Flamescapes: Simulating the Wildlandfire Urban Interface Supplementary Material

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1 Modeling Urban Scenes

Here we provide a description of the urban scene modeling components of our WUI framework.

1.1 Procedural Modeling of Combustion-Ready Buildings

To prepare a scene for simulation with our WUI framework we aim to represent buildings with *atomic modules*. To procedurally generate combustion-ready buildings we use WFC and SSA to model 3D buildings from OSM polygons.

WFC and Semantic State Space. To model buildings we define the vertical wall parts of the houses. Specifically, for each line segment of the footprint polygon, we define a two-dimensional uniform grid where the bottom of the grid is spanning the extent of the polygon line. Each grid cell is initialized with a set of possible semantic states representing architectural and structural elements, we call *atomic modules* (Fig. 4, a, b, main text). These include structural components such as beams (rafters, joists, studs, etc.) with different positional (left, bottom, right, top, center) and orientational (horizontal, vertical) roles as well as facade elements such as windows and doors to encode their relative position within an opening (left, right, bottom, or top), see Tab. 1 and 2 for a full list of states. Depending on the wall length and height, grids have approx. 150–250 cells per wall. We solve the semantic assignment on each wall grid using WFC [Alaka and Bidarra 2023; Karth and Smith 2017] over a 4-neighborhood (left, right, up, down). Following construction, materials are assigned according to Tab. 3.

1.2 WFC Rule Formalism

Each semantic state t exposes a discrete *interface label* on every side, $\sigma(t,d)$ for $d \in \{left, right, up, down\}$. Two adjacent cells with states (t_i, t_j) are compatible in direction d iff $\sigma(t_i, d) = \sigma(t_j, \bar{d})$, where $\bar{d}$ is the opposite direction. We construct σ deterministically

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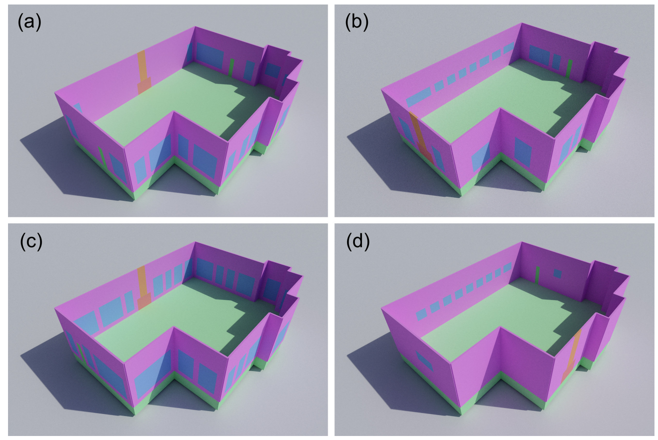

Fig. 1. To model buildings from OSM polygons we use WFC. For each edge we define a 2D grid with assignments of atomic modules for each grid cell. After resolving WFC we can obtain different plausible configurations of architectural elements for each polygon (a-d).

from the state parameters (class, orientation, and relative position labels), so that adjacency encodes architectural principles such as: (1) continuity of structural members across cells, (2) consistent tiling of openings (windows, fireplaces) via start, center, end boundary labels, (3) framing of openings by structural states, and (4) support and anchoring constraints (e.g., door bottoms are restricted to ground level).

Backtracking is used to ensure the constraints are satisfied and that they produce a globally consistent assignment of semantic states across the wall grid. The state space is discrete and low-dimensional to keep WFC tractable while still capturing meaningful architectural variation. Moreover, we define multiple sets of semantic states and assign them randomly to each building polygon to create buildings with different architectural properties. A few examples of architectural variation of atomic modules are shown in Fig. 1.

1.3 Architectural constraints

The architectural constraints are represented as rules

$$r = (S, T, E), \tag{1}$$

where S is the rule scope, T is the target condition, and E is the rule effect. Effects either keep compatible states, remove incompatible states, or modify state weights. When a cell is collapsed to a concrete state s, the solver generates both grid-local rules, which constrain

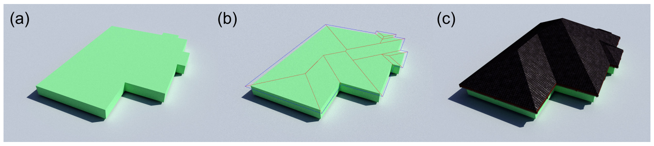

Fig. 2. We use the OSM polygons to generate roofs. A polygon (a) extended before we compute roof compartments with the SSA algorithm (b). We then elevate the compartments to obtain 3D roofs.

