Integrating Performance-Based Engineering and Urban Simulation to Model Post-Earthquake Housing Recovery

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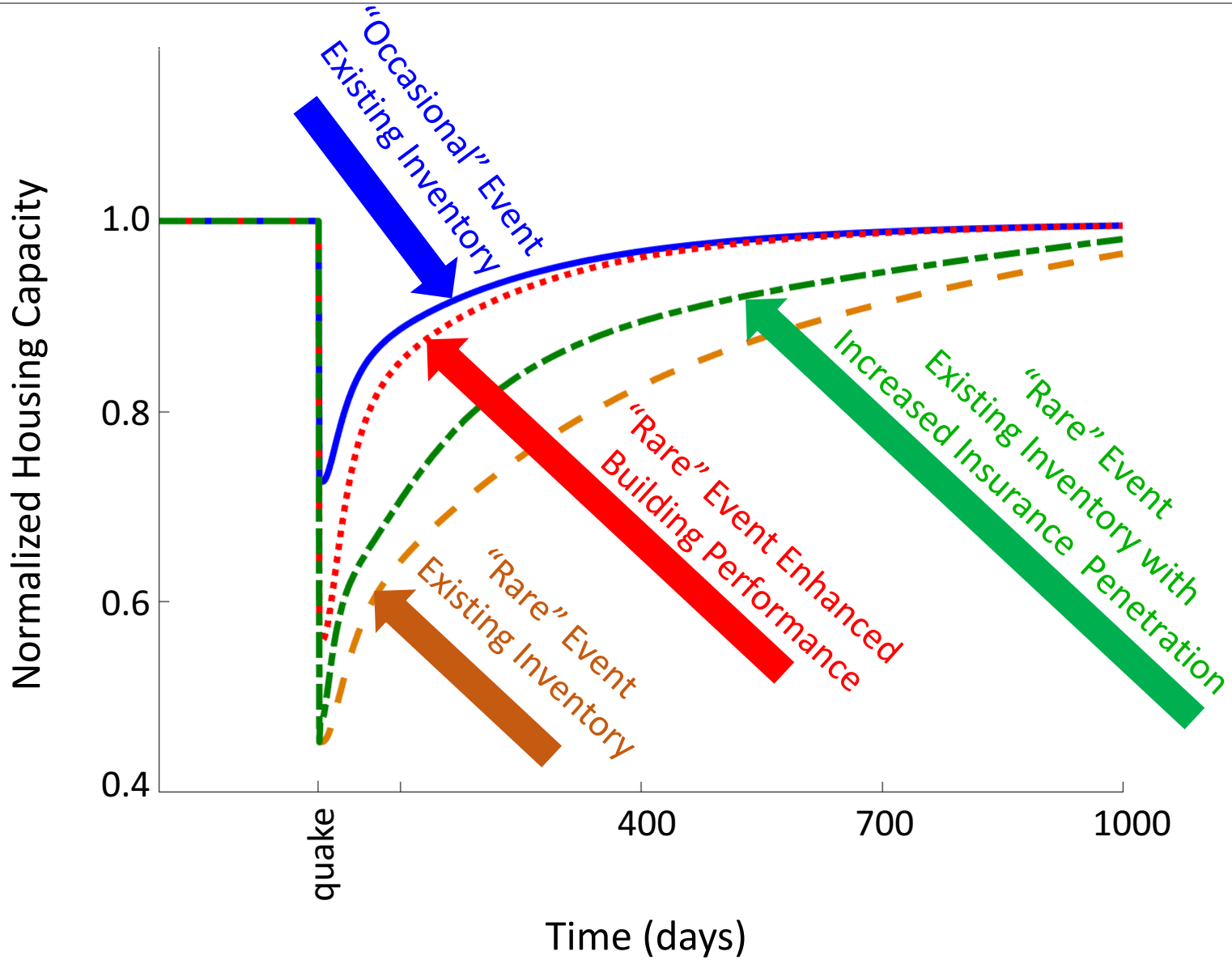
Engineering Sustainable Infrastructure for the Future

Practical Applications of Post-Earthquake Recovery Models: *Explore "What-If" Recovery Scenarios*



Practical Applications of Post-Earthquake Recovery Models:
Develop "Resilience-Based" Infrastructure Performance Targets

