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Review

The CAED Framework for the Development of Performance-Based Design at the Wildland–Urban Interface

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Abstract: The hazard posed by wildland–urban-interface (WUI) fires is recognized by the international fire research community and features as one of nine research need priority threads in the Society of Fire Protection Engineers (SFPE) Research Roadmap. We posit that the first step in the journey to enhancing fire safety engineering at the WUI is to develop a common understanding between developers, engineers, planners, and regulators of the development scope, wildfire problem, technical design solutions, and verification methods to be used. In order to define a fire safety engineering consultation process appropriate for the wildfire context, this paper aims to translate well-established and evidence-based performance-based design (PBD) consultation frameworks and approaches from traditional fire safety engineering to the wildfire context. First, we review international English-language fire safety engineering frameworks that have been developed for the urban context. Next, we distil the results into a streamlined framework, which we call the "CAED Framework". Finally, we apply and discuss the contextualization of the CAED Framework to the WUI context through a comparative case study of urban and WUI development. In doing so we seek to provide a structure for the development of standardized PBD within the WUI context across jurisdictions internationally, as well as to embed best practices into the emerging field of performance-based wildfire engineering.

Keywords: wildfire; WUI; PBD; performance-based design; fire safety engineering; fire safety

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1. Introduction

As the interface between wildlands and urban areas (known as the wildland–urban interface or WUI) increasingly expands, the potential for wildfires to impact the built environment grows correspondingly. In Australia, over a decade of devastating wildfires—including, most notably, the Victorian "Black Saturday" wildfires of 2009 [1], the Western Australian Yarloop wildfire of 2016 [2], and the New South Wales Black Summer wildfires of 2019 [3] have firmly cemented the need for enhanced wildfire resilience within the built environment as a priority of life safety engineering and urban design. Exactly the same trend, albeit on a larger scale, is observed in the USA, where the WUI has grown rapidly in the last few decades and wildfire impacts are increasingly devastating [4]. Even New Zealand, which has traditionally not had a significant perceived wildfire problem [5], has recently experienced an increase in development at the WUI [6], thus creating conditions with potential consequences such as those experienced in the 2017 Port Hills Fire, on the outskirts of New Zealand's second largest metropolitan area, Christchurch [7,8]. The hazard posed by WUI fires is recognized by the international fire research community [9] and features as one of nine research need priority threads in the current Society of Fire Protection Engineers (SFPE) Research Roadmap [10], the SFPE being an international industry professional body dedicated to fire safety engineering, and the Research Roadmap being the agreed future research needs for the fire protection and safety engineering profession. In the latter, the "Wildland/WUI Fires" thread in the roadmap identifies "risk assessment of WUI structures" as the highest research needs priority with regard to tools, applications, and methods, along with another high-priority area being the "design against exterior building fires". Within the built environment, appropriate fire safety engineering has long been recognized as a cornerstone of occupant life safety, cost-effective design, and evidence-based practice [11–14]. Key components to appropriate life safety design within the established safety engineering field are (1) design and consultation frameworks [11] and (2) appropriate performance requirements [15,16]. In a generic sense, a suitable life safety design can be achieved via either performance-based design (PBD) or deemed-to-satisfy (DtS) design (also known as "prescriptive" design). In countries that have a performance-based building code, such as Australia and New Zealand, PBD is "enabled" by the applicable building regulatory framework, while the building regulator will generally have also published some form of prescriptive DtS compliance provisions. Within the WUI, numerous jurisdictions within the USA have already implemented prescriptive codes [17–19] as an attempt to increase the level of safety of those communities. PBD codes, however, have not been implemented for building design in the WUI [20], despite being valuable in traditional fire safety engineering for the design of unconventional and/or innovative buildings, among others [14,21]. Where a DtS approach is used in traditional fire safety engineering to design a building, the designer essentially has to assess a series of prescribed fire safety provisions that apply to the type of building being designed. Where a PBD approach is used, the building code defines "what" performance requirements must be met, but not "how" to comply with the provisions. For example, as shown in Figure 1, the Building Code of Australia (BCA) [15,16], which is part of the National Construction Code, provides three compliance solution options to comply with the mandatory performance requirements, namely (1) a performance solution (i.e., PBD), (2) a DtS solution, or (3) a combination of the two. In other words, the entire design can be either 100% PBD, 100% DtS, or partially PBD and partially DtS.

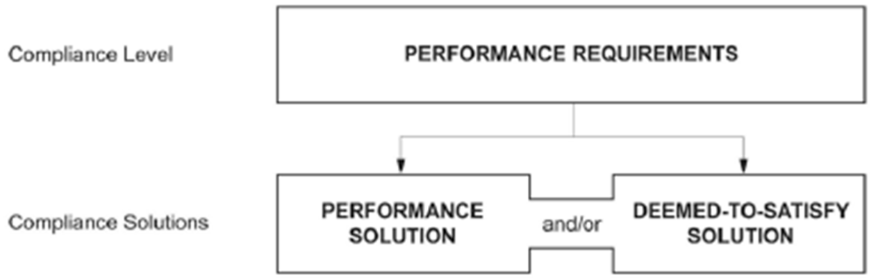

Figure 1. Two-tier hierarchy for compliance with the Building Code of Australia © Commonwealth of Australia and the States and Territories of Australia 2020 and used under a CC-BY-ND license.

One of the key components required in the development of PBD solutions is the Consultation process [11,12,21,22], in which the designer and key stakeholders (client, fire service, urban planning agency, local indigenous groups, etc.) define the general and specific objectives of the project. Within the WUI context, whilst some commonality exists within design frameworks between jurisdictions, our recent research [20] found a dearth of defined consultation frameworks within which to discuss, appraise, and review PBD. In this research [20] we (1) reviewed WUI codes, guidelines, and policy solutions from Australia, New Zealand, the United States, and Canada; and (2) completed a systematic literature review of English-language studies published from January 2000 to December 2020 on wildfire engineering and urban design at the WUI. A total of 838 titles and their abstracts were reviewed, with 57 identified as suitable for inclusion in the study. We then presented our findings, that focus on four lines of enquiry or themes: Governance; Fire Spread, Impact, and Control; Occupant Evacuation and Sheltering; and Fire Services Intervention.

