Supplementary Information

This Appendix provides detailed information on default values for parameters in RAAbIT, facilitating the replication of results in this study.

Household Agents

This section describes the default values used in RAAbIT's Household Agent. Table 2 presents the average dollar values for various sources of home equity and savings in the US, categorized by income quintile. Table 3 provides the US average percentage of households with home equity and savings. Table 4 provides multipliers to convert national averages to Census area averages. For example, the average Californian in the West Census area has 2.3 times more stocks and shares than the average American. The values in Tables 2, 3, and 4 are obtained from https://www.census.gov/data/tables/2020/demo/wealth/wealth-asset-ownership.html (last accessed February 2025). Lastly, Table 5 shows the distribution of time to build new single-family homes in the US per year, which is used to estimate the reconstruction time for destroyed buildings.

Table 2. Constants used to estimate the dollar value of savings and equity for Household Agents based on national averages.

Income quintile	Stocks & shares [$] ($F_{stocks}$)	Retirement accounts [$] ($F_{retirement}$)	Home equity [$] ($F_{home}$)	Rental equity [$] ($F_{rental}$)	Other equity [$] ($F_{other}$)
Lowest	10,000	22,000	100,000	140,000	38,800
Second	19,000	25,000	120,000	110,000	55,000
Third	20,000	40,000	130,000	105,000	50,000
Fourth	21,000	74,000	150,000	156,000	70,000
Highest	75,200	220,000	218,000	226,000	120,000

Table 3. Constants used to estimate the percentage Household Agents with savings and home equity based on national averages.

Income quintile	Stocks & shares [%]	Retirement accounts [%]	Home equity [%]	Rental equity [%]	Other equity [%]
Lowest	7.3	17.4	37.1	2.1	2.5
Second	14.5	44.5	53.4	4.1	4.7
Third	22.2	63.5	62	5.2	6.6
Fourth	30.8	79.2	74.1	7.8	10.2
Highest	50.8	89.8	83	15.2	16.9

Table 4. Multipliers used to convert savings and home equity national averages to Census area values.

Census region	Stocks & shares ($m^s_{us\to r}$)	Retirement accounts ($m^r_{us\to r}$)	Home equity ($m^e_{us\to r}$)	Rental equity ($m^l_{us\to r}$)	Other equity ($m^o_{us\to r}$)
Northeast	2.50	2.32	1.52	1.43	1.60
Midwest	1.25	1.90	0.85	1.14	1.10
South	1.50	1.53	0.95	1.38	1.44
West	2.30	2.00	2.00	2.38	2.00

Table 5. Distribution of time to build new single-family homes in the US [32].

	Percent distribution[1]						
Months	2015	2016	2017	2018	2019	2020	2021
3 or less	5	1	4	4	2	2	0
4 to 6	21	19	22	16	8	13	16
7 to 9	26	29	25	21	17	14	20
10 to 12	14	18	13	19	20	26	23
13 or more	34	34	36	40	54	44	40

[1]May not add to 100 due to rounding.

Federal Emergency Management Agency Housing Assistance Grants

The FEMA HA model is based on previous work by the authors [25, 47] and parameters established by the Federal Emergency Management Agency at `https://www.federalregister.gov/documents/2024/01/22/2024-00677/individual-assistance-program-equity` [1] (Last accessed February 2025) and `https://www.fema.gov/press-release/20240216/what-expect-after-applying-fema` [2] (Last accessed February 2025). The parameters of this model are shown in Tables 6 and 7.

Table 6. Parameters used in Eq. 11 to estimate FEMA IA approval rates.