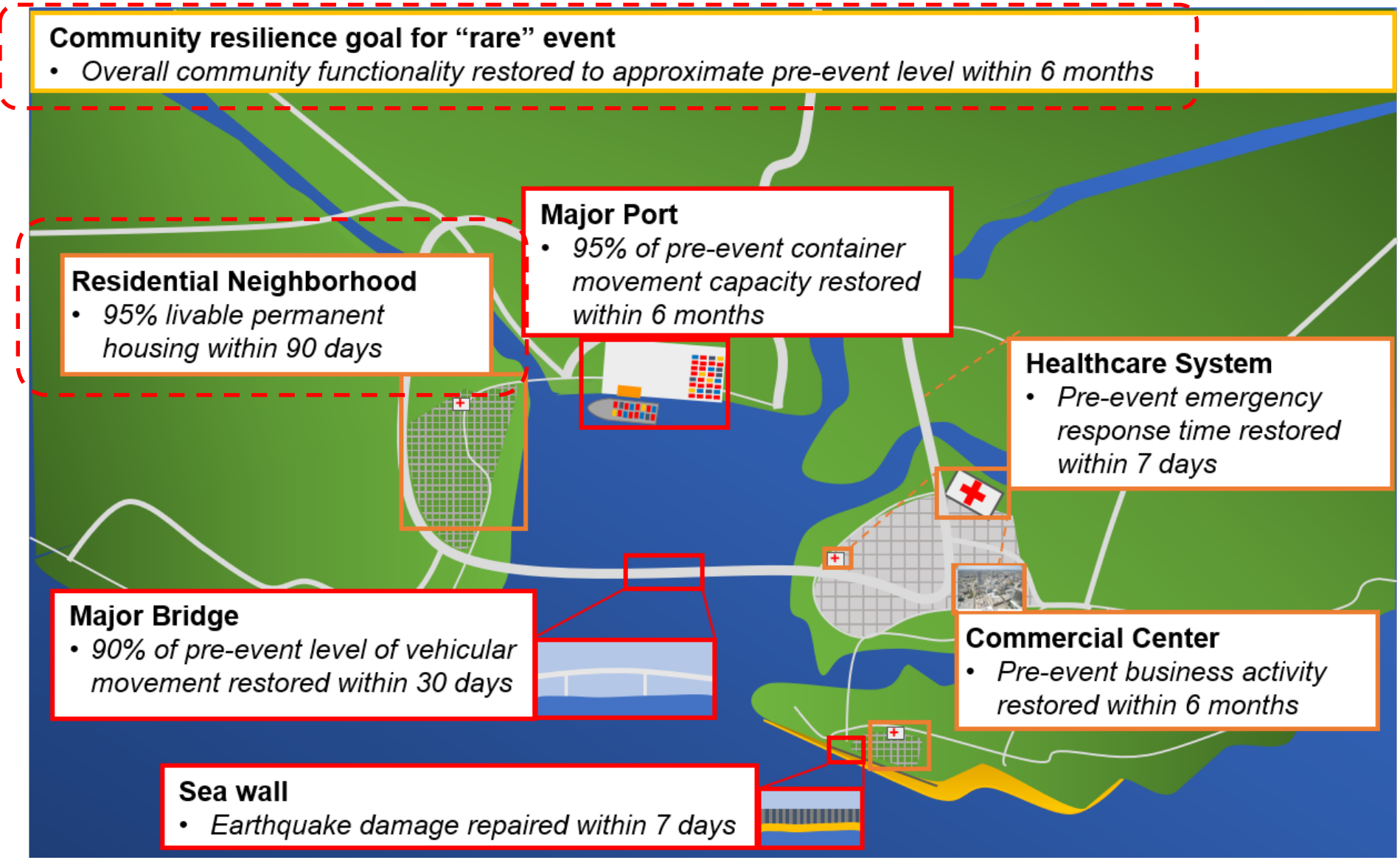
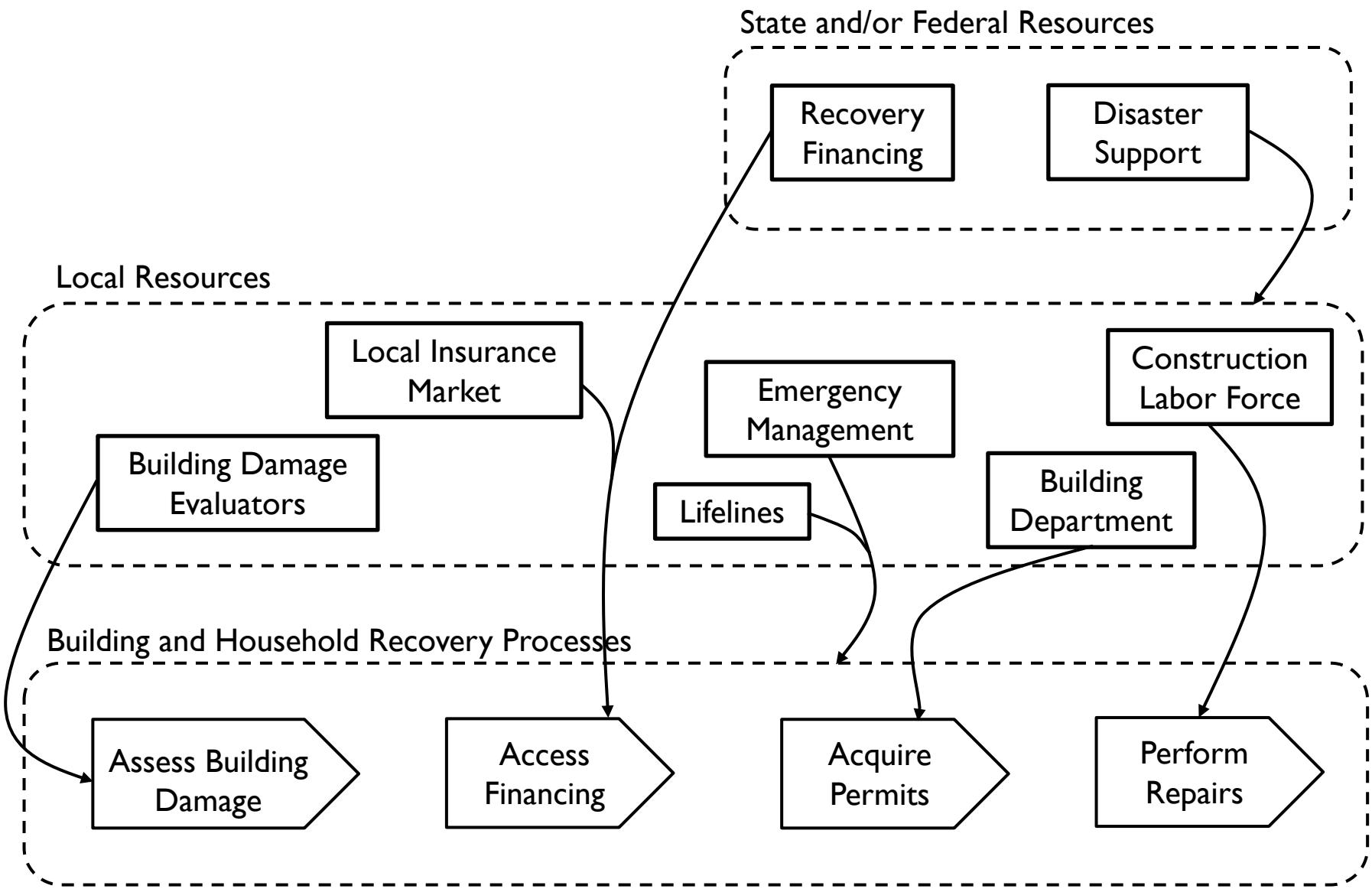
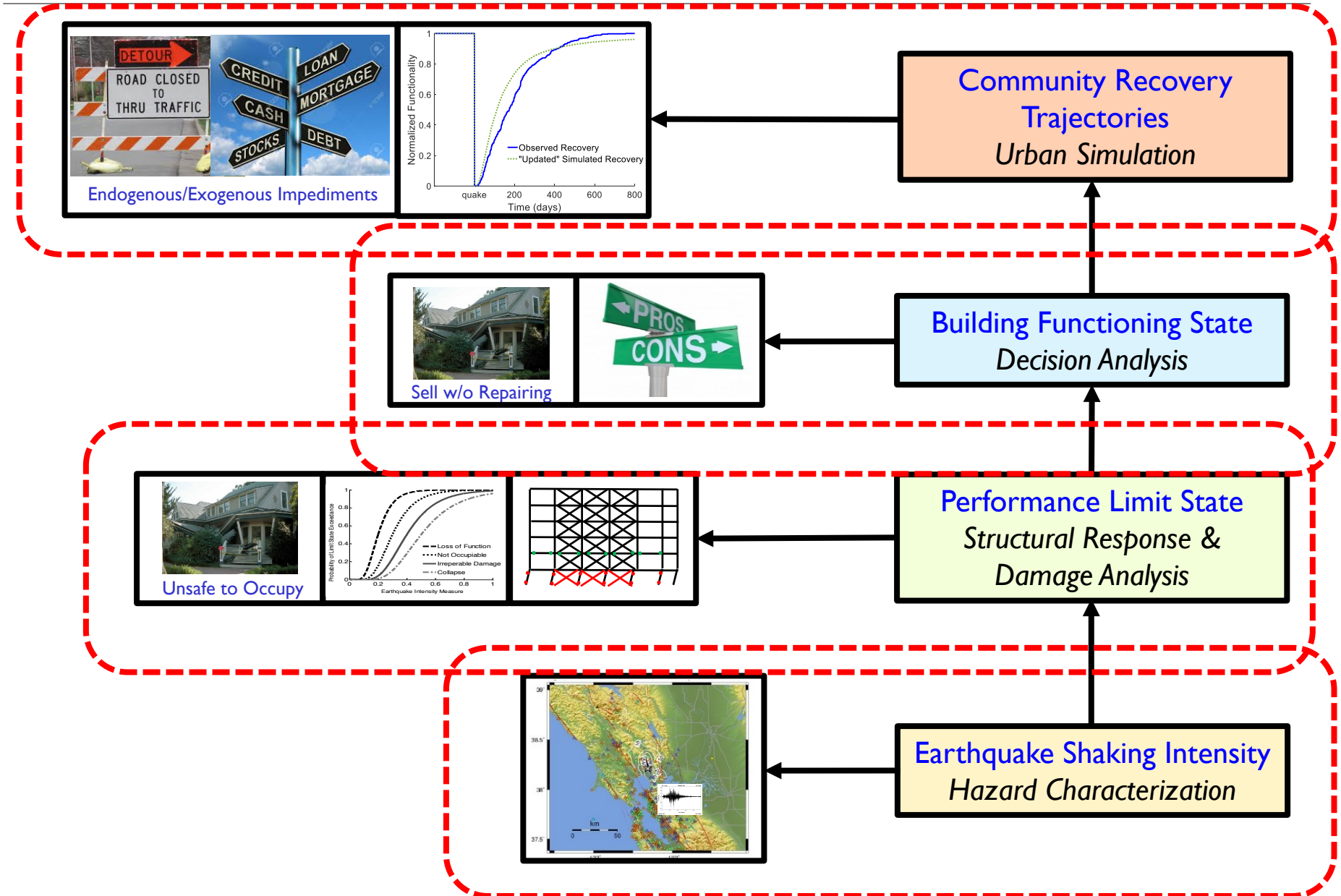


Figure adapted from Madeleine Flint (2017)