The results demonstrated that even amongst developed nations prone to wildfire impacts, including Australia, New Zealand, the United States, and Canada, an absence of defined fire safety engineering consultation processes within the WUI context existed.

The adoption of existing traditional fire safety engineering consultation frameworks into WUI environments without modification is also unsuitable due to differences in the governance, the fire dynamics, and the uncompartmentalized nature of urban development sometimes involving entire communities, in comparison to single, albeit often large, compartmentalized buildings [20]. In order to address this knowledge and practice gap, we posit that the first step in the journey to enhancing fire safety engineering at the WUI is to develop a common understanding between developers, engineers, planners and regulators of the development scope, wildfire problem, technical design solutions, and verification methods to be used.

In this study we therefore seek to provide a structure for the development of standardized PBD within the WUI context across international jurisdictions, as well as to embed best practices into the emerging field of wildfire engineering, focusing specifically on the Consultation process. First, our methodology is presented in Section 2; then, in Section 3, we review traditional English-language fire engineering PBD frameworks, from the SFPE [21] to the International Organization for Standardization [22], the International Fire Engineering Guidelines [12], and the Australian Fire Engineering Guidelines [11]. Next, in Section 4, we distil the results into a streamlined framework known as the "CAED Framework". Finally, in Section 5, we contextualize the CAED Framework to the WUI context through a comparative case study of urban and WUI development, focused specifically on the Consultation aspect of the framework.

Acknowledging the technical nature of the discussion, which includes multiple process lists, we attempt to provide a systematic and clear explanation for a desperately needed and critical fire safety engineering process within the immature wildfire engineering context [23]. In doing so we seek to provide a structure for the development of standardized PBD within the WUI context across jurisdictions internationally, as well as to embed best practices into the emerging field of PBD and wildfire engineering.

2. Materials and Methods

Literature reviews facilitate the collection and synthesis of existing knowledge and serve to create a firm foundation for the advancement of knowledge [24–28]. As this study aims to do exactly that within the context of fire safety engineering frameworks, a narrative literature review method is applied. As the frameworks reviewed are sequential processes involving a detailed qualitative description and do not include quantitative data, a narrative review, which seeks to identify and understand all potentially relevant practices within the context of the study and to qualitatively synthesize them instead of by measuring effect size (for example, statistical sampling), is applied.

To provide the study with the required level of scientific rigor, the study design adopted research phases and an article structure consistent with [24–28]:

1. Designing the review: for the reasons discussed above, a narrative review was selected.
2. Conducting the review: English-language traditional fire engineering PBD frameworks identified through database and hand searching were identified, reviewed, and synthetized. The structure of the review ensures each framework is individually analyzed and described, allowing the similarities and differences to be easily identified.
3. Building upon existing knowledge: the results from the review were built upon to develop the new CAED framework, which was then assessed through a comparative case study.
4. Concluding: the narrative and study journey are revisited to re-emphasize the key findings of the study in order to provide a foundation for improved practice and further research in the field.

3. Review of Existing Frameworks

A structured approach to PBD can either be mandated by the building regulator via the applicable building code or considered to be a good industry practice by the relevant stakeholders and practitioners, in which case it is subject to non-mandatory guidance. The following four sections provide a summary of the primary international English-language non-mandatory guidance on PBD. Acknowledging the list-style presentation of the following sections, the structured, systematic, and numbered approach is important, as it is a fundamental part of the sequential processes presented in the source references.

3.1. Society of Fire Protection Engineers

The SFPE Guide to Performance-Based Fire Safety Design was originally published in 2000 in recognition of the increased acceptance of PBD and to standardize the previously ad hoc approach to PBD throughout the greater industry in the United States of America [21]. The intent of the guide was (1) to provide a process by which engineers could develop fire protection measures deemed acceptable by stakeholders and without unnecessary constraints on other aspects of building design, (2) provide guidance for the determination of specific fire safety goals, and (3) provide guidance regarding parameters that should be considered in the PBD analysis. The steps in the SFPE design process, of which steps 1–6 make up the Fire Engineering Brief, are as follows [21]:

1. Defining the project scope—this includes project or design constraints and schedule; relevant stakeholders; proposed building construction, occupancy and usage; applicable codes or regulations; and the project management or delivery method. Once this stage is completed, a clear high-level understanding of the needs of the project is reached.
2. Identifying the fire safety goals of the project—this includes levels of protection for occupants, business continuity, heritage preservation, and environmental protection. Fire safety goals are expressed qualitatively in broad terms, facilitating the understanding of how the building is expected to perform, and are usually expressed in terms of life safety, property protection, mission continuity, and environmental protection.
3. Development of objectives—this includes the refinement of goals into tangible values that can be expressed in fire safety engineering terms. As in the case of fire safety goals, objectives are defined in different ways relative to the project, such as allowable injury level or length of loss of operation.
4. Defining the performance criteria—these are the objectives that are refined into numerical values against which the PBD can be quantitatively assessed. For example, this may include threshold values for thermal exposure, smoke obscuration, or gas levels.
5. The development of fire scenarios and design fire scenarios—fire scenarios are the descriptions of possible fire events consisting of fire, building, and occupant characteristics. Design fire scenarios are the filtered subset of fire scenarios against which trial designs are assessed, and are quantitively defined through risk assessment methods (e.g., statistical data of fire, fault tree analysis, failure analysis, etc.)
6. Develop trial designs—these are the preliminary designs intended to meet the project requirements. Trial designs should include all proposed fire protection systems, construction features, and other aspects which are required for the design to meet the performance criteria. At this stage, the evaluation or analysis methods should be developed, agreed on by all relevant stakeholders, and documented.
7. Evaluation—each trial design is then evaluated against each design fire scenario.
8. Selecting the final design—only those trial designs that meet the performance criteria are eligible for consideration in the final design.
9. Design documentation—ensuring that all stakeholders understand the necessary implementation, maintenance, and operation of fire safety systems and final design to meet the objectives for the life of the building.
10. Completing the final report—this details each of the previous stages as well as summarizing the discussions, assumptions, and factors behind critical decisions.

