BUILDING RESILIENCE

Using Parametric Modelling and Gaming Engines to Simulate the Impacts of Secondary Structures in Bushfire Events

ANASTASIA GLOBA[1], DAGMAR REINHARDT[2], ADRIENNE KEANE[3] and PETER DAVIES[4]
[1,2,3] *The University of Sydney, School of Architecture, Design and Planning.* [4]*Macquarie University, Faculty of Science and Engineering*
[1] *anastasia.globa@sydney.edu.au, 0000-0002-4749-5675*
[2] *dagmar.reinhardt@sydney.edu.au, 0000-0003-0477-492X*
[3] *adrienne.keane@sydney.edu.au, 0000-0002-6991-8528*
[4] *peter.davies@mq.edu.au, 0000-0002-2711-891X*

Abstract. Bushfires are a global phenomenon, closely connected to climate change and safety, resilience and sustainability of cities and human settlements. Government agencies, architects and researchers across institutions are committed to improving Australia's resilience to bushfires yet grappling with ways to further mitigate risks. 'Build back better' is the often-used phrase to support bushfire resilience, yet there remains a limited understanding of how secondary structures, such as storage sheds, garages, and fences contribute to or mitigate fire loss. These secondary structures are integral to properties yet fall, largely, outside land use planning approval processes and other regulations. Computational modelling can be adapted to deliver visualisations that increase awareness. We developed several simulation approaches which addressed distances, relationship to and the construction materials of secondary structures, terrain slopes and environmental forces. We conclude that gaming engines may offer the optimal immersive opportunity for residents and others to visualise fire risks related to secondary structures to increase awareness and improve bushfire readiness behaviours.

Keywords. Bushfire; Simulation; Game Engine; Visualisation; SDG 11.

1. Introduction

Bushfires are a global phenomenon, closely connected to climate change, rising temperatures, and dry vegetation (Van Oldenborgh, et al. 2021). The 2019/20 Black Summer bushfires devastated communities throughout NSW (Australia) with over 3000 homes lost (Australian Institute for Disaster Resilience, 2022). Reflecting the aims of Sustainable Development Goal 11 government agencies, councils, architect

POST-CARBON, Proceedings of the 27th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2022, Volume 2, 749-758. © 2022 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

chapters, and researchers across institutions are committed to improving Australia's resilience to bushfires yet are grappling with ways to further mitigate future disasters and ask better questions to address risk and rebuild in a way that offers safeguards against environmental and structural damage in the future.

To build back better, understanding the resilience of structures affected by bushfires is critical. Bushfire resistance of buildings, including construction, typologies, materials, and situating has been subject to extensive research and consequent changes to building codes. However, less is known about the behaviour of secondary or auxiliary structures and outbuildings, collectively referred to in this paper as secondary structures. These are inclusive of Class 10 structures, defined by the National Construction Code, Volume 1 (Australian Building Codes Board 2019), which are structures subject to state policies where no development application or approval is required, such as "ancillary" or exempt development provisions of the NSW planning system, or which are simply unregulated in terms of their location on a lot and construction quality. These range from permanent to semi-permanent structures such as storage sheds, garages, and fences, but also include temporal assemblies which can play a significant role in elevating fire risks such as wood stacks, garden furniture or domestic debris.

Numerous studies have reported that these structures can serve to protect or contribute to the loss of houses as a source of heat and ember attack. Consequently, this research focuses on the impact of secondary structures (Brown 2018) and user habits/adaptations of plots that may or may not fall outside of land use planning regulations on their fire promotion or resilience in bushfire prone areas. We focus also on distances, relationship to and construction of secondary structures, materials, terrains and environmental forces that can contribute to fire progression and consequent loss of habitable structures through ember attack, radiant heat or direct flame.

There are various ways in which fire behaviour can be simulated digitally, including parametric modelling, use of game engines, or dynamic simulations. Phoenix Rapidfire was developed in 2014 as a Bushfire Simulator (2014). Recent visualisation of a bushfire spread simulation adopts SPARK software developed by CSIRO using the Workspace workflow engine. In this study we focus on the development of a simulation and interface that deploys critical aspects of secondary structures by using Grasshopper3D and game engine Unity3D. Figure 1 illustrates the workflow, input, and output parameters of both approaches that were adopted in this study, further detailed in sections 3.2.1 and 3.2.2.