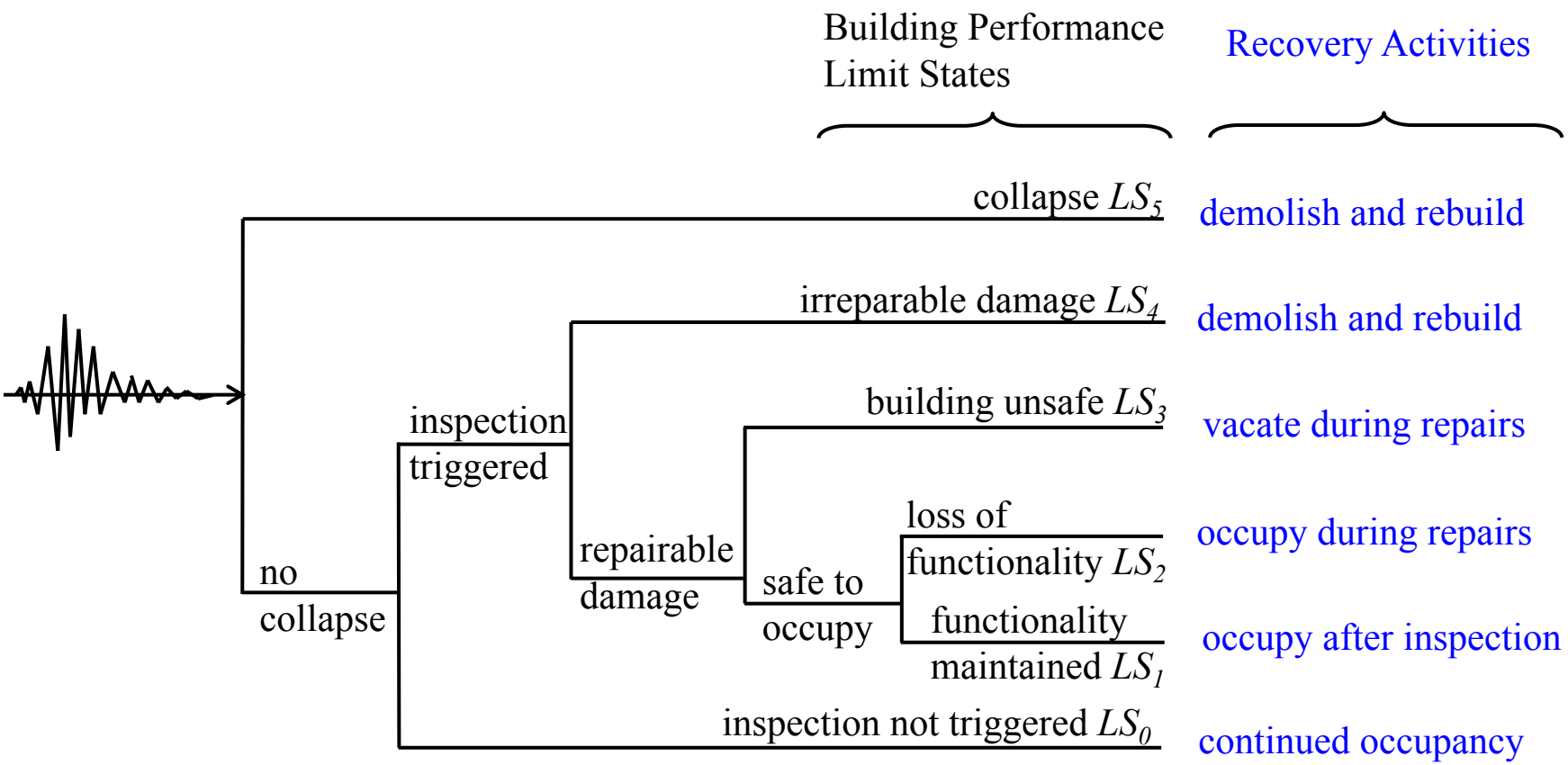
Post-Earthquake Recovery Modeling Framework: ***Multi-Scale Process-Based Model***



Rupture-to-Recovery Modeling Framework:
Performance-Based Engineering Meets Urban Simulation



Building Performance Limit States that Inform Post-Earthquake Recovery and Functionality



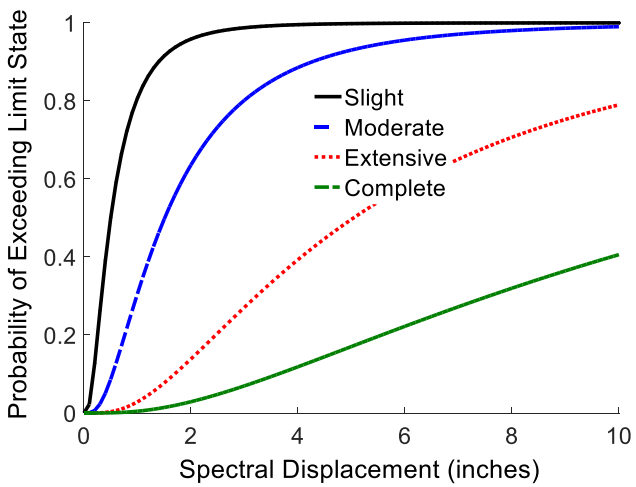
Burton, H., Deierlein, G., Lallemant, D., Lin, T. "A Framework for Assessing Building Performance Limit states that Inform Community Seismic Resilience," *ASCE Journal of Structural Engineering*, 10.1061/(ASCE)ST.1943-541X.0001321 , C4015007.

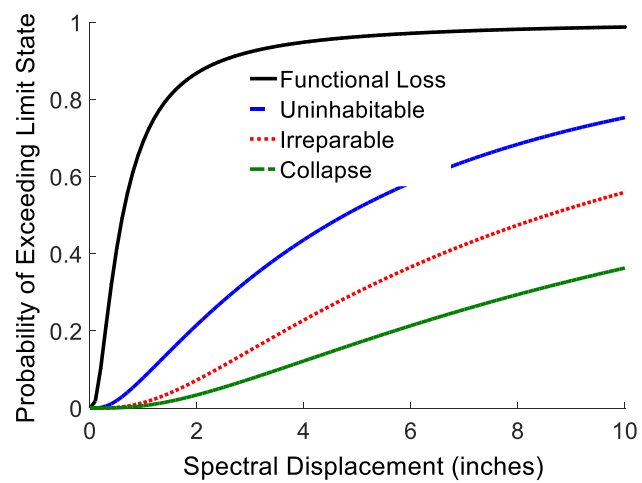
Mapping Fragility Function Parameters from "Loss-Based" to "Recovery-Based" Limit States

$$P\left(RBLS = rbls_i \mid S_d\right) = \sum_{j=1}^{n_{lbds}} P\left(RBLS = rbls_i \mid LBDS = lbds_j\right) \cdot P\left(LBDS = lbds_j \mid S_d\right)$$

$RBLS$: *Recovery-based limit state* $LBDS$: *Loss-based damage state* S_d : *Spectral displacement*

Loss-Based Damage States	$P\left(RBLS = rbls_i \mid LBDS = lbds_j\right)$				
	LS1 Fully Functional	*LS2* Loss of Functionality	*LS3* Unsafe to Occupy	*LS4* Damaged Beyond Repair	*LS5* Collapse
None	1.00	0.00	0.00	0.00	0.00
Slight	0.20	0.80	0.00	0.00	0.00
Moderate	0.05	0.75	0.20	0.00	0.00
Extensive	0.00	0.20	0.40	0.30	0.10
Complete	0.00	0.00	0.00	0.20	0.80