3.2. International Standards Organization

International Standard ISO 23932-1:2018 [22] provides the general principles and requirements for fire safety engineering (FSE) that can be applied to buildings. ISO 23932-1 essentially provides guidance on a systematic, 12-step fire safety PBD process. The steps in the design process are as follows:

1. Set the FSE project scope—a statement that contains project-related information that is relevant for the PBD process, including aspects such as the project, site, and building characteristics, affected parties, external factors, and the extent of the PBD application. It is essential that the scope statement clarifies whether the design involves refurbishment, expansion, or a change of occupancy/use, or is a newly built construction work.
2. Identify fire safety objectives (FSOs)—generally, FSOs will be either mandatory (e.g., regulatory requirements enforced by the authority having jurisdiction, or AHJ) or voluntary (e.g., additional objectives from the building owner). An individual FSO will typically address one or more of the following aspects of fire safety:
    a. Life safety.
    b. Property protection.
    c. Continuity of operations.
    d. Protection of the environment.
    e. Protection of heritage.
3. Identify functional requirements (FRs)—each FSO needs to be associated with one or more FR. A FR is a statement in terms of the function of the PBD that is required to achieve the relevant FSO. FRs relate to elements of the building that can be controlled by the design process, such as the structure of the building, compartmentation, material usage, and fire protection systems.
4. Select a risk analysis approach—risk analysis will typically consist of a comparison of the estimated risk to the tolerable risk. The tolerable risk is either absolute (i.e., is explicitly stated) or is comparative (i.e., it is implicit). In prescriptive or DtS provisions, the tolerable risk is implicitly defined by the regulations, whereas in a PBD, the tolerable risk must be explicitly stated in numerical terms. The risk analysis approach is defined in terms of how the uncertainty in the risk analysis is treated. The lowest level of treatment is a qualitative analysis, an intermediate level of treatment is a (quantitative) deterministic analysis, and the highest level of treatment is a (quantitative) probabilistic analysis.
5. Identify performance criteria (PCs)—these are engineering metrics that are stated in a deterministic or probabilistic form, depending on the risk analysis approach adopted, e.g., absolute vs. comparative, qualitative vs. quantitative.

The first five steps in the ISO 23932-1 PBD process define the boundaries of the analysis that is being undertaken. The next four steps (steps 6 to 9) form the core "design" phase in the PBD process.

6. Create the fire safety design plan—the trial fire safety design plan consists of a series of fire safety design elements and is essentially the more detailed construct of the fire safety strategy for the building. The fire safety design elements can be grouped into the following categories:
    a. Fire initiation and smoke production.
    b. Spread of fire and smoke.
    c. Compartmentation and structural stability.
    d. Detection and suppression.
    e. Human behavior and evacuation.
    f. Firefighting response.
7. Determine the design scenarios—the design scenarios can be in one of two categories, namely, design fire scenarios and design occupant behavioral scenarios. To be able to develop design scenarios, a hazard identification is generally a necessary precursor.

Design fire scenarios typically describe the fire development in a manner to suit the risk analysis approach that has been selected and should include the impact of any manual or automatic intervention on the fire development. Design occupant behavioral scenarios describe the occupant numbers, their distribution, familiarity with the building, their abilities, etc.

8. Select engineering methods—appropriate engineering tools must be selected to test the trial fire safety design plan against the FSOs for the project. This includes the selection of suitable fire and egress models, verification and validation, sourcing suitable engineering data, analysis of suitable fire testing information, and engineering judgement.
9. Evaluate design—the trial fire safety design plan is evaluated by using the selected engineering methods to conduct the necessary engineering analyses. The evaluation involves the quantification of the design scenarios (e.g., sourcing input data, estimating the consequences, and estimating the frequency of occurrence), dealing with uncertainty, comparison to the PCs, and an assessment of the impact on any other FSOs.

The final three steps (steps 10 to 12) cover the implementation and management phases of the PBD process.

10. Document in the final report—all the information involved in the PBD process for the building (i.e., step 1 to step 9, inclusive) needs to be documented in a final report, including the quality assurance processes that have been undertaken. The final report should also include any relevant conditions of use, consistent with the assumptions made in the PBD process, and all inspection and maintenance procedures. The format of the final report is typically governed by the jurisdiction for the building project, and the approval of the AHJ is generally required.
11. Implement the fire safety design plan—a conformity assessment is required, i.e., determining whether the construction complies with the design, and where any changes have occurred these need to be reviewed and approved by the affected parties and/or the AHJ, and the documentation updated accordingly.
12. Execute fire safety management—once the building project has been completed and the building becomes operational, fire safety management and independent inspection procedures need to be implemented throughout the lifetime of the building, and life-cycle analyses conducted when a change in use, occupancy, or fuel load occurs during the lifetime of the building.

3.3. International Fire Engineering Guidelines

The International Fire Engineering Guidelines or IFEG were developed as a collaborative venture between the National Research Council of Canada, the International Code Council of the United States of America, the Department of Building and Housing of New Zealand, and the Australian Building Codes Board to meet the joint needs of each jurisdiction [12]. The IFEG process is executed through a Fire Engineering Brief (FEB). The purpose of the FEB is to "set down the basis, as agreed by the relevant stakeholders, on which the fire safety analysis (including any PBD) will be undertaken" ([12], p. 1.2-2). It is intended to be agreed to by all stakeholders prior to any analysis of PBD. The steps of the FEB framework are as follows [12]:

1. Define the scope of the project, including the contractual context, regulatory framework, and project schedule.
2. Identify relevant stakeholders so that the process is collaborative, noting that not all stakeholders will contribute equally to the project. Typical stakeholders will include the client, fire engineer, architect/designer, consultants, fire service, AHJ, insurance company representative, building operations management, and potentially tenants.