In the following, the paper provides a background to the phenomenon of bushfire and gaps in legislative framework for structures. Methodologies and simulation approaches are introduced and discussed as a first pilot study into best practice for visualisations through parametric modelling that increase understanding for the impacts of secondary structure placements in bushfire prone areas. The paper concludes with an evaluation of results and an outlook to future research.

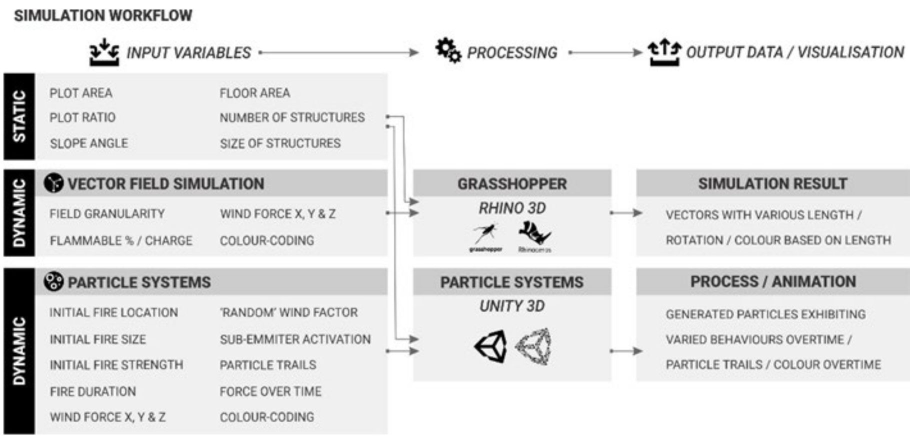

Figure 1. Simulation workflow: input / Processing / output for 2 tested approaches.

2. Background

Bushfires destroy houses and have significant environmental, social and economic impacts (Stephenson et al. 2013). They are becoming more frequent, larger and fiercer (Canadell et al. 2021). Research into the impacts of bushfires on houses has mostly identified the proximity of houses with bushland or vegetation as being the major factor for bushfire destruction. For instance, Crompton et al (2010) in their analysis of building damage and fatalities as part of the 2009 Black Saturday fires identified 25% of building damage occurred to properties located within a bushland setting and 60% of losses were less than 10m from the adjoining bushland. Such findings have supported various policies such as the 10:50 vegetation clearing policies, in effect giving the ability of a landholder to clear vegetation within 10m of a structure without consent from an authority, with some restrictions (Salgo and Gillespie 2018). Bushfire induced property loss and proximity to bushland has also been confirmed in studies in Europe and North America (Ganteaume et al. 2021; Masoudvaziri et al. 2021).

As cities grow and the need for housing people intensifies, planners are faced with the dilemma of where new housing should be located. Driven by economic and social pressures, some city responses include growing cities at their fringes and in the interface with bushland while cognisant that these areas are more vulnerable to bushfires. Increasingly these subdivisions and developments therein are the subject of increasing standards and regulations to manage bushfire risks reflecting policy gaps of the past (Ganteaume 2021). In NSW the cornerstone is provided by the Planning for Bushfire Protection guideline that links together planning and bushfire laws with building and construction standards, property to bush firefighting operational and maintenance requirements, and vegetation clearing maintenance among other elements. From a building perspective, the new standards are prospective and do not cover the extent of risks that may arise from secondary structures.