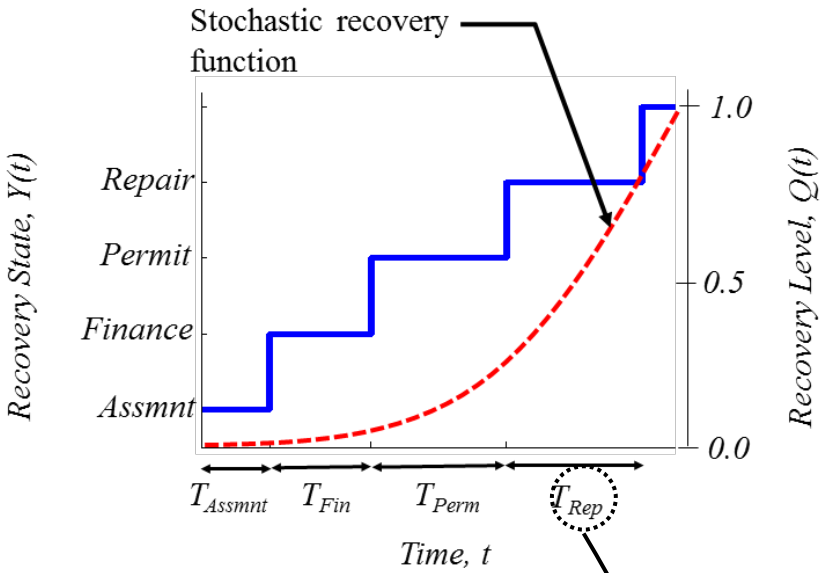
Modeling Household Decision-Making

Recovery-Based Limit State, $[LS_i]$

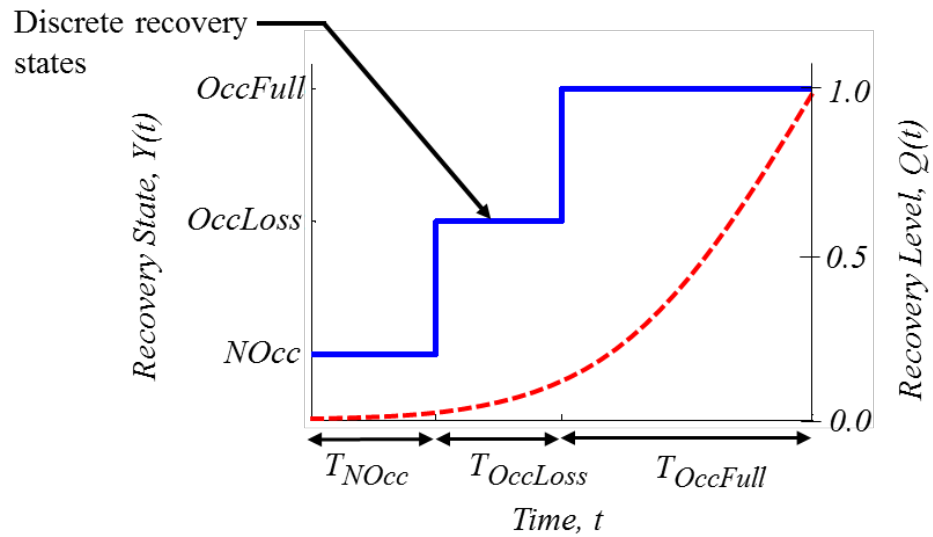
- Repair/replace + sell, $[A_1|LS_i]$
- Repair/replace + reoccupy, $[A_2|LS_i]$
- Abandon, $[A_3|LS_i]$
- Sell without repairing, $[A_4|LS_i]$

No.	Neighborhood Vacancy	Physical Damage to Residence	Loss of Utilities	Building Access	You have earthquake insurance			You do NOT have earthquake insurance		
					Reoccupy	Sell w/ Repair	Sell w/o Repair	Reoccupy	Sell w/ Repair	Sell w/o Repair
1	**Almost Half**	None	0	0	☐	☐	☐	☐	☐	☐
2	None	None	**24hrs**	0	☐	☐	☐	☐	☐	☐
3	*Almost Half*	None	**24hrs**	0	☐	☐	☐	☐	☐	☐
4	None	Minor or None	**2 weeks**	0	☐	☐	☐	☐	☐	☐
5	*Almost Half*	Minor or None	**2 weeks**	0	☐	☐	☐	☐	☐	☐
6	*Almost Half*	Moderate or Lower	**3months**	<3 months	☐	☐	☐	☐	☐	☐
7	*Almost All*	Moderate or Lower	**3months**	< 3 months	☐	☐	☐	☐	☐	☐
8	None	**Minor**	<2 weeks	0	☐	☐	☐	☐	☐	☐

Building-Level Recovery: ***Empirically-Based* Stochastic Process Model**



$$P(t < T < t + \Delta \mid T > t) = 1 - \frac{e^{-\lambda(t+\Delta)}}{e^{-\lambda t}}$$

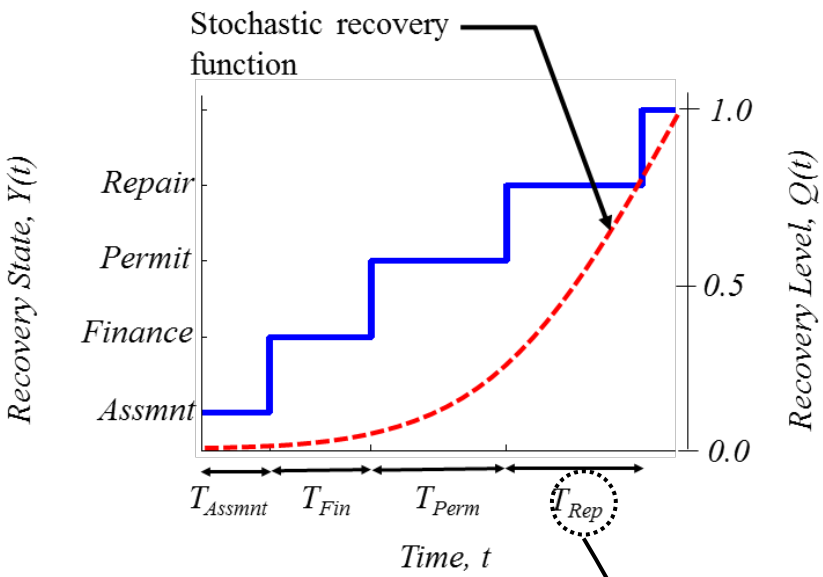


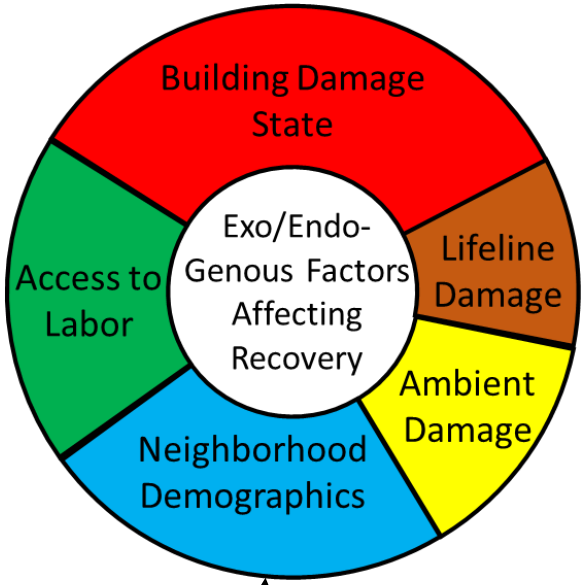
OccFull: Occupiable and fully functional

OccLoss: Occupiable with loss of functionality

NOcc: Not occupiable

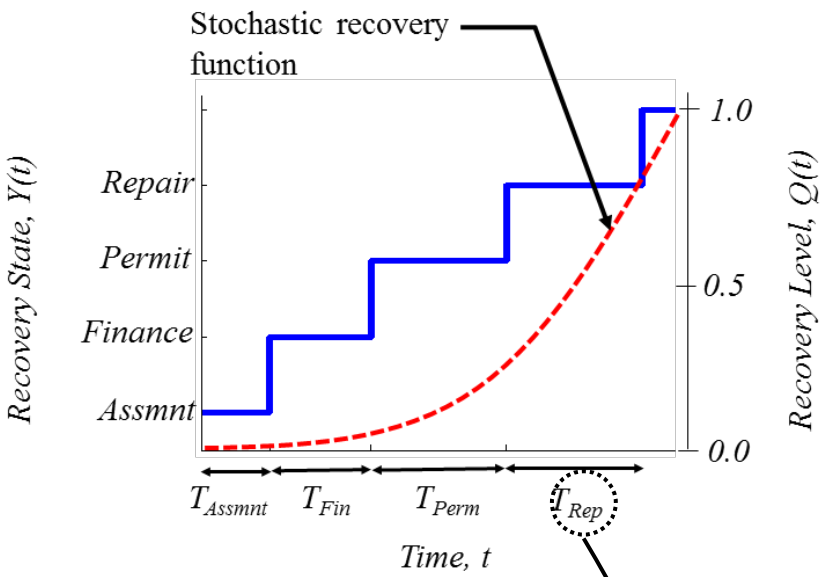
Building-Level Recovery:
***Empirically-Based* Stochastic Process Model**