3. Defining the principal building characteristics including occupancy, location, size and shape, structure, hazards, fire protective measures, management, maintenance, environmental conditions, value, and other matters, including firefighting concerns.
4. Defining the principal occupant characteristics including distribution, state, physical and mental attributes, levels of assistance required and available, occupant group roles, activity at the outbreak of fire, and familiarity with the building.
5. Defining the fire safety objectives for the project, including:
    i. Building regulatory objectives such as protecting occupants, facilitating emergency services response, protection of the property in question, and prevention of fire spread.
    ii. Other regulatory objectives such as environmental protection, workplace health and safety, fire services, dangerous goods, land use and other planning matters.
    iii. Non regulatory objectives such as limiting structural, contents or equipment damage, safeguarding community interests and infrastructure, and maintaining business continuity or operations.
6. Defining hazards such as hazardous layouts, activities, ignition sources, and fuel sources, as well as detailing the preventative and protective measures, including:
    i. Sub-system A, being Fire Initiation and Development and Control
    ii. Sub-system B, being Smoke Development and Spread and Control
    iii. Sub-system C, being Fire Spread and Impact and Control
    iv. Sub-system D, being Fire Detection, Warning and Suppression
    v. Sub-system E, being Occupant Evacuation and Control
    vi. Sub-system F, being Fire Services Intervention
7. Developing the trial designs, being the fire safety designs that are to be assessed using agreed fire engineering techniques.
8. Where PBD is included in the project, non-compliances with DtS provision must be identified, and specific objectives or performance requirements for each PBD must be clearly detailed.
9. Once the specific objectives or performance requirements for PBD are defined, the approaches and methods of analysis must be documented. This also includes the identification of any sensitivity, redundancy, or uncertainty studies required during the analysis.
10. Defining the acceptance criteria, being the criteria used to determine whether the results of the analysis of the trial design are equivalent to a DtS design or meet the specified performance requirements. This stage also includes defining any factors of safety to be utilized in the analysis.
11. Defining fire scenarios and parameters for design fires, applying a three-step process ([12], p. 1.2-27):
    i. Determining potential fire scenarios.
    ii. Selecting the design fire scenarios to be used for developing the design fires.
    iii. For each design fire scenario, specifying a schematic design fire.
12. Defining the design occupant groups, including the most common, vulnerable, or influential occupant groups impacted by the design fire scenarios.
13. Defining how high or low the standards of construction, commissioning, management, use, and maintenance are expected to be post completion.
14. Completing the FEB Report which details each of the previous stages as well as summarizing the discussions, assumptions, and factors behind critical decisions.

3.4. Australian Fire Engineering Guidelines

Introduced in July 2021, the Australian Fire Engineering Guidelines (AFEG) [11] are specific to the Australian built environment context, and where a project involves PBD, it must follow a four-step procedure:

1. A performance-based design brief is prepared in consultation with the relevant stakeholders.

2. Carry out the engineering analysis using suitable assessment methods.
3. Evaluate the results of the analysis against the acceptance criteria agreed in the performance-based design brief.
4. Prepare a final report to document the process.

While the AFEG are generally classified as non-mandatory guidance, this four-step procedure for PBD is in fact a mandatory requirement from section A2.2 of the BCA Volume One [15] or Volume Two [16], with both code volumes being part of the NCC suite of compliance documents.

4. CAED Framework

As discussed in the previous sections, the SFPE, ISO, and IFEG PBD frameworks contain between 12 and 15 discrete steps. While these three flowcharts may appear to be more complex and detailed than the four-step process in the AFEG in Australia, the former three frameworks can in fact be distilled down to the same four key elements, subsequently referred to as the "CAED Framework", namely:

1. Consultation,
2. Analysis,
3. Evaluation, and
4. Documentation.

There are some fundamental components associated with each of the four elements of the CAED Framework, as follows:

1. Consultation
   There are a number of discrete but interrelated components to the Consultation element in the CAED Framework:
   1.1. Scope—identify and describe the scope of the project, e.g., occupancy, physical parameters, etc.
   1.2. Stakeholders—identify the key stakeholders for the project and include them in the consultation process, e.g., fire service, urban planning agency, AHJ, insurers, design team, client, developer, financier, community, local indigenous groups, etc.
   1.3. Objectives—identify the primary objectives and outcomes for the project, e.g., life safety, property protection, fire service intervention, urban planning, preservation of heritage, continuity of occupation, environmental impact, etc.
   1.4. Performance Metrics—identify the key performance metric(s) associated with each objective and how they are to be quantified.
2. Analysis
   The Analysis element in the CAED Framework is essentially an iterative process of design refinement, consisting of the following components:
   2.1. Methods of Analysis—identify how the performance is to be quantified and analyzed with respect to the performance metrics.
   2.2. Initial Design—proposed an initial design that generally complies.
   2.3. Analysis—conduct the various engineering analyses required to test the initial design against the performance metrics.
   2.4. Refinement—adjust the initial design where opportunities to optimize the design exist and iteratively test these refinements against the performance metrics.
   2.5. Finalization—finalize the design.
3. Evaluation
   The Evaluation element of the CAED Framework consists of a systematic process to evaluate whether the final version of the design meets all the objectives that have been identified during the Consultation stage of the project, as follows:
   3.1. Evaluate—evaluate the various aspects of the design against the performance metrics that apply.

   3.2. Confirmation—confirm that each of the objectives have been met.
   3.3. Signoff—obtain approval in principle from stakeholders.
4. Documentation
   The Documentation element of the CAED Framework consists of the documentation and associated quality control process required to achieve the final approval from the AHJ that the final design meets all regulatory requirements for the project, as follows:
   4.1. Design Documentation—produce documentation to summarize the key elements and conclusions of the design process.
   4.2. Quality Control—undertake and document a quality control process commensurate with the scale and complexity of the project and as agreed with the stakeholders, e.g., internal review/approval, external/independent peer review.
   4.3. Regulatory Approval—complete and submit all documentation required for the regulatory approval and respond to any requests for information, etc., from the AHJ.
   4.4. Construction Documentation—produce drawings, specifications, etc., as required for the construction and commissioning of the project.

5. Contextualization to the WUI Context: Consultation Process

In order to clarify the differences between traditional fire engineering and wildfire engineering contexts we now apply the CAED Framework to two comparative cases, namely, we compare Case A, consisting of PBD in the urban built environment, i.e., remote from the WUI, and the parallel scenario Case B of PBD at the WUI. To give the comparison a meaningful context, we use a hypothetical building for Case A, being a proposed multi-story apartment building in an existing central city setting, while for Case B it is a proposed new residential subdivision, inclusive of a school, shops, holiday chalets, and petrol station, on the outskirts of an urban area that borders a wildland area.