Table 1. Atomic module classes and associated semantic state counts used for wall discretization.

Class	Parameters	Allowed Values	# States
Studs	(n, o, p)	$n \in \{1,2,3\}$, $o \in \{\mathrm{H}, \mathrm{V}\}$, $p \in \{\text{start, center, end}\}$	156
Windows	(p_x, p_y)	$p_x, p_y \in \{\text{start, center, end}\}$	9
Doors	p_y	{bottom, center, top}	3
Fireplace bases	(p_x, p_y)	$p_x, p_y \in \{\text{start, center, end}\}$	9
Chimneys	p	{start, end}	2
Total			**179**

neighboring cells within the same wall grid, and building-global rules, which propagate constraints across larger building regions, such as suppressing repeated door placement. To construct our buildings we used the following constraints:

Door constraints. Doors are restricted to the ground-level portion of a wall. If a door is placed at row $j \leq 4$, all cells in the corresponding column are forced into a coherent vertical door stack: rows 1–3 become Door(Center), row 4 becomes Door(Top), and row 0 becomes Door(Bottom). If a cell in the same ground-level band is resolved as a non-door state, all door states are removed from rows 0–4 of that column. A building-global suppression rule additionally reduces repeated door placement on the same wall or nearby building regions.

Window constraints. Window states encode their position within larger openings. Horizontal and vertical boundary states remove incompatible window states in adjacent cells and keep only states that can continue the opening. A Window(Center, Center) state forces a local 3×3 window neighborhood, producing coherent window blocks. Additional rules enforce horizontal and vertical line continuity, suppress conflicting window bands, and remove fireplaces, doors, and chimneys from immediate horizontal neighbors.

Stud continuity constraints. Structural states enforce continuity of framing members. A vertical stud at the right, left, or center position forces compatible vertical studs or supporting horizontal members in the cells above and below. Center studs also remove window states from neighboring cells when the corresponding opening would intersect the structural member. These rules maintain connected load-bearing elements while still allowing facade variation.

Double-wall constraints. Double states encode common structural combinations such as horizontal members with vertical supports. Bottom horizontal double states promote compatible top-edge windows, doors, or fireplace states in the cell below.

Table 2. Implementation-level WFC wall cell states $w \in W$.

State	Description	Parameters
Straight(o)	Single wall segment or stud	$o \in O$
Double(o_1, o_2)	Two independent wall segments	$o_1, o_2 \in O$
Triple(o_1, o_2, o_3)	Three wall segments; used for corners	$o_1, o_2, o_3 \in O$
Junction(o_1, o_2)	Two segments, one of which is half-length	$o_1, o_2 \in O$
Door(v)	Door opening at vertical location v	$v \in V$
Window(h, v)	Window opening at horizontal and vertical location	$h \in H,\ v \in V$
FirePlace(h, v)	Fireplace opening	$h \in H,\ v \in V$
Chimney(h)	Chimney column	$h \in H$

Table 3. Role-based material class assignment at geometry spawn.

Class	Assigned geometry
Dense biomass	framing, siding, trim studs, plates, doors, tree trunks and branches
Sparse biomass	tree canopy
Metal	gutter segments, spouts, fixtures
Stone	curbs, floor slabs, fireplace base and chimney, fireplace / chimney, ground plane, roads
Glass	window panes
Scene-config meshes: class authored per entity in the scene file.	

Fireplace constraints. If a wall is initialized with a fireplace feature F = True, additional constraints are applied. Chimney columns are forced across all rows above the cell. For fireplaces, the lower rows of the selected column span are forced to fireplace states with appropriate horizontal and vertical position labels. Corner cells are assigned compatible triple states, left and right edge cells receive boundary vertical members, and top or bottom cells receive horizontal boundary members.

1.4 Roof Geometry

The roof, in contrast to the rest of the house, uses the SSA [Aichholzer and Aurenhammer 1996; Cheng and Vigneron 2007] instead of WFC. The original building footprint polygon, is first extended outward to create roof overhangs. We then compute the skeleton of the polygon which defines the roof geometry. Given the separate roof polygons we generate different roof elements such as rafters and shingles that are then assigned different material properties relevant for the combustion simulation. Together, these steps produce complex 3D building models that plausibly describe architectural components of real houses. Fig. 2 shows an extruded input polygon (a), the extended roof polygon computed with the SSA (b) and the final 3D roof geometry (c).