Research into the cause of bushfire destruction of homes has demonstrated that fire damage is magnified by the proximity of buildings and secondary structures, whereby fires, through ember attack, radiant heat or flame, can travel from one structure to another (Blanchi and Leonard 2005). Given the complexities that relate to property loss associated with bushfires, few studies offer any clear statistical relationship between the inter-structure proximity and loss (Costin 2021) while greater research attention has focused on the proximity of a structure and bushland. Roberts et al. (2021) modelled the effects of embers on property loss. In developing their risk calculations, they note that the risk will be influenced by many variables that relate to the natural and built environments. For the purpose of impact on buildings, this includes a range of considerations such as choice of building materials, the shape and orientation of homes and other structures (Syphard et al. 2012), the distance between structures, and the presence of shade sails, decks, and pergolas. From a risk mitigation perspective, the direction of the prevailing wind, thus ember attack, can have a significant impact on mitigating bushfire loss. To reduce the risk of short-range embers, for example, the construction of non-flammable structures, such as high metal fences, water tanks, sheds constructed to bushfire standards upwind of a house may reduce ember attack.

3. Method and Simulation approaches

Simulation models have been applied to understand fire behaviour (Garcia 2003), fire progression (Ohgai et al., 2005), firefighting activities, building evacuation (Jabi et al., 2019) and fire management. While this research has focused on primary dwellings and largely fire progression, our aim is to increase the understanding of and investigate the impact of secondary and auxiliary structures in bushfire-prone areas. A criteria framework has been developed and explores the use of algorithmic modelling tools and gaming engines to simulate the impacts of auxiliary structures in bushfire events. This leverages the affordances of computation and simulation tools that enable the rapid visualisation of various scenarios, controlling crucial parameters related to both environmental forces and urban conditions.

It should be acknowledged that the aim of this study is not to predict the spread of fire with full accuracy. Precise fire simulations are extremely hard to achieve because they involve many fluctuating variables and uncertainties (Cox 1994). Instead, this study aims to simulate and effectively communicate via visualisations the fundamental inter-dependencies of the fire-spread probability. The overarching goal is to make these visualisation methods available to a range of stakeholders, including urban planners, architects, legislators, and dwellers themselves, and to communicate the importance and potential impact of secondary structures within a lot on the spread of fire.

Initial investigation into the parameters of typical dwelling configurations in the context of Australia has revealed that in recent years the relationship between the size of a house and the size of a land plot has shifted dramatically (Hall, 2010). Comparing between 2005-2006 and 2019-2020 (for newly built houses) across five capital cities, the sizes of plots are shrinking while the sizes of houses (floor area) are growing. When calculating a *combined average land area for the ‘unbuilt’ spaces (plot area minus house floor area), in 2006 this measured 368m² and in 2020 was reduced to 219m². This means that the average ‘unbuilt’ area surrounding the main dwelling has reduced by 42% over 15 years. This highlights two bushfire risks: greater urban densities and a consequent lessening of space between houses; and the reduced available distance between various secondary structures and the primary dwelling.

3.1. CRITERIA FRAMEWORK

The primary setup for our multi-criteria parametric model has considered a range of conditions to describe and explore the impact of auxiliary structures. Data from a 2020 survey on the average sizes of house plots and dwellings were used as a reference point for a range of context iterations, testing for both smaller and larger than average scenarios. The average plot size considered was 467m², with a floor area of 248m², slope angle of <5 degrees and a plot width-to-length ratio as 1x2. Twenty-four iterations of static input variables (Figure 2) were explored in this generative study including: plot area, plot ratio, slope angle, house floor area, number of secondary structures and their size that were used as the 'static context' or 'base scenarios' to test two simulation approaches adopted in this study.

As illustrated in figure 1 the test criteria were split into two distinct groups: 1) static input variables and conditions that relate to the attributes of 'solid' structures, surfaces and objects in the system; and 2) dynamic input variables that relate to the internal or external 'forces' such as wind strength and direction and flammable potential 'charge' of elements in the system, that could fluctuate due to humidity or temperature. Static variables have informed the experimental set-up: dimensions and configurations of the house and the land plot; location of the main dwelling and secondary structures, with distances/ proximity to dwelling or themselves; size and number of secondary elements; volume and dimensions of the main dwelling and terrain (flat / slightly or lot sloped). The dynamic input variables included: flammable / non-flammable materials, and buildings addressed as conductors (the 'charge': stop or propagate fire); and the location, strength and directional force (wind) direction and force of 'fire' propagation.