From a traditional fire engineering perspective, it would be very unlikely that a PBD approach would be adopted for a single residential building in a suburban setting, but the investment could be justified at the subdivision scale. To clarify the use of the term "subdivision", this means a larger piece of land that is subdivided into smaller plots of land upon which residential homes are built. One conceptual way to compare the two cases is that Case A is a "vertical suburb", while Case B is a "horizontal suburb" (or part thereof). We do not propose that the CAED Framework will be suitable for single house infill development within existing WUI subdivisions, For the same reason, it would not be suitable to conduct a separate and independent fire engineering analysis for a new apartment built on the top of an existing 30-story building that completely ignores the fire safety designs and limitations of the existing FEB Report.

We limit our comparison to the first element of the CAED Framework, namely the Consultation element. We anticipate that of the four elements that we include in our CAED Framework construct, the Consultation element is where the key differences between Case A and Case B will occur, at the level of specific detail. For the remaining three elements of the CAED Framework, whilst technical approaches may differ, we consider that the broad principles of the Analysis, Evaluation, and Documentation will generally equally apply to both Case A and Case B. We also use Australia and the BCA as the basis for the comparison.

5.1. Consultation Element of CAED Framework—Component: Scope

5.1.1. Occupancy

Within the context of Case A, an apartment building is generally owner-occupier or rental apartments. In terms of the BCA, this is Building Class 2 [15,16] in the full list of Building Classes as classified by the BCA, summarized in Table 1. It should be noted that while this type of building is typically designed for the primary occupancies noted, it is often used effectively as a hotel, with short-term guests—for the purposes of this example, such possible building usage is ignored. It is also common to have other occupancy types, such as retail and carparking, in this category of building, but again this is ignored for the purposes of this case study.

Table 1. Building Classes under the BCA [15,16] © Commonwealth of Australia and the States and Territories of Australia 2020 and used under a CC-BY-ND license.

Australian Building Class	Description
Class 1a	A single dwelling being a detached house, or one or more attached dwellings, each being a building, separated by a fire-resisting wall, including a row house, terrace house, town house, or villa unit.
Class 1b	A boarding house, guest house, hostel, or the like with a total area of all floors not exceeding 300 m^2, and where not more than 12 reside, and not located above or below another dwelling or another Class of building other than a private garage.
Class 2	A building containing 2 or more sole-occupancy units, each being a separate dwelling.
Class 3	A residential building, other than a Class 1 or 2 building, which is a common place of long-term or transient living for a number of unrelated persons. Example: boarding-house, hostel, backpackers accommodation, or the residential part of a hotel, motel, school, or detention centre.
Class 4	A dwelling in a building that is Class 5, 6, 7, 8, or 9 if it is the only dwelling in the building.
Class 5	An office building used for professional or commercial purposes, excluding buildings of Class 6, 7, 8, or 9.
Class 6	A shop or other building for the sale of goods by retail or the supply of services directly to the public. Example: café, restaurant, kiosk, hairdressers, showroom, or service station.
Class 7a	A building which is a car park.
Class 7b	A building for the storage or display of goods or produce for sale by wholesale.
Class 8	A laboratory or a building in which a handicraft or process for the production, assembling, altering, repairing, packing, finishing, or cleaning of goods or produce is carried on for trade, sale, or gain.
Class 9	A building of a public nature.
Class 9a	A health care building, including those parts of the building set aside as a laboratory.
Class 9b	An assembly building, including a trade workshop, laboratory or the like, in a primary or secondary school, but excluding any other parts of the building that are of another class.
Class 9c	An aged care building.
Class 10	A non-habitable building or structure.
Class 10a	A private garage, carport, shed, or the like.
Class 10b	A structure being a fence, mast, antenna, retaining or free standing wall, swimming pool, or the like.
Class 10c	A private bushfire shelter.

Within the WUI context (Case B) the occupancy may contain multiple primary and secondary occupancies, including all Building Classes. Whilst BCA Classes 1–3 (essentially residential dwellings) and, depending on their proximity to the dwelling, some Class 10 buildings (garages, sheds, etc.) may be subject to enhanced wildfire resilient construction requirements, the remaining Classes (shops, professional offices, public buildings, car parks, etc.) are not. From a life safety perspective, this is important, as, in contrast to Case A, where the ultimate objective is for a building to provide a safe environment from an internal fire whilst occupant evacuation occurs, in Case B the objective is to provide a safe refuge from an external and uncompartmentalized wildfire. In Case B, the differences in occupancy are typically identified as normal, "high-risk", including industrial developments, and "vulnerable", including schools, hospitals, aged care, and even tourist facilities [29–34]. This in turn can result in discrepancies between enhanced bushfire construction requirements between the BCA and jurisdictional planning policy, further complicating the efforts to achieve wildfire safety engineering objectives within the WUI [23].

5.1.2. Physical Parameters

Physical Scope

For Case A this is essentially the building itself, with a relatively small footprint that may only be equivalent to a few suburban allotments in a subdivision. The key difference is that for Case B this is a whole subdivision consisting of many individual allotments which, collectively, are likely to cover a large area, e.g., 1 km^2 or more. The subdivision will also include infrastructure such as roading and amenities such as parks.

Fire Service Vehicular Access

Typically, in Case A, there is at least one street frontage, but the other sides of the building could well be very close to the allotment boundary on other non-street sides, with very limited or no vehicular access. There is no possibility of the fire services becoming overrun and entrapped by fire during the vehicular response to the building. By contrast, in Case B whilst many allotments would be expected to have a street frontage on at least one side, the key difference is that fringe development and lifestyle blocks are more likely to propose "tight" access routes for fire service vehicles down a narrow right-of-way (e.g., driveway). In addition, the potential for fire services to be overrun and entrapped by wildfire is an unfortunate yet all too common occurrence [35]. For this reason, in Case B fire service vehicular access should also be designed with the consideration of whether firefighters should actually be accessing the area at all, for example where it is demonstrated that an area contains no assets of value or where fire scenario analysis reveals that an area is physically undefendable due to the severity of wildfire conditions [36] or insufficient firefighting water supply [37]. An important distinction regarding fire services' vehicular access is that in Case A the access may also be used for normal occupant access and evacuation, whereas in Case B fire service access is typically considered as a separate requirement to public road access and egress design.