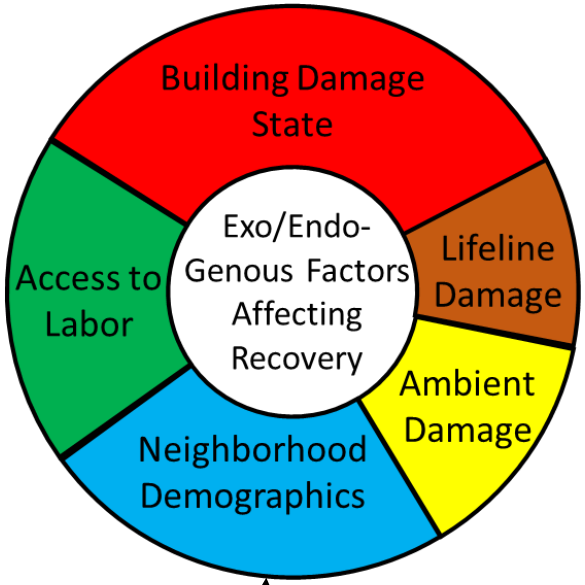




$$P(t < T < t+\Delta \mid T > t) = 1 - \frac{e^{-\lambda(t+\Delta)}}{e^{-\lambda t}}$$

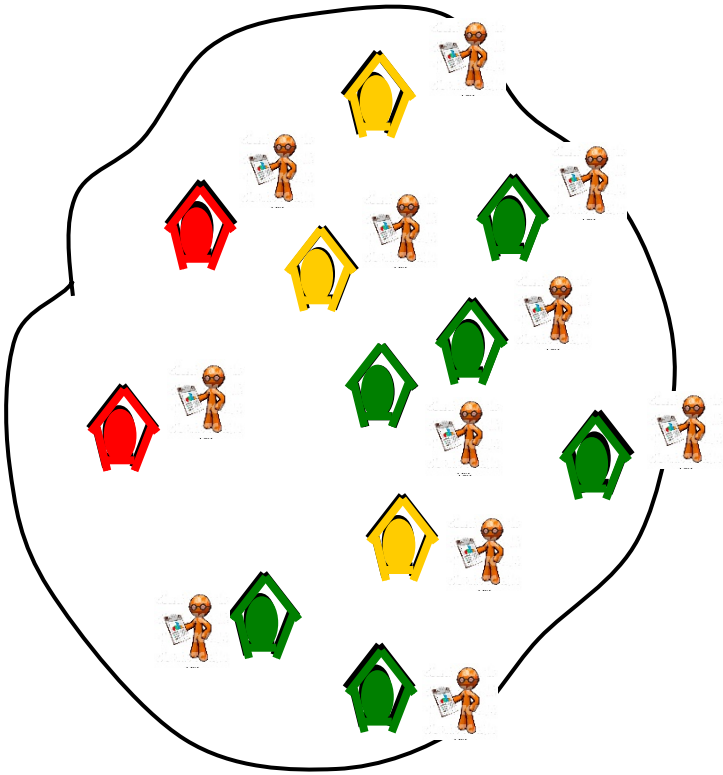
Building-Level Recovery:
***Simulation-Based* Stochastic Process Model**



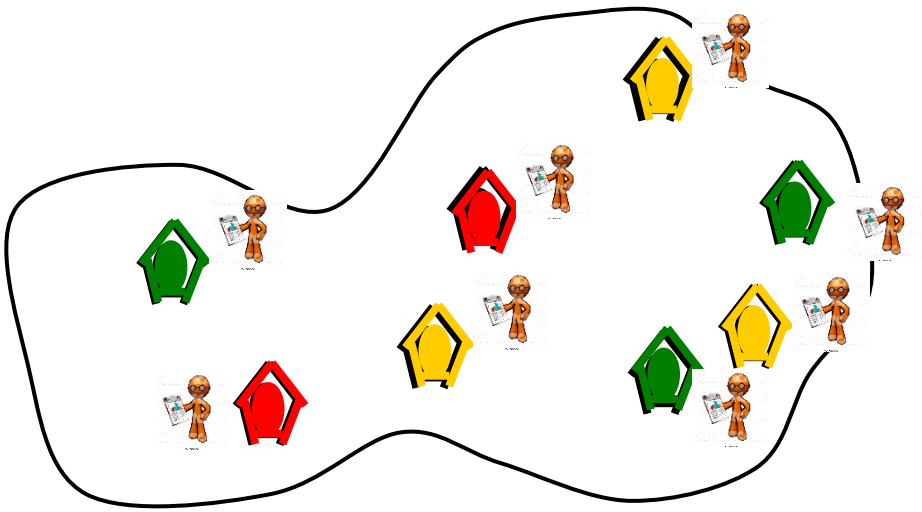


Simulate Process Dynamics with Explicit Consideration of Resources, Interactions and Impeding Factors

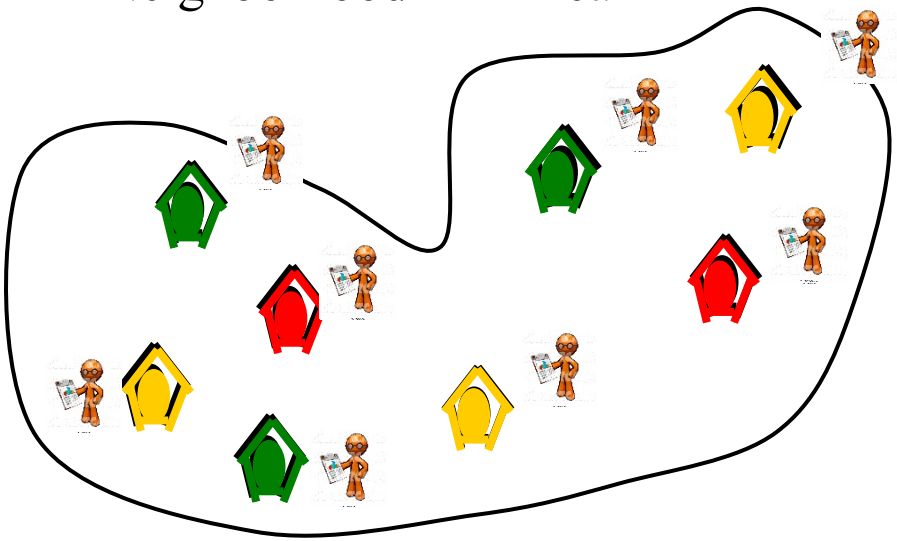
Simulating Building Damage Evaluation Dynamics