1.5 Modeling of Urban Scenes with Vegetation

We use the OSM building footprints and street center lines to compute a 2D SDF of the urban scene. The SDF is used for generating ground geometry and to assign areas with distinct materials, such as asphalt for roads, concrete for curbs and sidewalks. Additionally, we compute the shortest distances between building footprints and street centerlines to model driveways. Areas not occupied by roads or buildings are classified as vegetated ground, such as lawns or vegetated ground. This SDF-based formulation enables smooth transitions between surface types and robust handling of complex urban layouts, including irregular parcel shapes and intersections.

Vegetation density is controlled by adjusting both the minimum plant distance and the padding thresholds of the underlying distance field. For the placement of plant models, we employ Poisson disk-based sampling to distribute plant models within vegetated ground regions. Poisson disk sampling enforces the minimum distance between samples, producing a spatially uniform distribution that avoids overlap. By adjusting the padding thresholds and the minimum plant distance, we can generate vegetation layouts ranging from sparse plantings to high-density fuel distributions. To reduce the geometric complexity of plant models during rendering, we employ stochastic pruning [Cook et al. 2007] – a randomly selected subset of leaves is removed for each tree, while the remaining leaves are scaled to preserve overall projected coverage and silhouette.

2 Algorithms

The following algorithms show the procedures used for the ray-based thermal radiation as well as the ember and flame front particle to grid sampling. The thermal radiation step is shown in the main text in Algorithm 1 in line 15. The ember and flame front sampling are referenced in lines 16-18.

ALGORITHM 1: Thermal Radiation.

Input: Eulerian grid with gas and solid properties.
Output: Updated temperatures and incoming thermal radiation.
forall *Grid Cells* **do**
  Determine available radiation directions;
  Calculate outgoing thermal radiation;
  Update temperatures T_s, T_g;
  Cast rays in all available directions with a fixed energy budget;
  forall *Rays* **do**
    Deposit energy in solid surface cells and volumes on hit;
  Update temperatures T_s, T_g;

ALGORITHM 2: Particle to grid.

Input: Eulerian grid and Lagrangian particles.
Output: Updated grid.
Sort particles into grid cells;
forall *Grid Cells* **do**
  `// - Embers -`
  Initialize thermal energy from embers: $\dot{q} \leftarrow 0$;
  forall *Ember Particles in this Cell* **do**
    Determine excess thermal energy: $\dot{q}_e \leftarrow m_e \cdot (T_e - T_s) \cdot C_e$;
    Deposit excess thermal energy: $\dot{q} \leftarrow \dot{q} + \dot{q}_e$;
  Update solid temperature: $T_s \leftarrow T_s + \dot{q} \cdot \rho_s C_{p,s}$;
  `// - Flame Front -`
  Initialize maximum flame front temperature: $T_f \leftarrow 0$;
  forall *Flame Front Particles in this Cell* **do**
    Store maximum temperature: $T_f \leftarrow max(T_f, T_p)$;
  During gas combustion, use: $max(T_f, T_s)$;

2.1 Parameter Values for Real Experiment Comparisons

The simulation parameters used for the validation experiments (Sec. 6.2 in the main text) are summarized in the tables Tab. 4, 5, and 6.

Table 4. Simulation parameters for the radiative heat flux validation.

Parameter	Range / Value	Units
Combustion & Pyrolysis		
Gas fuel type	IsoOctane	–
Combustion CO_2 fraction	0.850	–
Combustion residual fraction	0.150	–
Pyrolysis fuel fraction	0.900	–
Pyrolysis residual fraction	0.100	–
Gas residual reaction fraction	0.600	–
Heat Transfer		
Convection coefficient	3.0	–
Radiation ray energy	0.100	J
Residual absorption coefficient	500	–
Fluid Dynamics		
Vorticity confinement strength	20.0	–
Wind velocity (x, y, z)	$(0.0,\ 0.0,\ 0.0)$	$m\,s^{-1}$
Porous solid velocity multiplier	0.100	–
Ambient temperature	300	K
Ambient gas density	1.1726	$kg\,m^{-3}$
Gravitational acceleration	−9.81	$m\,s^{-2}$
Porous solid density threshold	10.0	$kg\,m^{-3}$
Solid density threshold	100.0	$kg\,m^{-3}$
Particle System		
Particle capacity	262,144	–
Ember spawn rate	1.0	–
Ember lifetime	$[1.0,\ 10.0]$	s
Ember mass	$[10^{-6},\ 10^{-4}]$	kg
Ember emissivity	0.95	–
Ember mass loss rate	–	$kg\,s^{-1}$
Ember grid velocity factor	0.500	–
Flame-front lifetime	0.5	s
Flame-front speed	8.0	$m\,s^{-1}$
Procedural Scene Generation		
OSM request size	–	m
Vegetation density	–	–
Leaf thickness	–	m
Minimum house distance	–	m
Minimum road distance	–	m
Computational Domain		
Fixed timestep	0.00833	s
Maximum simulation time	∞	s
Grid resolution (x, y, z)	$164 \times 164 \times 328$	voxels
Domain size (x, y, z)	$20.0 \times 20.0 \times 40.0$	m

Table 6. Simulation parameters for the wind-driven structure exposure experiment.