Construction

In Case A, the primary structure (what holds the building up) will typically be reinforced concrete and structural steel. The external cladding could be aluminum/glazing (e.g., curtain-wall system) or combustible or non-combustible cladding with windows. The key difference for Case B is the scale of the structures. Typically, detached and semi-detached houses are one- or two-story structures. The primary structural system could be either (1) timber framing, (2) lightweight steel framing, (3) double brick, or (4) structural insulated panels. Cladding systems consist of many options, ranging from non-combustible (e.g., brick or steel) to limited combustible (e.g., fiber cement sheet) to combustible (e.g., timber weatherboards).

Building Code Provisions

The BCA Vol. 1 [15] applies to Case A. Generally, there are specific fire safety provisions, primarily in Section C, Section D, and Section E of the BCA Vol. 1, which relate to "fire resistance", "access and egress", and "services and equipment". For clarity, Part G5, "construction in bushfire prone areas", is not considered relevant for Case A due to its inner-city location. Primarily, the BCA Vol. 2 [16] applies to Case B, but in large developments involving retail, commercial, and industrial occupancies, the BCA Vol. 1 [15] also applies. The key difference is that there are generally very few fire safety provisions for detached or semi-detached residential homes. The BCA Vol. 2 [16] has "spread of fire" and "automatic warning for occupant" provisions (Part 2.3, Vol. 2), as well as provisions for "buildings in bushfire prone areas" (Part 2.7, Vol. 2)

Fire Hazards

For Case A there would be a range of fire hazards, typically within the building (e.g., ignition of combustible contents and construction materials), but the possibility of an external fire (igniting combustible cladding materials) would also be considered. Typically, building occupants could be exposed to thermal, toxicity, and visibility hazards, as well as the hazard associated with building collapse.

The key difference and primary fire hazard of interest for Case B is external, namely wildland fire exposure, which would typically consist of a fast-moving flame front preceded by burning brands and embers ahead of the flame front. A number of man-made or natural materials can be ignited, such as: (1) combustible external construction materials (e.g., cladding, roofing, decking); (2) vegetation on allotments (e.g., trees); (3) planting (e.g., hedges and planted border shrubs); (4) accumulated dead vegetation (e.g., leaves or pine needle build-up in gutters); and (5) combustible contents inside the dwelling (e.g., curtains and drapes on windows, insulation in roof spaces). As the authors have previously reported [20], in Australia the use of Australian Standard AS 3959 Construction of Buildings in Bushfire Prone Areas [38] has been extended into jurisdictional planning provisions [29–34] as a method for determining whether land use is "appropriate" from a wildfire impact perspective. The appropriateness of a development is measured by a hazard level known as the "bushfire attack level" (BAL), which is derived from the worst-case calculated radiant heat flux in accordance with AS 3959 [38]. Development is considered "appropriate" in areas subject to radiant heat flux not greater than 29 kW/m^2 (BAL-29), while high-risk or vulnerable land use is not permitted in areas exceeding 12.5 kW/m^2 (BAL-12.5). It should be noted that development in these areas is conditional on construction standards in accordance with AS 3959.

Occupant Warning Systems

The Case A building will have a reasonably sophisticated detection and alarm system to warn building occupants (timescale of minutes). Depending on the location of the fire, this may only alert occupants in what is called a single occupancy unit (SOU) if the fire occurs in an apartment, or a building-wide alarm if the fire occurs in a common area (e.g., a corridor used as common access to multiple apartments). The key difference for Case B is that the occupant warning will generally be further in advance than in Case A (although this may not always be the case, as it may occur with sudden or unexpected changes in weather conditions) and will consist generally of media coverage and emergency service warnings in advance (timescale of minutes to days) of exposure to hazardous conditions.

Occupant Egress

For Case A, occupants would generally be expected to self-evacuate based on warnings provided by various detection and alarm systems within the building. For occupants on higher floors, evacuation options would generally be limited to two or more stairwells. Depending on the specifics of the buildings (e.g., occupant numbers, egress options, etc.), bottlenecks are possible at entry points to the stairwells and within the stairwells (manifested by queuing) and delay the full evacuation of the building. Once occupants have exited the building, they are generally (but not always—e.g., fall debris from above) considered to have reached a place of safety. Where occupants are unable to self-evacuate, fire service personnel are likely to render assistance.

The key difference for Case B is that rather than a single building evacuation (Case A), a suburb-wide evacuation must be considered. In Case B as opposed to planning for mass occupant evacuation with little to no warning it may be decided that the best strategy is to shelter in place [20], whereby the development relies on occupants sheltering in their wildfire resilient dwellings. Therefore, rather than occupants self-evacuating down a flight of stairs from an upper floor to the exterior of the building (typical Case A place of safety), homeowners are likely to need to self-evacuate in their own personal motor vehicle to a place of safety remote from the advancing fire front (e.g., to suburb different from that in which they live). The equivalent to Case A queuing and bottlenecks in evacuation stairs for Case B is traffic jams caused by a large number of motor vehicles using roads to evacuate to safety. Whereas, for example, in Case A, evacuating occupants may be exposed to untenable conditions within corridors and stairwells, for Case B evacuating occupants are exposed to smoke, moving fire fronts, and embers/burning brands on a larger, external scale as they evacuate in their motor vehicle on the local roading network. Whilst the complexities of such evacuations are well documented [39–46], we previously [20] reported only a single study [47] providing guidance for the design of public road networks and access/egress points to facilitate mass evacuation as required for Case B.

Fire Service Response

Typically, a fire incident in an inner-city location (i.e., Case A) involves a single building. The role of the fire service is to undertake firefighting and rescue activities as dictated by the particular fire incident and the ability of building occupants to self-evacuate. As well as fighting the fire in the building in question, it is possible that the firefighting response may also need to deal with limiting fire spread to adjacent buildings. In a typical urban setting, a local fire station is in close proximity, with a response time of 5–10 mins reasonably expected. Because it is a single-building incident, there are generally sufficient fire service resources and firefighting water supply available to deal adequately with the fire incident.