Neighborhood 1 - > Team A



Neighborhood 2 - > Team B



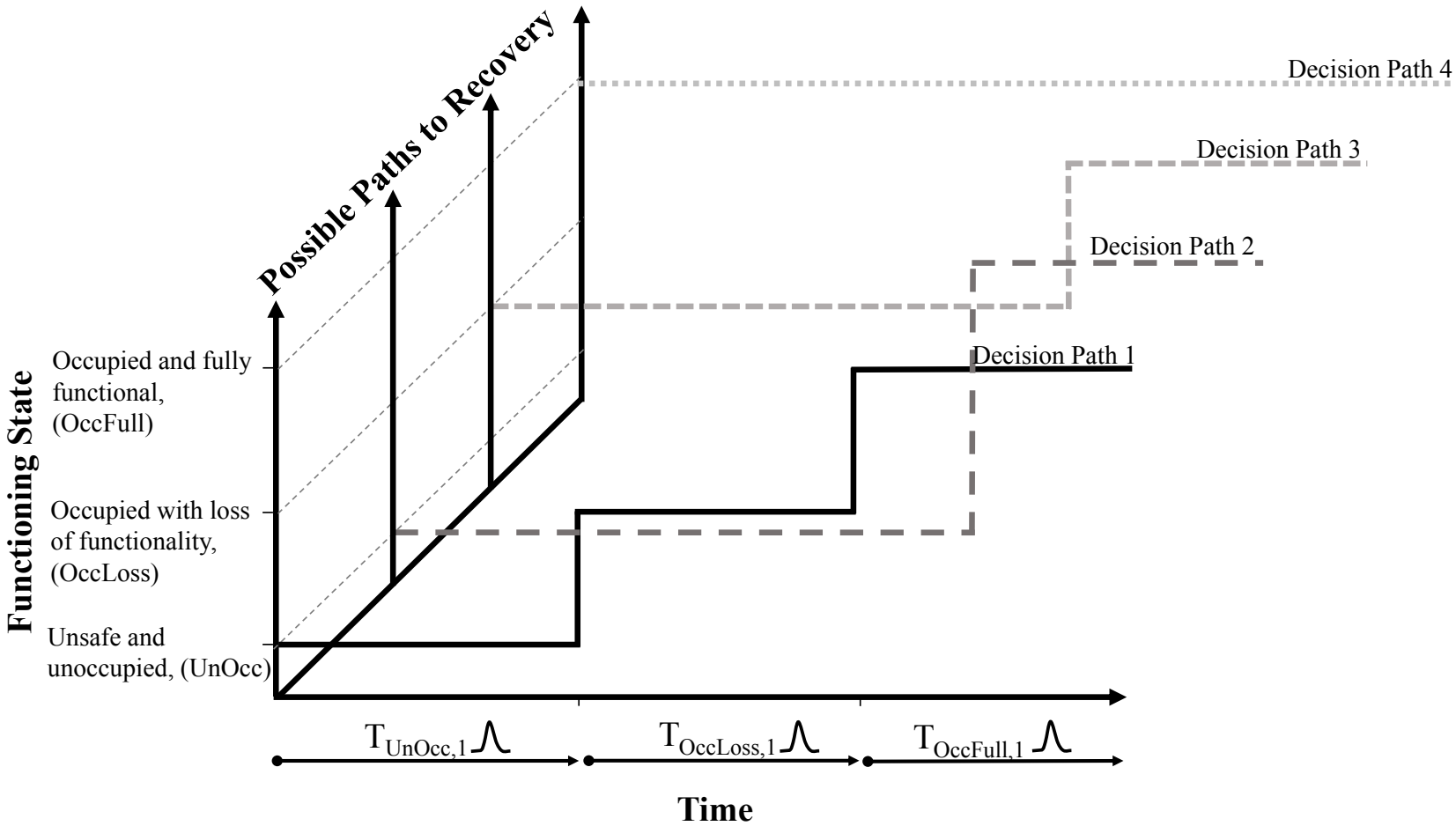
Neighborhood 3 - > Team C

Simulating Building Repair/Reconstruction Dynamics

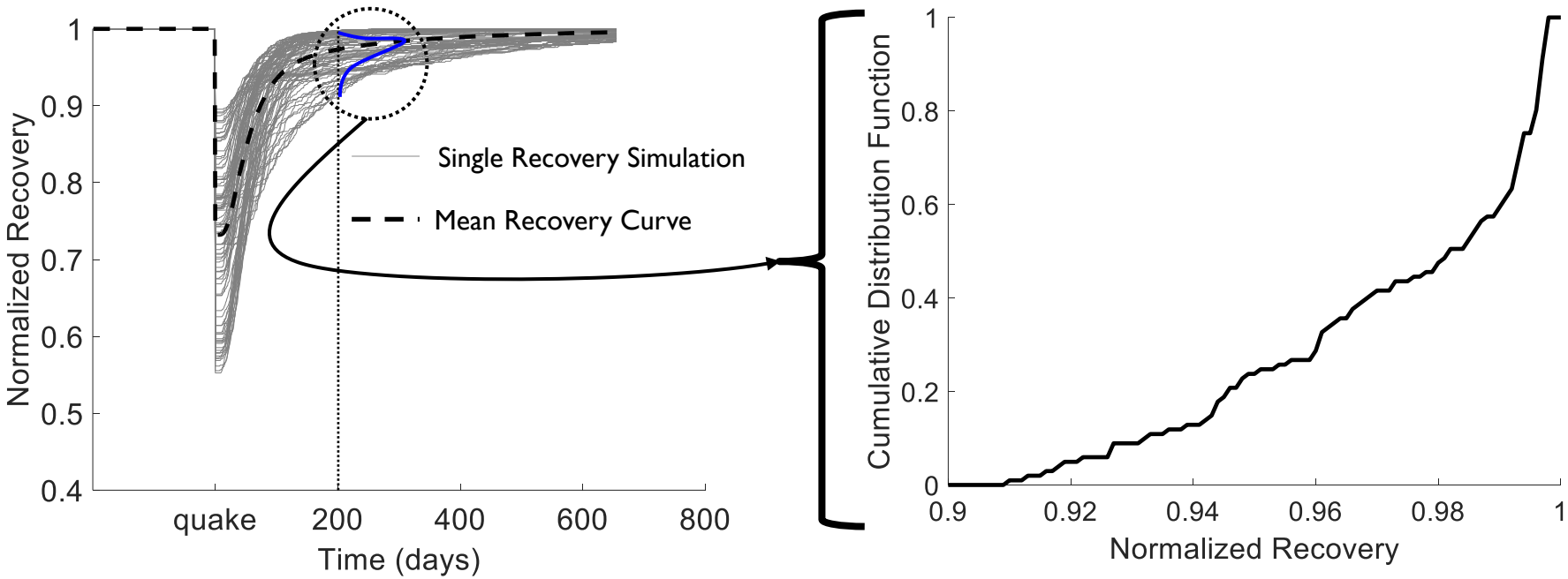
"Dealing card" algorithm for sequencing and allocating building repairs to contractors

Contractors	Number of Teams	Work-Hours Per Day Per Team	Capacity	Number of Assigned Buildings
Contractor A	5	10	5	500
Contractor B	3	10	3	300
Contractor C	2	10	2	200
			Total	**1000**

Integrating Stochastic Recovery Process and Household Decision Model: ***Probabilistic Decision Path Model***



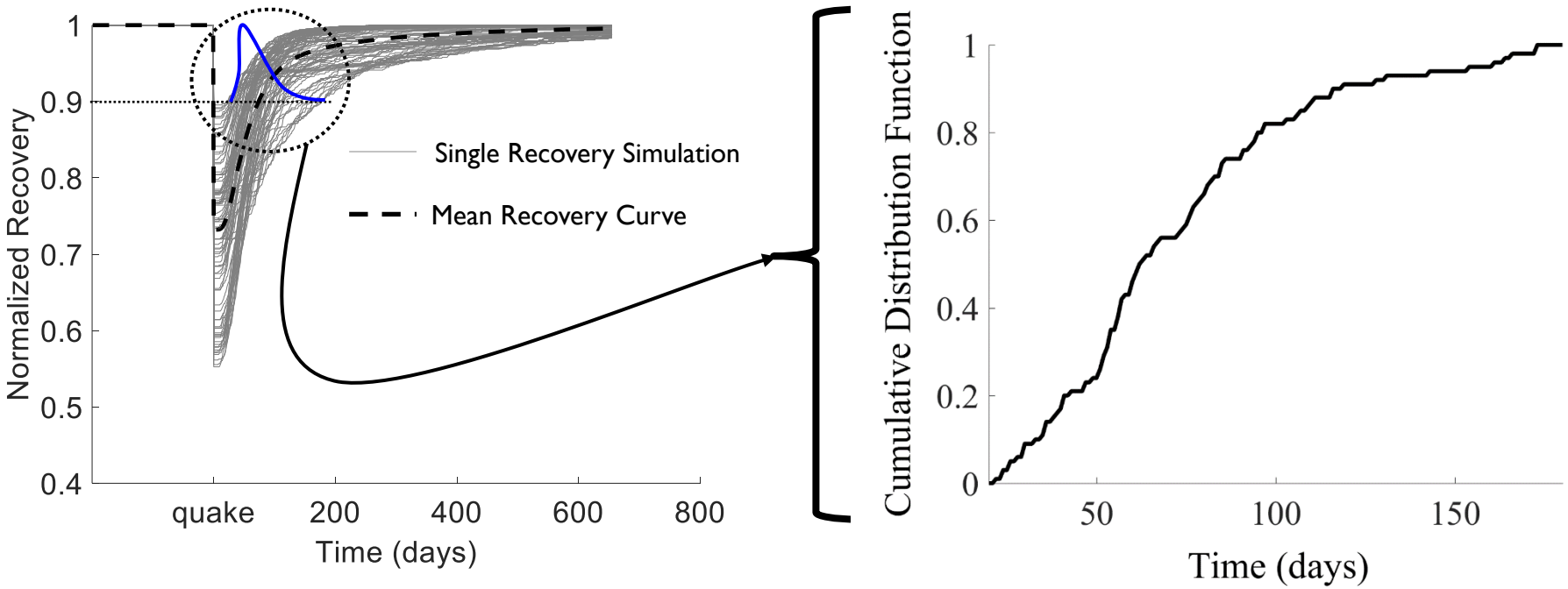
Probabilistic Community-Level Housing Recovery Trajectories