3.2. ALGORITHMIC MODEL AND GAME ENGINE IMPLEMENTATION

We compared two fire spread probability methods, examining their affordances and limitations. Firstly, a series of parametric models using Grasshopper3D; and secondly, using a gaming engine - Unity3D. Due to major differences in algorithmic logic of the developed simulation approaches and the limitations of software functionality the dynamic input variables were slightly different between the approaches (Figure 1), however static input variables remained the same for both test groups.

3.2.1. Vector Field Visualisation in Grasshopper3D

Visual programming in Grasshopper3D allows for development of sophisticated algorithms that can generate various forms, forces, and conditions in three dimensions. Several Grasshopper plugins were considered to be adopted for this study, including agent-based modelling in Physarealm plugin, utilising the shortest-path logic and allowing to introduce obstacle-objects within the constructed system; and RhinoCFD plugin, that uses computational fluid dynamics. The initial testing revealed these plugins were not the best match for the intended simulation scenario, being too restrictive and limited in their capacity to accommodate our established simulation objectives. For example, in the proposed scenario secondary structures should act as secondary sources of fire instead of merely being obstacles. Therefore, it was decided to develop algorithmic definitions bypassing any additional plugins and focus on a visualisation of a Vector field, applied to all 24 context configurations to illustrate the variety of results depending on the input parameters.