In Case B the key difference is that a typical wildland fire incident will be at least a suburb-wide event involving fire attacking multiple buildings concurrently. Due to the scale of the incident, the fire service response may be drawn from multiple agencies, and it is likely that resources will be stretched beyond capacity and as a result the fire service will be unable to respond to all requests for assistance. It is also likely that firefighting water may be in short supply due to multiple street hydrants being connected simultaneously. As such, the response will have similarities to other large-scale fire events, such as post-earthquake fires where there will also be a reduced likelihood of fire service intervention due to the regional scale of the event and damage to roading networks. The fire service response will typically be to defend buildings externally at the WUI in the face of an approaching fire front, and then redeploying as conditions become untenable. When combined with the considerations that human tenability and firefighter operational effectiveness thresholds are less than 3 kW/m^2 [36], and the wildfire rate of spread can result in external conditions that might change from tenable to nonsurvivable in seconds, the result is that entrapment is a major cause of fatality during wildfire events [35].

Fire Safety Systems and Procedures

The fire safety systems in the Case A building typically include the fire safety sub-systems detailed in the IFEG [12] and AFEG [11]. Adopting equivalent categories for Case B, a contextualization and comparison are provided in Table 2. In Case B, rather than having a whole range of electro-mechanical and hydraulic fire safety systems in the Case A building that suppress the fire, the fire service and/or occupants may be able to defend buildings that are threatened by an approaching fire front but are likely to have to abandon such efforts if conditions become untenable. Other differences include the ability of the various sub-systems to limit or impact internal smoke and fire spread within a compartmentalized urban structure (Case A) compared to an external wildfire with potentially hundreds of kilometers in fire perimeter moving through an uncompartmentalized landscape, the nature of evacuations (previously discussed), and the reduced capacity of responding fire services to control a wildfire compared to a structure fire in an urban environment.

5.2. Consultation Element of CAED Framework—Component: Stakeholders

Stakeholders for both Case A (urban) and Case B (WUI) will be similar and include the fire service, urban planning agency, Authorities Having Jurisdiction, insurers, design team, client, developer, financier, community, local indigenous groups, etc.

Table 2. Fire safety sub-system comparison between an urban environment (adapted from [11], Table 2.2.3) and the WUI.

Sub-System	Case A (Urban)	Case B (WUI)
SS-A Fire initiation, development, and control	• Limitation of ignition sources • Limitation of nature and quantity of fuel • Arrangement and configuration of fuel • Separation of ignition sources and fuel • Management of combustibles including housekeeping measures • Electrical safety equipment • Regular plant maintenance (where applicable) • Adherence to procedures for "hot work" (e.g., welding)	• Reduced fuel zone buffers surrounding development, incorporating arrangement and configuration of fuel. • Maintenance requirements for common land areas including road verges, parks, and fauna corridors. • Restrictions on works/activities (e.g., campfire or hot work bans)
SS-B Smoke development, spread, and control	• Smoke barriers • Natural smoke venting • Mechanical smoke management	• N/A due to nature and scale of wildfire smoke plumes
SS-C Fire spread, impact, and control	• Separation of fuel • Separation of buildings • Fire resistive barriers • Fire resistive structural elements • Fire resistive air-handling ducts • Fire resistive dampers • Exposure protection	• Separation of buildings • Wildfire resistant construction (such as AS 3959) • Enforcement of property fire protection notices and local laws (such as Firebreak Notices)
SS-D Fire detection, warning, and suppression	• Automatic and manual detection equipment • Automatic and manual warning equipment • Surveillance equipment • Automatic suppression equipment • Manual suppression equipment	• N/A as wildfire detection and warning remain the remit of fire services
SS-E Occupant evacuation and control	• Evacuation plans • Occupant training • Emergency communications • Egress signage • Egress routes (including fire-isolated elements)	• Vehicular evacuation routes and egress signage
SS-F Fire services intervention	• Type of fire services available (full-time/permanent or volunteer) • Characteristics of Fire Services' capability and resources • Fire services' access to the site and the building • Water supplies and infrastructure	• Characteristics of fire services' capability and resources (including aerial firefighting capability), noting that large wildfires may require interstate or even international support • Water supplies and infrastructure

5.3. Consultation Element of CAED Framework—Component: Objectives

Whilst the fire safety objectives essentially remain the same between Case A and Case B, and the objectives can be placed into the three broad categories similar to those detailed by ABCB [11] being (i) building/planning regulatory objectives, (ii) other regulatory objectives, and (iii) non-regulatory objectives, there are differences between the urban and WUI contexts. The main difference between Case A and Case B is that planning and urban design processes will have more of an influence in the WUI environment, particularly in contexts such as Australia, where development suitability is first assessed by means of an urban design planning process which consider all buildings, infrastructure, and other assets within the development prior to individual building by building analysis under the BCA [15,16]. This is reflected in the escalation of the priority of planning objectives in Case B compared to Case A. A comparison of potential objectives between Case A and Case B is summarized in Table 3.

Table 3. Comparison of objectives between the urban environment (adapted from [11]) and the WUI.

Case A (Urban)	Case B (WUI)
Building regulatory objectives • protecting building occupants • facilitating the activities of emergency services personnel • protecting the property • preventing the spread of fire between buildings.	Planning regulatory objectives • protecting occupants and visitors within the entire development • facilitating the activities of emergency services personnel • protection of community interests and infrastructure • dangerous land use • environmental protection • heritage conservation • energy efficiency • compliance with zoning and scheme requirements • other planning matters Building regulatory objectives • protecting building occupants • facilitating the activities of emergency services personnel • protecting the property • preventing the spread of fire between buildings.
Other regulatory objectives • environmental protection • occupational health and safety • fire services • dangerous goods • land use and other planning matters.	Other regulatory objectives • occupational health and safety • fire services
Non-regulatory objectives • limiting structural and fabric damage • limiting building contents and equipment damage • maintaining continuity of business operations and financial viability • safeguarding community interests and infrastructure • protecting corporate and public image • protecting heritage in older or significant buildings • limiting the release of hazardous materials into the environment.	Non-regulatory objectives • limiting structural and fabric damage • limiting building contents and equipment damage • maintaining continuity of business operations and financial viability • protecting corporate and public image

