebook with the use of the Python Library for Probabilistic Graphical Models (known commonly as ‘pgmpy library’). In **pgmpy**, the implementation of a BN involves various algorithms for learning the structure and parameters of the network. The specific algorithms used depend on the functionalities within pgmpy. The pgmpy model is created to store nodes and edges (connections between nodes) with their CPDs (conditional probability distributions). However, some of the key algorithms and functionalities include:

- **Structure Learning:** The pgmpy library uses a number of algorithms for learning the structures of models, such as Bayesian Network. Some of the commonly used algorithms for BNs include hill climb search, MMHC Estimator (maximum minimum hill climbing estimator), tree search and exhaustive search. The hill climbing algorithm, which is the most commonly used algorithm, explores different network structures by adding and removing edges based on a scoring metric.
- **Parameter Learning:** The Bayesian parameter estimation or parameter learning can be implemented in pgmpy using one of the common types of estimators, such as Bayesian estimator, MaP (maximum a-Posteriori) Estimator, or EM (expectation maximization). The ‘**Bayesian Network’** class provides methods for estimating parameters based on Bayesian principles.
- **Exact Inference: ‘**pgmpy’ uses algorithms for exact inference in a Bayesian Network, such as Variable Elimination and Belief Propagation, to calculate probabilities and perform queries on the network.
- **Approximate Inference:** For larger networks, pgmpy supports approximate inference methods, including methods based on sampling like Gibbs Sampling and Likelihood Weighting.

After the network is created in Python, the different combinations of input node states are selected to generate the probabilities for output node states.

5 Benefit of interventions to mitigate cladding risk

In this section, a case study of four IF-SCAN = 2 cluster types will be presented to identify the cladding risk premium and risk-benefit of interventions to the clusters. Schematics of cluster types considered in this case study have been shown in Figure 4. A similar approach could be conducted for IF-SCAN = 3 clusters with the addition of the third SOU following the same methodology. In this case study, inputs of node 39 are generated from a round-robin of expert judgment with a CSV internal panel. In the development of a particular cluster typology, the input is from FDS fire spread simulation, as presented in Figure 2.

Four types of clusters include:

- 2H no balcony: A cluster of two SOUs on the same floor with no balcony;
- 2H balcony: A cluster of two SOUs on the same floor both with balconies on each SOU that could possibly take part in the external fire spread via combustible cladding;
- 2V no balcony: A cluster of two SOUs in a vertical stack with no balcony; and
- 2V balcony: A cluster of two SOUs in a vertical stack both with balconies on each SOU that could possibly take part in the external fire spread via combustible cladding.