Probabilistic Recovery Function

CDF of Recovery Level at 200 days

Probabilistic Community-Level Housing Recovery Trajectories

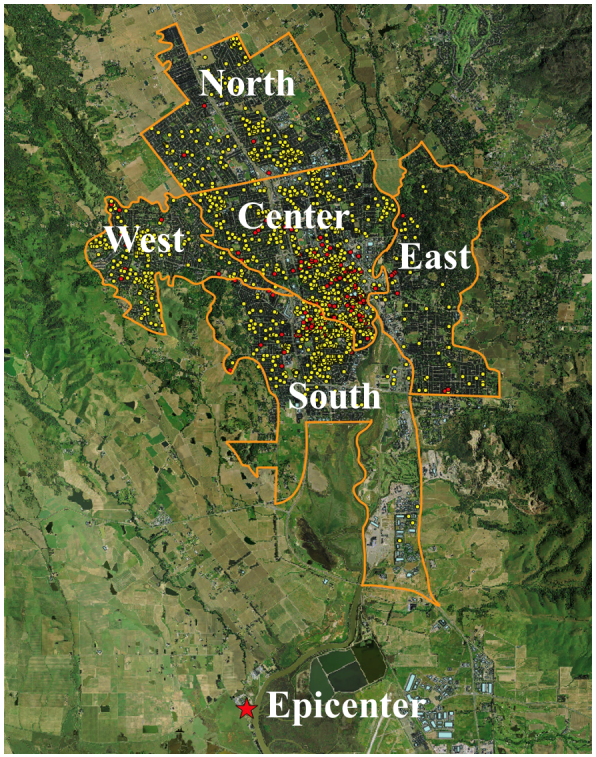


Probabilistic Recovery Function

CDF of Time to Recover to 90% Pre-Earthquake Capacity

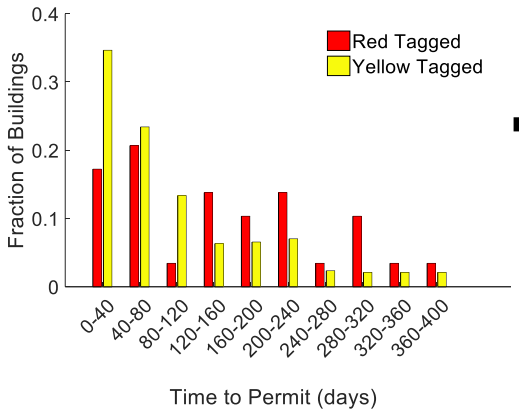
Validation Case Study: 2014 South Napa Earthquake

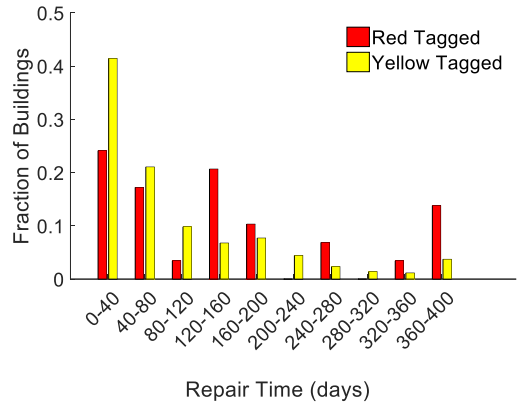
Data Type	Number of Buildings
Location, ATC-20 Tag, and damage description	1470
Sociodemographic (census) and building characteristic data	1470
Building permit issue and completion date	456

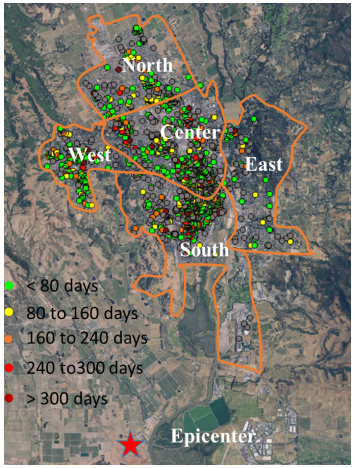


Observed Damage (red- and yellow-tagged buildings)

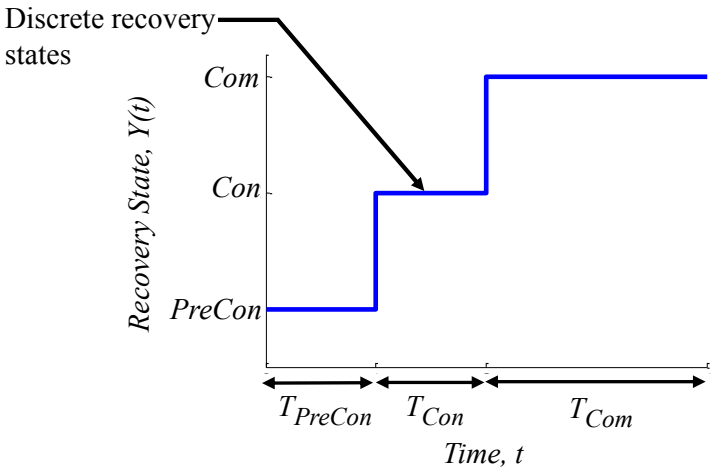
Validation Study: *1) Generate observed recovery curve for 456 damaged buildings based on time-to-permit and repair time*