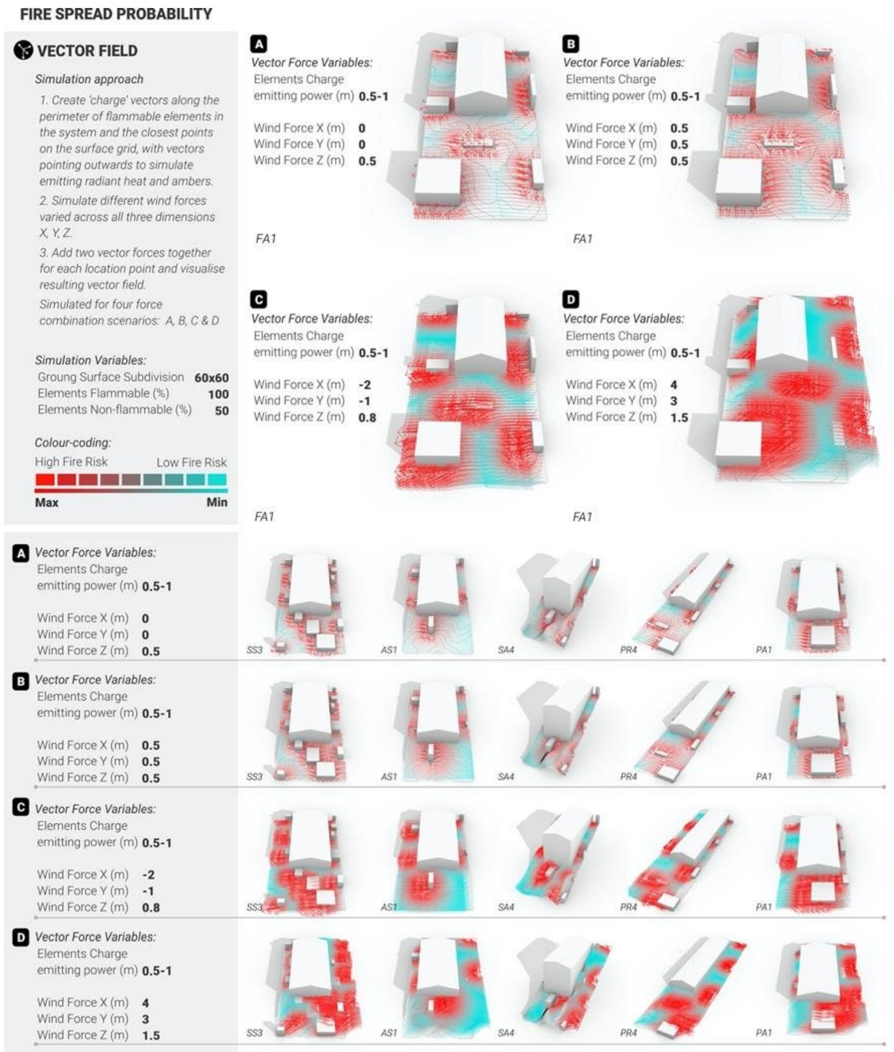

Figure 2. Vector Field visualisation approach using Grasshopper3D

The Vector Field approach was developed to simulate the effect of environmental forces - wind strength and direction in particular. This approach assumes that different elements in the system will have different directional fire potential / vector 'charges' (Figure 2). The algorithmic logic of this visualisation method progressed as follows: 1) secondary structures were assigned outward-facing 'positive charges'; 2) these charges were used to generate a vector field on the land-surface, with vectors located closest to the flammable objects facing perpendicular to the source objects and being longest and then becoming progressively shorter and cancelling each other out; 3) an external force was created, affecting the length and direction of all initial vectors - representing the wind. The resulting vector field was colour-coded based on the length of each vector, with red representing high fire risk areas and blue representing low fire risk areas.