Insurance status	Income	Equation parameter o_1	o_2	o_3
Uninsured	Very low	0.527	0.838	-3.3e-6
Uninsured	Low	0.523	0.829	-2.2e-6
Uninsured	Moderate	0.519	0.799	-1.9e-6
Uninsured	High	0.518	0.756	-7.9e-6
Insured	Very low	0.294	0.577	-2.8e-6
Insured	Low	0.290	0.556	-4.2e-6
Insured	Moderate	0.297	0.541	-3.8e-6
Insured	High	0.303	0.481	-3.9e-6

All fits resulted in R-squared > 0.95

Table 7. FEMA Agent Attributes

Attribute [units]	Default value	Source
[1]Current cap[$]	42,500 in 2024	1
[2]Disbursement time [days]	U(10,30)	2

HUD CDBG-DR Grants

To estimate $T_{\text{CDBG-DR}}$, we calculate the averages of data collected by [48], where $T_{\text{appropriation}} = 0.6$ years, $\Delta T_{\text{allocation}} = 0.2$ years, and $T_{\text{award}} = 0.2$ years. The grant caps for the Tubbs Fire and Camp Fire are collected from the action plans developed by the California Department of Housing and Community Development, available at `https://www.hcd.ca.gov/funding/dr/action-plans-federal-register-notices` (last accessed February 2025).

Table 8. HUD Agent Attributes

Attribute [units]	Model value Santa Rosa	Paradise
Grant cap [$]	150,000	200,000
Appropriation delay [year]	0.6	0.6
Allocation delay [year]	0.2	0.2
Award delay [year]	0.2	0.2
1st expenditure delay [year]	0[1]	0
Program duration [year]	1.9[1]	1.9

[1] For housing repair expenses.

Benchmark Recovery Financing Values

For the Tubbs Fire, the action plan developed by the California Department of Housing and Community Development (HCD) provides two estimates for the replacement cost for a building destroyed by the 2017 fires in California. The first estimate, $300,000, is an HCD-estimated average, whereas the second is an SBA-estimate at $314,968. Considering the 1,855 buildings in Santa Rosa in the case study, losses should be in the order of $556.5 million to $584.3 million. Data collected from the OpenFEMA portal indicates Sonoma County (where Santa Rosa is located) received $2.13 million in FEMA housing repair assistance [36]. Note that only single-family, owner-occupied buildings are eligible for FEMA housing repair assistance. According to the Action Plan, 3,044 single-family buildings were destroyed in Santa Rosa, out of which 2,061 were owner-occupied buildings. The case study data comprised 965 single-family, owner-occupied buildings. Hence, if the FEMA assistance is evenly distributed among buildings and corrected by the under-representation of owner-occupied buildings in our sample, the FEMA IHP received should be in the order of $1 million (i.e., $(965/2,061) \times 2.13$). Data from the OpenSBA portal indicate Sonoma County received $99.3 million. If evenly split among all buildings in the case study, Santa Rosa should have received close to $60.5 million (i.e., $(1,855/3,403) \times 99.3$). Lastly, the action plan allocates $21.47 million CDBG-DR dollars to housing repair and reconstruction of owner-occupied housing. Sonoma County accounted for 67% of the total disaster losses in California in 2017 [19]. Thus, we estimate the CDBG-DR going to Sonoma County at $6.7 million ($(965/2,061) \times 0.67 \times 21.4$)

The benchmark values for the Camp Fire case are estimated similarly. As per Figure 58 in the HCS 2018 Action Plan [20], the cost of replacement per square foot in Butte County was $153.25 and on average, each building has 1,574 square feet. According to Figure 59 in the 2018 Action Plan, the average replacement cost per building in Butte County was $356,549. Thus, losses across the 1,524 buildings in our dataset are estimated to be in the range of $367.61 million to $543.39 million. Data collected from the OpenFEMA portal indicates that Butte County received $34 million in FEMA housing repair assistance. According to the Action Plan, 7,133 single-family, owner-occupied buildings were destroyed in Butte County. The case study data comprised 702 single-family, owner-occupied buildings. Hence, if the FEMA assistance is evenly distributed among buildings, the simulated results should be in the order of $3.34 million ($(702/7133) \times 34$. Data from the OpenSBA portal indicate Butte County received $291 million. If evenly split among all buildings in the case study, Santa Rosa should have received close to $37.3 million (i.e., $(1,524/11,888) \times 291$). According to Figure 60 in the Action Plan, all disasters in California in 2018 caused $11.9 billion in housing-related losses, of which $7.56 billion were experienced in Butte County. California received $205.1 million in CDBG-DR assistance for the reconstruction of single-family, owner-occupied homes. Assuming even distribution, Butte County should receive $130.3 million. Since our data set represents 6% of these buildings, the estimated CDBG-DR funding should be in the order of $12.78 million (i.e., $(702/7133) \times 130.3$).