Parameter	Range / Value	Units
Combustion & Pyrolysis		
Gas fuel type	Methane	—
Combustion CO_2 fraction	0.999	—
Combustion residual fraction	0.0005	—
Pyrolysis fuel fraction	1.000	—
Pyrolysis residual fraction	0.0005	—
Gas residual reaction fraction	0.001	—
Heat Transfer		
Convection coefficient	200.0	—
Radiation ray energy	0.500	J
Residual absorption coefficient	500	—
Fluid Dynamics		
Vorticity confinement strength	11.0	—
Wind velocity (x, y, z)	$(12.0,\ 0.0,\ 0.0)$	$m\,s^{-1}$
Porous solid velocity multiplier	0.140	—
Ambient temperature	300	K
Ambient gas density	1.1726	$kg\,m^{-3}$
Gravitational acceleration	-9.81	$m\,s^{-2}$
Porous solid density threshold	1.0	$kg\,m^{-3}$
Solid density threshold	1000.0	$kg\,m^{-3}$
Particle System		
Particle capacity	1,048,576	—
Ember spawn rate	0.0	—
Ember lifetime	$[0.0,\ 120.0]$	s
Ember mass	$[0.001,\ 0.002]$	kg
Ember emissivity	0.950	—
Ember mass loss rate	$1e-6$	$kg\,s^{-1}$
Ember grid velocity factor	0.100	—
Flame-front lifetime	5.0	s
Flame-front speed	5.0	$m\,s^{-1}$
Procedural Scene Generation		
OSM request size	–	m
Vegetation density	–	—
Leaf thickness	–	m
Minimum house distance	–	m
Minimum road distance	–	m
Computational Domain		
Fixed timestep	0.005	s
Maximum simulation time	365.0	s
Grid resolution (x, y, z)	$320 \times 160 \times 80$	voxels
Domain size (x, y, z)	$32.0 \times 16.0 \times 8.0$	m

Table 5. Simulation parameters for the vegetation combustion behavior experiment.

Parameter	Value	Units
Combustion & Pyrolysis		
Gas fuel type	Methane	—
Combustion CO_2 fraction	0.900	—
Combustion residual fraction	0.100	—
Pyrolysis fuel fraction	0.900	—
Pyrolysis residual fraction	0.100	—
Gas residual reaction fraction	0.500	—
Heat Transfer		
Convection coefficient	200.0	—
Radiation ray energy	0.100	J
Residual absorption coefficient	3000	—
Fluid Dynamics		
Vorticity confinement strength	10.0	—
Wind velocity (x, y, z)	$(0.0,\ 0.0,\ 0.0)$	$m\,s^{-1}$
Porous solid velocity multiplier	0.500	—
Ambient temperature	300	K
Ambient gas density	1.1726	$kg\,m^{-3}$
Gravitational acceleration	-9.81	$m\,s^{-2}$
Porous solid density threshold	1.0	$kg\,m^{-3}$
Solid density threshold	600.0	$kg\,m^{-3}$
Particle System		
Particle capacity	524,288	—
Ember spawn rate	0.500	—
Ember lifetime	10.0	s
Ember mass	$[10^{-6},\ 0.005]$	kg
Ember emissivity	0.95	—
Ember mass loss rate	0.006	$kg\,s^{-1}$
Ember grid velocity factor	0.500	—
Flame-front lifetime	1.0	s
Flame-front speed	8.0	$m\,s^{-1}$
Procedural Scene Generation		
OSM request size	–	m
Vegetation density	–	—
Leaf thickness	10^{-6}	m
Minimum house distance	–	m
Minimum road distance	–	m
Computational Domain		
Fixed timestep	0.004	s
Maximum simulation time	60.0	s
Grid resolution (x, y, z)	$240 \times 240 \times 200$	voxels
Domain size (x, y, z)	$3.60 \times 3.60 \times 3.00$	m

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