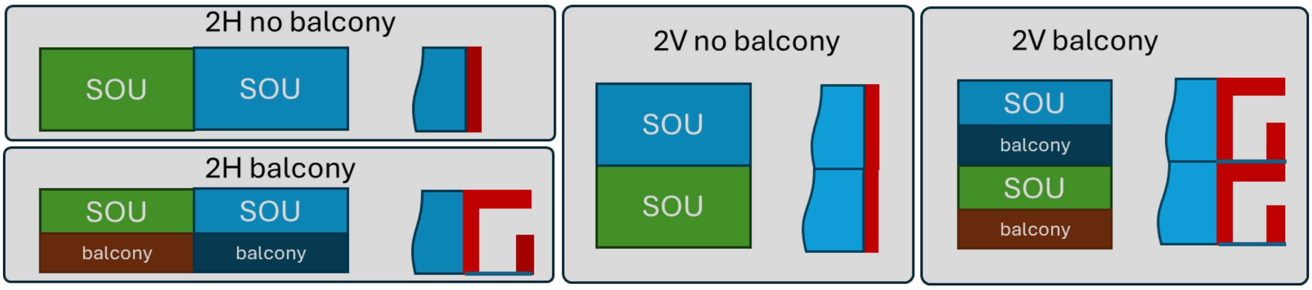


Figure 4: Schematic of clusters used in the case study

5.1 Cladding risk premium

Figure 5 presents the cladding risk premium C_R^C (as defined in section 2) calculated for different cluster types in high-density and low-density areas. It is expected that the cladding risk premium of ACP is higher than that of EPS, especially when it is coupled with the presence of a balcony. Balcony is evidently an important feature of the cluster that could significantly alter the cladding risk premium, to some extent more important than the horizontal or vertical orientation of the cluster. There is also an increase in cladding risk premium when the cluster is at height. Interestingly, it can be seen from Figure 5 that 2H cluster with no balcony at 4 storeys or below in high-density areas can benefit from the faster fire services intervention time as well as the higher possibility of a passerby informing the fire brigade owing to the more intense flame and smoke from a cladding fire.