Supplemental Materials: ODD Protocol for RAAbIT - Recovery Assessment using Agent-Based Tools

1. Overview

This study employs the ODD (Overview, Design Concepts, and Details) protocol [1, 2] to describe RAAbIT (Recovery Assessment using Agent-Based Tools), an agent-based model developed to simulate the dynamic process of post-disaster housing recovery. RAAbIT captures the micro-level interactions between households, financial institutions, contractors, and service providers, with a focus on how access to resources, institutional behaviors, and local market conditions shape the pace and equity of recovery.

The model conceptualizes recovery as a sequence of interdependent decisions and constraints, beginning with a household's need to secure financing, followed by contractor engagement, and culminating in reconstruction. These decisions are mediated by various agents representing real-world actors—such as banks, government aid programs, and construction contractors—each with their own attributes, rules, and institutional behaviors. The simulation aims to uncover emergent patterns of recovery disparities stemming from differences in socioeconomic status, institutional access, and service prioritization.

By formalizing this system through an ODD structure, the model supports transparency, replicability, and extensibility for use in diverse post-disaster contexts. The following sections provide detailed descriptions of the agent types, their decision rules, and their interactions within the RAAbIT framework.

2. Entities, State Variables, and Scales

Spatial scale: Parcel/building level.
Temporal scale: Daily time steps.

3. Process Overview and Scheduling

Each Household Agent goes through:

1. Financing: Applies to funding sources.
2. Permitting: Applies for and waits on a permit.
3. Contractor access: Waits for contractor assignment.
4. Construction: Undergoes repairs until complete.

Total recovery time T is computed as:

$$T = T_{\text{finance}} + D_{\text{permit}} + D_{\text{materials}} + D_{\text{contractor}} + T_{\text{repair}}$$

Table 1: Agent Types and Attributes in RAAbIT

Agent Type	Description	Key Attributes
Household Agent	Represents households responsible for rebuilding after disaster losses.	Income, location, damage level, insurance status, equity, savings, funding progress, recovery status
Insurance Agent	Simulates private insurance coverage for structural damage.	Coverage rate, deductible, disbursement delay $T_{\text{insurance}}$
FEMA Agent	Represents the FEMA Individuals and Households Program (IHP).	Eligibility model, grant formula, disbursement delay T_{FEMA}
SBA Agent	Provides low-interest loans to eligible households.	Loss-dependent approval, loan cap, disbursement delay T_{SBA}
Bank Agent	Offers private mortgages conditional on income and collateral.	Debt-to-income ratio, equity test, interest rate, disbursement delay T_{bank}
HUD Agent	Allocates unmet needs grants via CDBG-DR through state authorities.	Unmet need formula, funding cap, multi-phase disbursement delay T_{CDBG}
Permit Assessor Agent	Regulates permit approvals before construction.	User-defined delay distribution or time series
Materials Provider Agent	Optional agent modeling construction material shortages.	Delay distribution $D_{\text{materials}}$ (user-defined)
Job Market Agent	Tracks contractor demand and adjusts workforce availability.	Responsiveness factor R, contractor creation/removal
Contractor Agent	Executes construction jobs for assigned households.	Prioritization logic (e.g., density-based, FCFS, random), availability

4. Design Concepts

Basic Principles: RAAbIT simulates agent interactions under real-world constraints that amplify recovery disparities.
Emergence: Model outcomes reveal clustering and inequities in recovery across income and spatial dimensions.
Adaptation: Households seek multiple funding sources; contractor supply evolves in response to demand.
Stochasticity: Approval, delays, and repair times are randomly sampled from empirically derived distributions.
Sensing and Interaction: Agents operate on local knowledge; contractors may prioritize based

on spatial KDE:

$$\mathrm{KDE}(z) = \frac{1}{n}\sum_{i=1}^{n} \frac{1}{2\pi|\mathbf{H}|^{1/2}} \exp\left(-\frac{1}{2}(z-z_i)^T \mathbf{H}^{-1}(z-z_i)\right)$$