3.2.2. Particle Systems in Unity3D

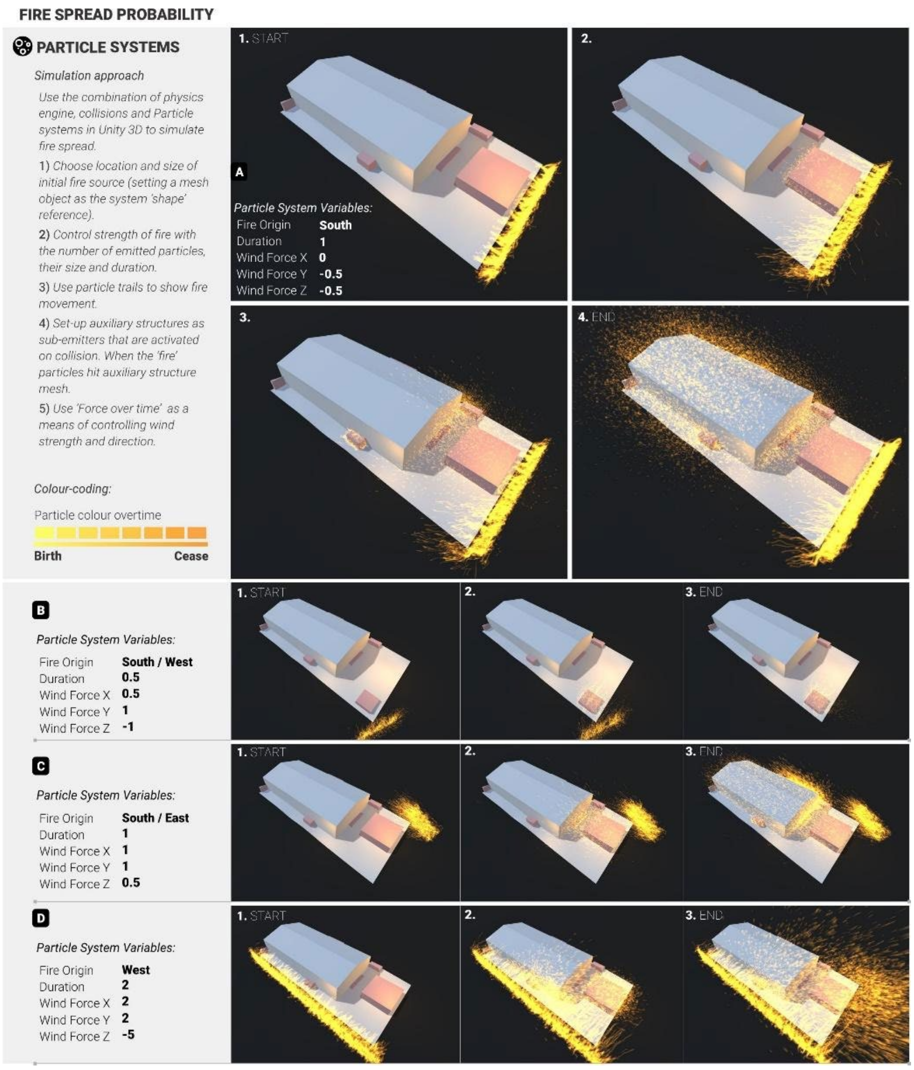

Figure 3. Particle Systems visualisation approach using Unity3D

A second stage of the fire-spread visualisations was implemented using advanced simulation capabilities of a game development platform - Unity3D. Unity3D is a powerful tool that has in-built Physics and Particle systems packages and can be customised and adapted to simulate complex particle or agent behaviours, such as fire spread. For the Particle System visualisation approach our initial static 'design context' or setup, which included the land plot, main dwelling, and secondary structures, were imported to Unity directly from Rhino as solid /collidable mesh geometries via FBX files. A particle system was introduced into the scene to simulate the fire spread that determined multi-criteria fire/particle behaviour (Figure 3).

The prototype of the fire spread particle system was developed from the KriptoFX Mesh Effect 6 prefab. The input parameters for the resulting system included: 1) the location, shape and size of the fire origin was set as initial particle-emission source; 2) intensity of fire was regulated by the number, size and lifetime of particles; 3) environmental forces such as wind were simulated using the 'force overtime' function; 4) fire particles' paths and movement were visualised using particle 'trails'; 5) colour-coding was set as time-dependent, where at birth particles were bright yellow but gradually changed colour to orange closer to their end-of-life; 6) secondary structure geometries were set as customisable sub-emitters to be triggered at collision. Several scenarios were tested for varied fire locations and wind forces (direction and strength). Particle systems allowed the incorporation of 'random direction' movement criteria for particles, which helped to simulate different wind changes and gusts.

4. Discussion

Reducing the risks of natural disasters and their impacts on urban settlements remains a core element to meeting the SDG 11 sustainable cities and communities. While this research has focused on secondary structures, this is significant as urban developments are projected to increase their spread into the present peri-urban and often bushland areas and increase in density that is likely to increase bush fire risk. While research on the impact of secondary structures as a contributory factor to fire risk is nascent, past major bushfires in Australia point to the importance of structures from a risk and loss perspective.

We suggest visualisation tools can support individuals in their decision making yet there is a porosity of this research for fire risk from a behavioural perspective. Our study has developed and compared visualisations from different fire spread probability methods. Both developed simulation approaches have high potential of bringing new insights and rising awareness among key stakeholders (such as homeowners, designers, builders and legislators) regarding the role of auxiliary structures in relation to the potential spread of fire. The simulation results suggest that the particle animation (Figure 3) is successful as a visualisation due to highly appealing graphics and simpler user navigation. As the Unity software supporting this approach uses a gaming engine, this further has the potential fort fire simulations as immersive first-person VR or AR applications. This communication and engagement tool may offer individuals a wider range of sensory experiences and support fire awareness and thus preventive behaviours. Specifically, the impact of secondary structures (which may otherwise by-pass land use planning assessment processes as they are not subject to fire rating construction standards) may be better understood as users relate to, configure, and use spaces within the lot. Care however needs to be undertaken when interpreting these results as the modelling does not purport to model fire behaviour.

Achieving change in how secondary structures are considered as a bushfire risk will require a concerted effort involving interdisciplinary approaches across architecture, planning, construction, modelling and community engagement. Our fundamental goal is to inform and influence behaviour (Brown 2018) to manage bushfire risks from those structures and activities that are left unregulated.

5. Conclusion and Future Research

This research illustrates alternative visualisation methods to enable users to better understand the consequences of decisions in relation to what and the placement of secondary structures in bushfire-prone areas. The aim of this empirical study has been to explore approaches and frameworks for bushfire risk visualisation.

Future research will further develop the utility of 3D data and simulation packages towards predictive modelling and pilot the output of the modelling with residents in a bushfire affected area to test its ability to inform and manage household-level risks associated with secondary structures. Future iterations of this study will involve further development of additional and more advanced simulation approaches and testing their implementation with potential stakeholders. The testing will include both comparative studies, evaluating the effectiveness of approaches separately and testing them as a complementary set of visualisations. Through benchmark testing, collaborations with councils and stakeholders on open-access data resources, we aim to provide crucial information on structural resilience and guide and support individuals one step closer to future proofing their house and local communities.