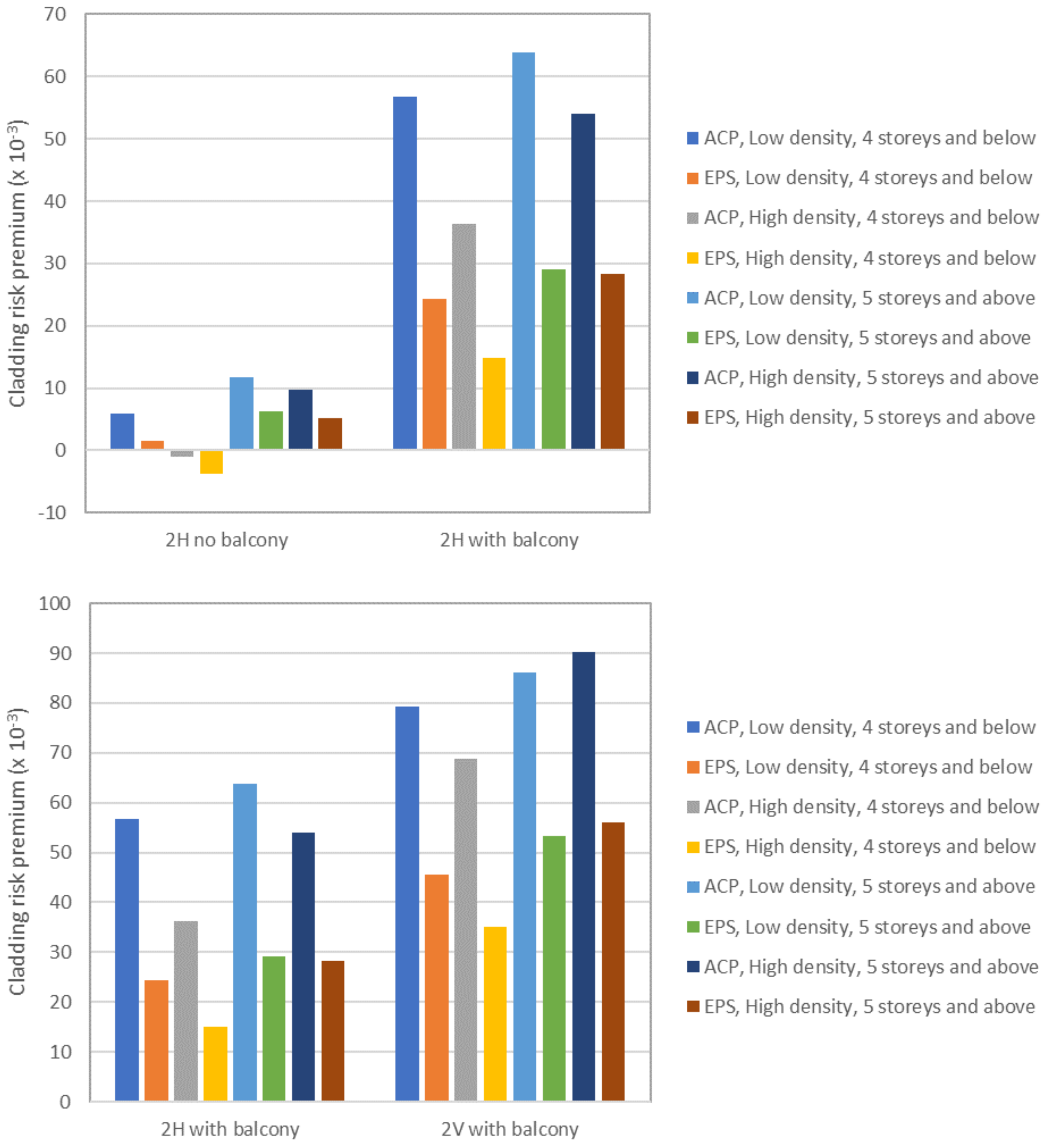


Figure 5: Cladding risk premium of 2H and 2V clusters

5.2 Risk-benefit index of interventions

Use of smoke detection in bedroom

The addition of smoke detection in the bedroom is selected as the most practical intervention. It is generally not required to have smoke detection devices in bedrooms unless they are part of a fire safety engineers' requirement when preparing a performance solution for the building. The positive impact of smoke detection in residential environments has been generally acknowledged in literature. Smoke detection/alarm is known, and has been shown, to provide more risk-benefit in situations where the occupants are not awake, when their situational awareness of the surroundings is reduced, limiting their egress probability. For this reason, the risk-benefit index will be analysed at different time as day and night separately.

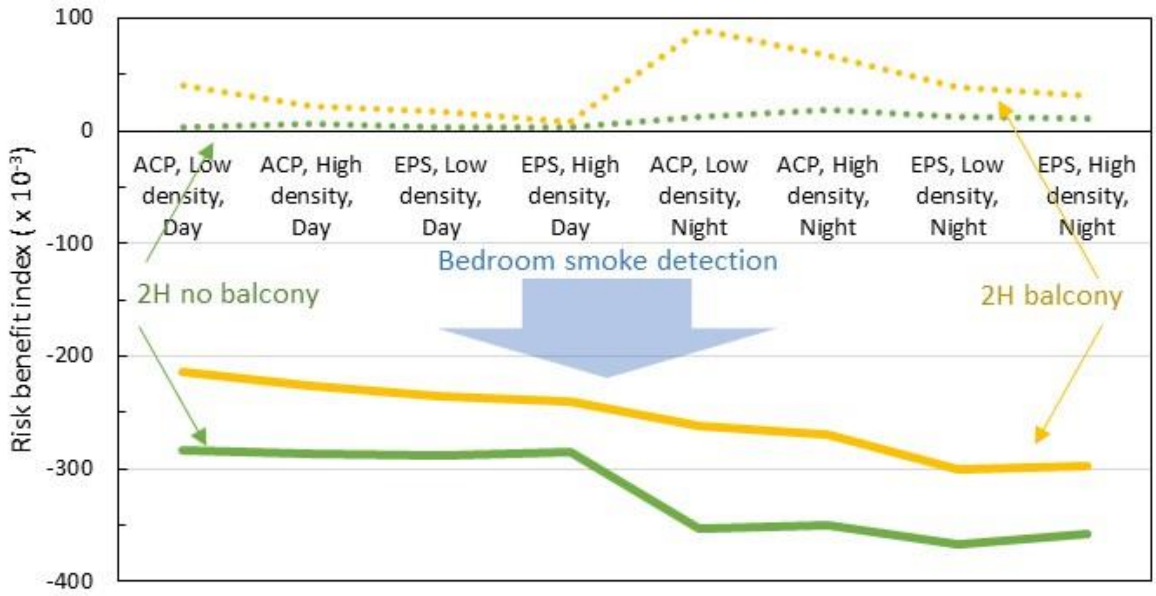


Figure 6: Risk-benefit of bedroom smoke detection in 2H clusters

The results of 2H no balcony and 2H balcony clusters are presented in Figure 6. In a 2H cluster, the two SOUs are generally of equal risk, thus, only the cluster risk-benefit index is shown. It is evident that this intervention is sufficient to bring the risk down to lower than the benchmark building. Additionally, it is expected that this intervention is more effective at night, as shown in Figure 6.