5.4. Consultation Element of CAED Framework—Component: Performance Metrics

Following the selection and defining of appropriate objectives, the Performance Metrics, also known as Performance Criteria, need to be set, as, whilst the objectives provide a qualitative description of the required outcomes of the design, they lack the specificity required to facilitate the quantitative engineering analysis necessary to numerically assess the proposed design [21]. Generally taking the form of damage indicators [21], their exact formulation will depend on the analysis approach selected [22]. For a comparative approach, the PBD in question is assessed against a DtS design in the same situation [21,22]. In such instances, the Performance Metric will be presented in such a way that a comparison against the prescriptive approach is presented. For example, in the WUI context, the Performance Metric of a PBD public road network could be defined by the criterion that it must facilitate the evacuation of the occupants of the proposed development to the same standard, measured in number of occupants and required safe evacuation time, as the design prescribed in relevant planning or urban design specifications. For an absolute approach the PBD would be assessed against agreed acceptance criteria without reference to the DtS or prescriptive design elements [12]. As an example, in the WUI context, the Performance Metric of a PBD public road network could be defined by the criterion that it must facilitate the evacuation of occupants of the proposed development prior to tenability thresholds being reached—in other words, the required safe evacuation time is less than the available safe evacuation time.

The SFPE [21] suggest that within the urban environment (Case A), Performance Metrics can be separated into Life Safety Criteria, being (1) thermal effects on human beings, (2) toxicity, and (3) visibility; and Non-Life Safety Criteria, being (1) thermal effects on structures, (2) smoke damage, (3) fire barrier damage and structural integrity, (4) damage to exposed areas, and (5) damage to the environment. Whilst all Performance Metrics applicable to buildings within the Case A context still apply to Case B, as building fires can occur within WUI developments independently of any wildfire event, additional wildfire specific metrics will also apply.

Within the WUI context (Case B), several key differences must be considered when selecting and categorizing Performance Metrics [23]. These differences include but are not limited to:

- Unlike the urban context, where occupants evacuate from a fire within a building to tenable conditions in the external environment, during a wildfire the buildings themselves are required to be shelters for occupants and at times firefighters from untenable external conditions. Therefore, in the context of Case B, thermal effects on structures and structural integrity must also be considered Life Safety Criteria.
- There is little evidence to support visibility or toxicity being necessary life safety criteria in the WUI context [48,49], except in the cases of wildfire bunkers or shelters such as those described in the Private Bushfire Shelters Performance Standard [50], which will be assessed independently of the greater WUI development. Therefore, we suggest it may be appropriate to exclude visibility and toxicity as Life Safety Criteria for Case B.
- In Case A, whilst a significant incident as catastrophic as the Grenfell Tower fire of 2017 can result in significant loss of life, it does not impact critical infrastructure affecting the life safety of occupants in neighboring buildings or suburbs. By comparison, wildfires such as those routinely experienced in California and Australia may result in the destruction of vital infrastructure and utilities, which in turn can result in humanitarian crises for thousands of people, requiring interstate or even military aid intervention. In WUI contexts, the destruction of critical infrastructure such as bridges can result in evacuating occupants becoming trapped, whilst the damage or destruction of telecommunications infrastructure can prevent community warnings and information being transmitted. In both cases the results can include large numbers of fatalities. Therefore, in the context of Case B, damage to critical infrastructure may also be considered a life safety Performance Metric.
- Unlike the multitude of fire safety systems available to suppress, contain, and extinguish fires in the urban context (Case A), wildfires (Case B) require a significantly greater reliance on firefighters and machinery to complete this tasking. Therefore, we suggest a strong argument exists for firefighter tenability to be considered as a life safety criterion.

Taking into account these differences, we suggest Life Safety Criteria for the WUI context (Case B) that include (1) thermal effects on occupants; (2) thermal effects on responding firefighters; (3) thermal effects on the structural integrity of buildings serving as refuges, and this includes any dwelling or other building in which occupants or firefighters may seek shelter from the impacts of wildfire as well as private bushfire shelters and similar bunkers; (4) thermal effects on structural integrity and the operation of critical infrastructure; and (5) suitability of public road evacuation designs. Unfortunately, despite the importance of these Life Safety Criteria and the magnitude of recurrent wildfire impacts experienced globally on an annual basis, in a recent systematic literature review [20] we reported limited evidence-based performance thresholds suitable as measures within these criteria. As such, it remains an area needing significant and urgent future research focus.

6. Conclusions

Our previous research concluded that even amongst developed English-speaking nations prone to wildfire impacts, an absence of defined fire safety engineering consultation processes within the WUI context exist. In order to address this knowledge and practice gap, in this study we therefore sought to provide a structure for the development of standardized PBD within the WUI context across international jurisdictions, as well as to embed best practices into the emerging field of wildfire engineering, with a specific focus on the Consultation process.

To achieve this, we have reviewed existing English language fire engineering best practice frameworks in the traditional urban context, and subsequently distilled and contextualized them into the wildfire context through the development of the CAED framework. The application of the CAED Framework was then illustrated by a simultaneous contextualization of the key element of the framework to both an urban and WUI case study. Whilst a detailed explanation of all components of the CAED Framework is not possible within the limitations of a research article, this paper provides the general structure of the framework itself and a detailed explanation of the most complicated and critical element in the CAED Framework, namely the Consultation element, and each of the subsequent technical components of the Consultation element.

The successful in-parallel application of the Consultation element of the framework to both an urban and a WUI case study, and acknowledging that the application of remaining Analysis, Evaluation, and Documentation elements of the CAED Framework is largely similar between the urban and WUI contexts, demonstrates that the CAED Framework is suitable for undertaking PBD in WUI applications. Importantly, it also provides a foundation for further studies in the wildfire engineering field to build upon.

Whilst the development of the CAED framework is significant in that it contributes to the adoption of a standardized process for PBD development within the WUI context across international jurisdictions, further research is required in order to develop both evidence-based quantitative performance criteria and verification methods. Until such research is completed, and the findings are embedded into the urban design process at the WUI, fire safety engineering within the wildfire context will remain an immature profession compared to its more mature urban counterpart. Arguably, this will continue to result in both a lower level of comparative safety and increased pressure on fire services to protect inappropriately designed wildland communities.

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