References

Australian Building Codes Board (2019). National Construction Code, Volume One. Canberra, Australian Building Codes Board.

Australian Institute for Disaster Resilience. (2022). Bushfires - Black Summer. Australian Disaster Resilience Knowledge Hub, https://knowledge.aidr.org.au/resources/black-summer-bushfires-nsw-2019-20/

Blanchi, R., & Leonard, L. (2005). Investigation of bushfire attach mechanisms resulting in house loss in the ACT bushfire 2003. *Bushfire CRC*. Highgett, Victoria.

Brown, D.N. (2018). Domestic Architecture and the Perception of Risk in Bushfire-Prone Areas, The University of Sydney. Unpublished PhD thesis.

Canadell, J. G., Meyer, C.P, Cook, G D, Dowdy, A, Briggs, P.R, Knauer, J, Pepler, A., & Haverd, V, (2021). Multi-decadal increase of forest burned area in Australia is linked to climate change. *Nature Communications* 12(1): 6921.

Costin, G. P. (2021). Bushfire: Retrofitting Rural and Urban Fringe Structures—Implications of Current Engineering Data. *Energies (Basel)* 14(12): 3526.

Ganteaume, A., Barbero, R, Jappiot, M and Maillé, E, (2021). Understanding future changes to fires in southern Europe and their impacts on the wildland-urban interface. *Journal of Safety Science and Resilience* 2(1): 20-29.

Garcia, R. (2003). Feeling the Heat - Exploring the Impact of Fire in Architectural Structures though Multimodal Interaction. *10th International Conference on Computer Aided Architectural Design Futures*. Taiwan.

Hall, T. (2010). Goodbye to the Backyard? -The Minimisation of Private Open Space in the Australian Outer-Suburban Estate. Urban Policy and Research 28(4): 411-433.

Jabi, W., Chatzivasileiadi, A, Wardhana, M. M., Lannon, S., and Aish, R. (2019). The synergy of non-manifold topology and reinforcement learning for fire egress. *Architecture in the Age of the 4th Industrial Revolution - Proceedings of the 37th eCAADe and 23rd*

SIGraDi Conference. J. Sousa, J. Xavier and G. Castro Henriques. Porto, Portugal, University of Porto. 2: 85-94.

Masoudvaziri, N., Szasdi Bardales, F., Keskin, O.K., Sarreshtehdari, A., Su, K,, and Elhami-Khorasani, N., (2021). Streamlined wildland-urban interface fire tracing (SWUIFT): Modeling wildfire spread in communities. *Environmental Modelling & Software* 143: 105097.

NSW Government, N. (2008). State Environmental Planning Policy (Exempt and Complying Development Codes) 2008. NSW Government.

NSW Rural Fire Service (2019). Planning for Bush Fire Protection, NSW Government.

Ohgai, A., Gohnai, Y., Ikaruga, S., Murakami M., and Watanabe K., (2005). Japan Cellular Automata Modeling for Fire Spreading as a Tool to Aid Community Based Planning for Disaster Mitigation. *Recent Advances in Design & Decision Support Systems in Architecture and Urban Planning* J. P. van Leeuwen and H. Timmermans, J,P. Dordrecht, Kluwer Academic Publishers: pp. 193-209.

Roberts, M. E., Rawlinson, A.A., and Wang, Z., (2021). Ember risk modelling for improved wildfire risk management in the peri-urban fringes. *Environmental modelling & software: with environment data news* 138: 104956.

Stephenson, C., Handmer, J., and Betts, R (2013). Estimating the economic, social and environmental impacts of wildfires in Australia. Environmental hazards 12(2): 93-111.

Syphard, A. D., Keeley, J. E., Massada, A. B., Brennan, T. J., & Radeloff, V. C. (2012). Housing arrangement and location determine the likelihood of housing loss due to wildfire. *PloS one*, 7(3), e33954.

Van Oldenborgh, J., Krikken, G., Lewis, S., Leach, N.J, Lehner, F., Saunders, K.R., Haustein, K., Sparrow, S., and Arrighi, J., (2021). Attribution of the Australian bushfire risk to anthropogenic climate change. *Natural hazards and earth system sciences* 21(3): 941-960)