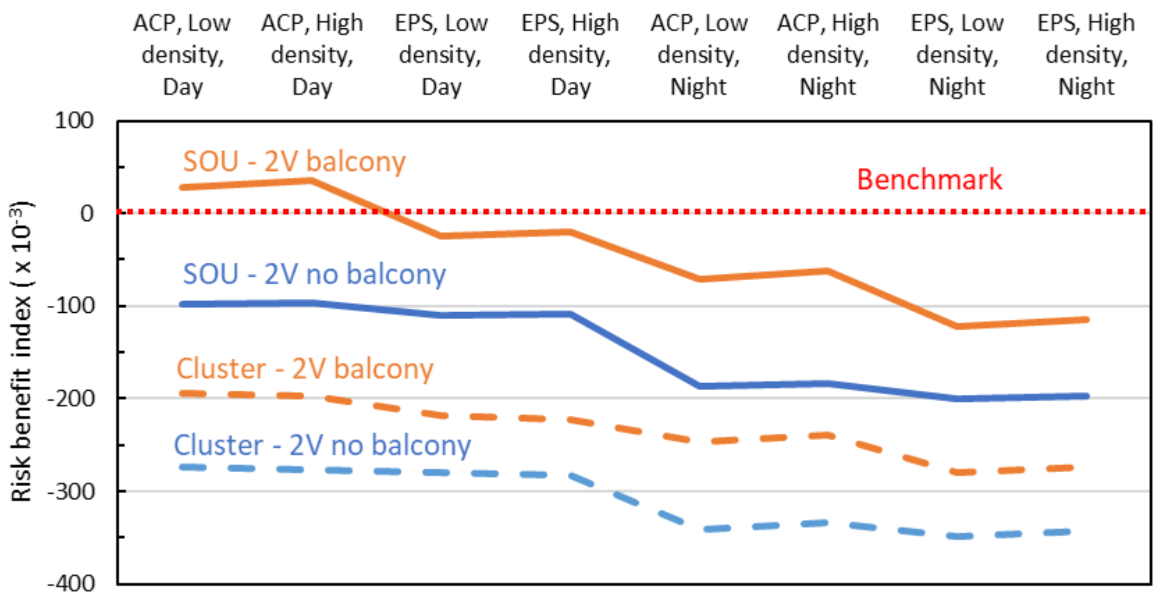


Figure 7: Risk-benefit of bedroom smoke detection in 2V clusters

Regarding 2V clusters, as the SOUs are in a vertical stack, they naturally carry different risks relating to the upward spread nature of fire. While the risk-benefit is sufficient for the overall cluster risk, the individual SOU risk could not be fully compensated by the selected intervention in 2V with balcony and ACP (as evident from Figure 7). Further intervention must be considered for this cluster type.

Additional interventions for ACP - 2V balcony clusters

Since the first selection of interventions does not provide a sufficient risk reduction compared to the benchmark, the next set of interventions is selected, including an additional thermal detection device in common areas of the SOU where an opening is associated with combustible cladding. The thermal detection devices must be interlinked building-wide and share signals to activate the alarm system, providing not less than 75 dB measured at the bedhead. The results are presented in Figure 8, which shows the sufficiency of this selected intervention set.