5. Details

5.1 Initialization

Household initialization includes:

- Building characteristics (area, quality)
- Damage level and estimated losses
- Replacement cost:
$$B_{\mathrm{rc}} = A_{\mathrm{main}} \cdot C_{\mathrm{main}} + A_{\mathrm{bsm}} \cdot C_{\mathrm{bsm}} + \mathbf{1}_g \cdot C_g$$
- Income, savings, equity from U.S. Census datasets

5.2 Submodels

FEMA Grant Model:

$$F_{\mathrm{FEMA}}(X) = a_1(X) \cdot L^2 + a_2(X) \cdot L + a_3(X)$$

Job Market Agent (Contractor Dynamics):

$$C_{\mathrm{new}}(t+\Delta t) = R \cdot [(C_a + C_h) - (C_a + C_w)]$$

Repair Time (Complete Loss): Sampled from a multinomial distribution based on U.S. Census construction duration data.

5.3 Termination Criteria

The simulation ends when either:

- A fixed number of time steps is reached (e.g., 5 years), or
- All recoverable households complete reconstruction or are deemed unrecoverable

6. Agent Interaction Diagram (Figure 6)

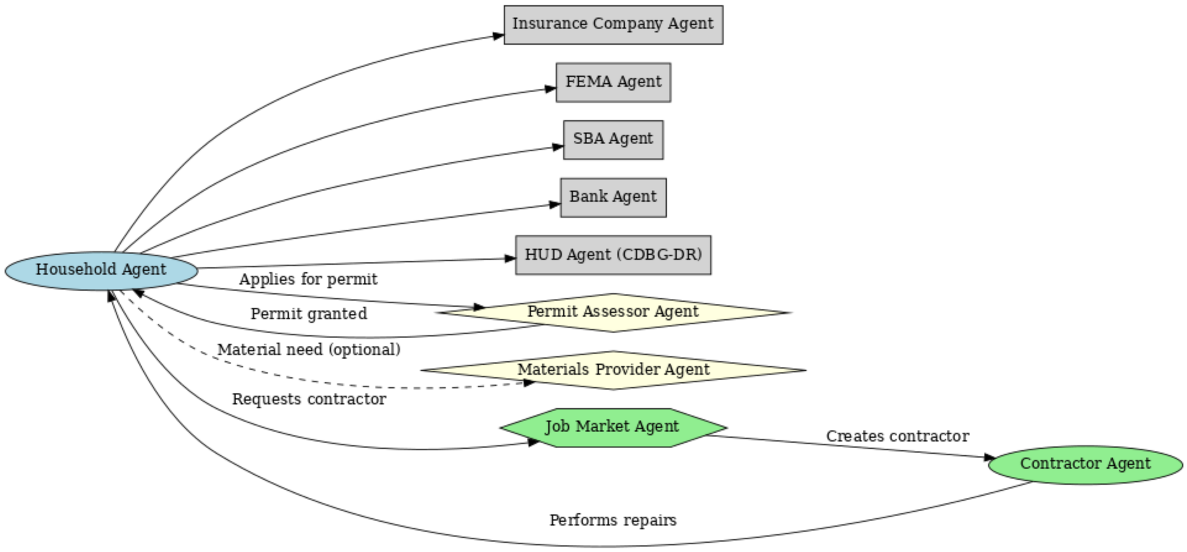

Figure 6. Agent interaction flow in RAAbIT. Household Agents interact with finance providers, permitting services, and contractor pools, each governed by distinct behaviors.

References

[1] Volker Grimm, Uta Berger, Finn Bastiansen, Sigrunn Eliassen, Vincent Ginot, Jarl Giske, John Goss-Custard, Tamara Grand, Simone K Heinz, Geir Huse, et al. A standard protocol for describing individual-based and agent-based models. *Ecological modelling*, 198(1-2):115–126, 2006.

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