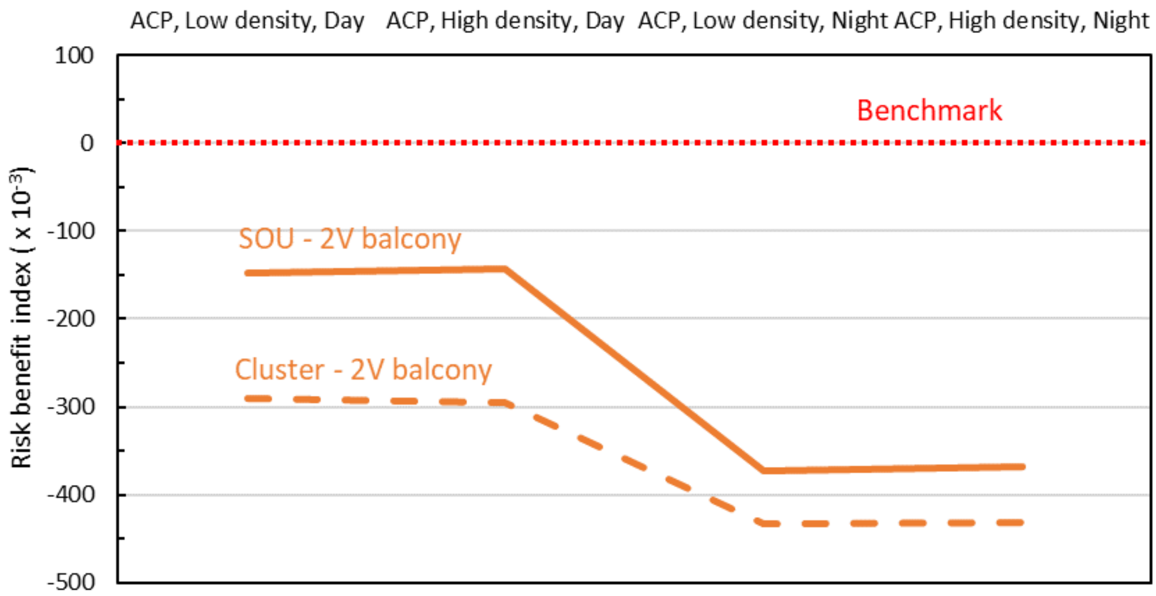


Figure 8: Risk-benefit of additional interventions for ACP-2V cluster

6 Concluding remarks

A method to determine the risk-benefit of the implementation of selected intervention solutions to a cluster in the PMCR has been developed. The method was built upon the method using the Bayesian Network (BN) developed by Matellini et al [4,5] and combined with the probability of fire spread via cladding using Computational Fluid Dynamics (CFD) modelling utilising the FDS software. The probabilistic analysis of fire spread using FDS is fully described in *Support Package D.02 – External Fire Threats to Cladding.* The model analysed the cladding risk premium of each cluster and then determined the risk-benefit of a selected intervention set. The intervention selection is based on the risk profile and the practicality of the interventions.

A case study was conducted using this developed methodology for selected clusters of IF-SCAN = 2. A summary of the findings from this case study includes:

- In settings where the building is located in high-density areas and of limited height (4 storeys or less), the cladding risk premium could be negative owing to the short commuting distance for fire services and the higher probability of a passerby recognising the external fire and taking actions.
- The balcony plays a significant role in the increase of cladding risk premium of these clusters owing to the direct interaction of combustible claddings on balconies that can take part in and contribute to the acceleration of the fire.
- The use of smoke detection in bedroom is effective in compensating the cladding risk premium to a level below the benchmark level (i.e. the same building with no combustible cladding – as described in the Protocols for Mitigating Cladding Risk (PMCR) for all clusters except a cluster of 2V with balcony and clad with ACP.
- For the ACP - 2V cluster with balconies, while the use of smoke detection in bedrooms could provide a risk-benefit sufficient for the overall cluster, the individual SOU (i.e. the upper one) in the cluster experiences a higher risk owing to its vertical settings. In addition to smoke detection in bedrooms, thermal detection in common areas of the SOUs that are interlinked to the building-wide occupation warning system with a noise level measured at the bedhead of 75 dB could sufficiently provide a risk-benefit for both overall cluster and individual SOUs to a level lower than the benchmark.

A similar approach could be conducted with IF-SCAN = 3 clusters.

7 References

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8 Appendices

8.1 Appendix A – PMCR document set and flow