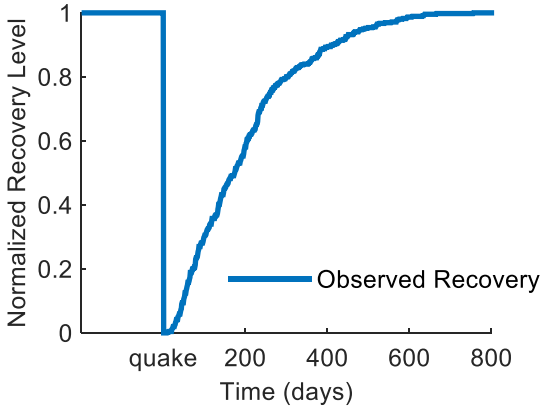






Time to Permit

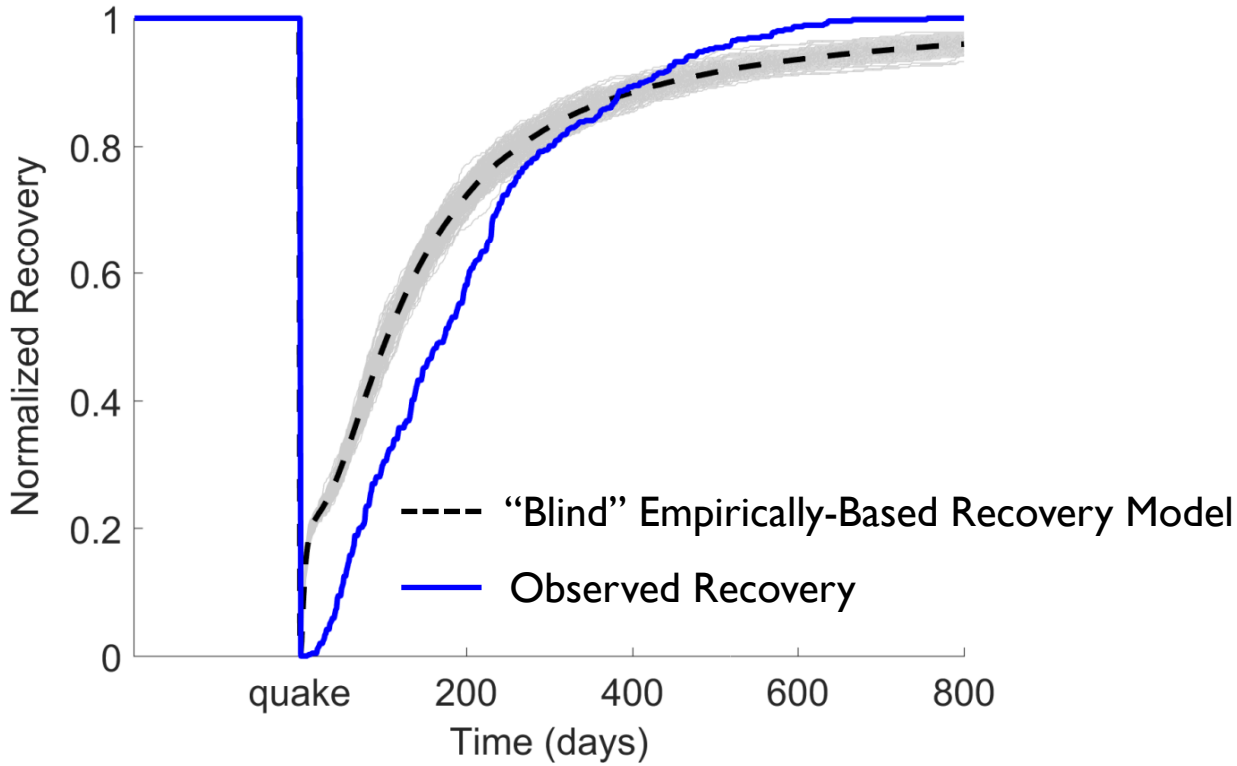




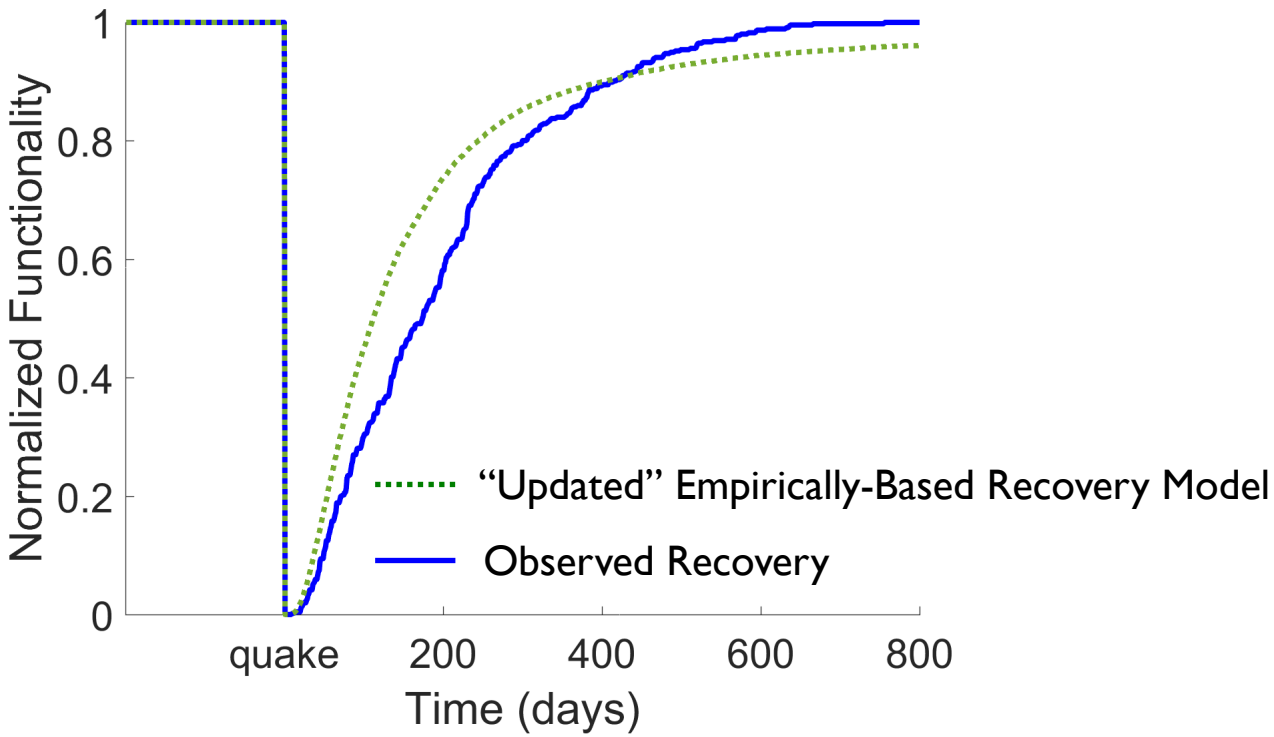
Validation Study: *2) Assign HAZUS-Type damage states to all 1470 damaged buildings*

Building No.	Field Inspection Damage Description	ATC-20 Tag	HAZUS Damage State Description	HAZUS Damage State
1	Top of brick chimney fell down	Yellow	Toppling of tall masonry chimneys	moderate
2	Racking, cracking and separation of cripple walls; floors uneven/waving; unstable house	Red	Large foundation cracks, some structures may slip and fall off the foundations, and may collapse	complete
3	Minor cracks in chimney; no structural issues; suggest inspect chimney for integrity	Yellow	Small cracks in masonry chimney	slight
4	Numerous wall cracks throughout living room kitchen and dining room; chimney collapsed	Yellow	Large diagonal cracks across wall panels or plywood joints; toppling of most brick chimneys	extensive
5	Collapse imminent	Red	Structural colllapsed occurred or is imminent due to failure of cripple wall or the lateral load resisting system	complete

Validation Study: *3) Generate empirically-based "blind" recovery trajectory using HAZUS recovery times*

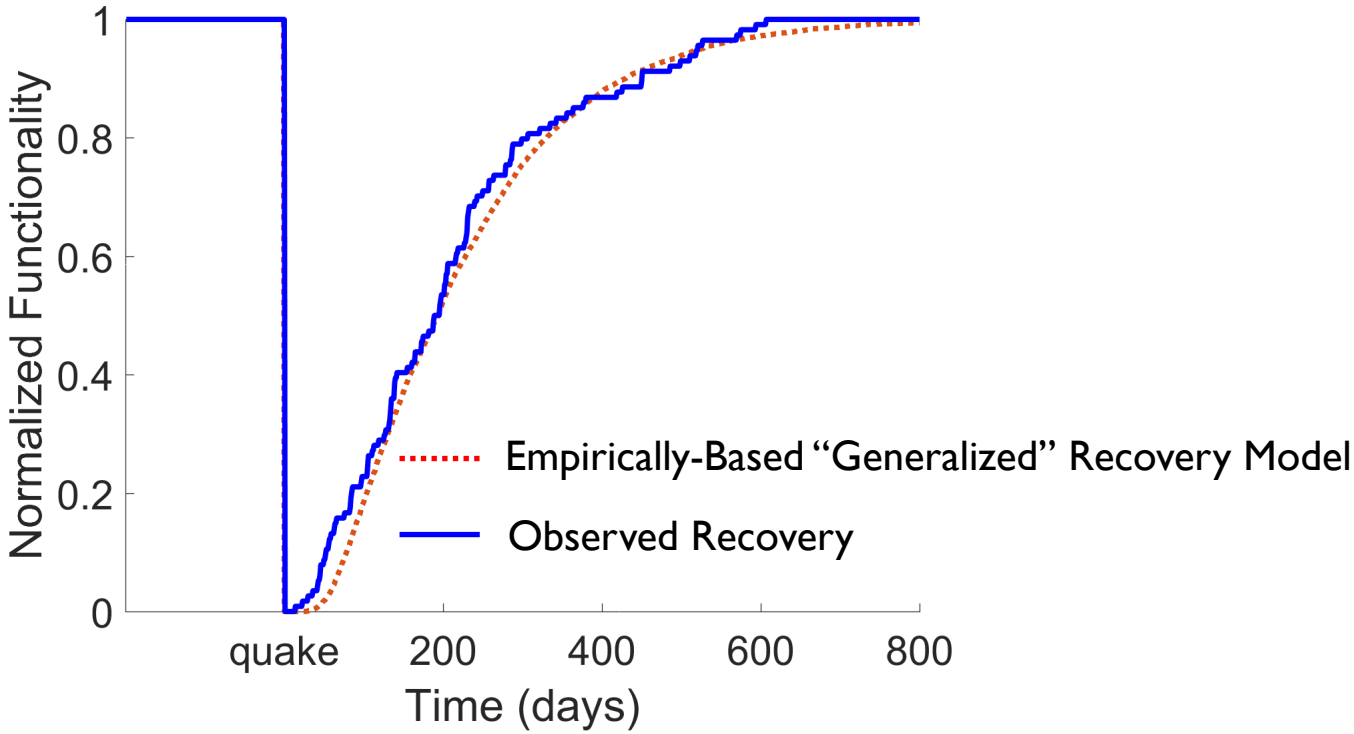


Validation Study: *4) Generate empirically-driven recovery trajectory using mean time-to-permit and repair time dataset*

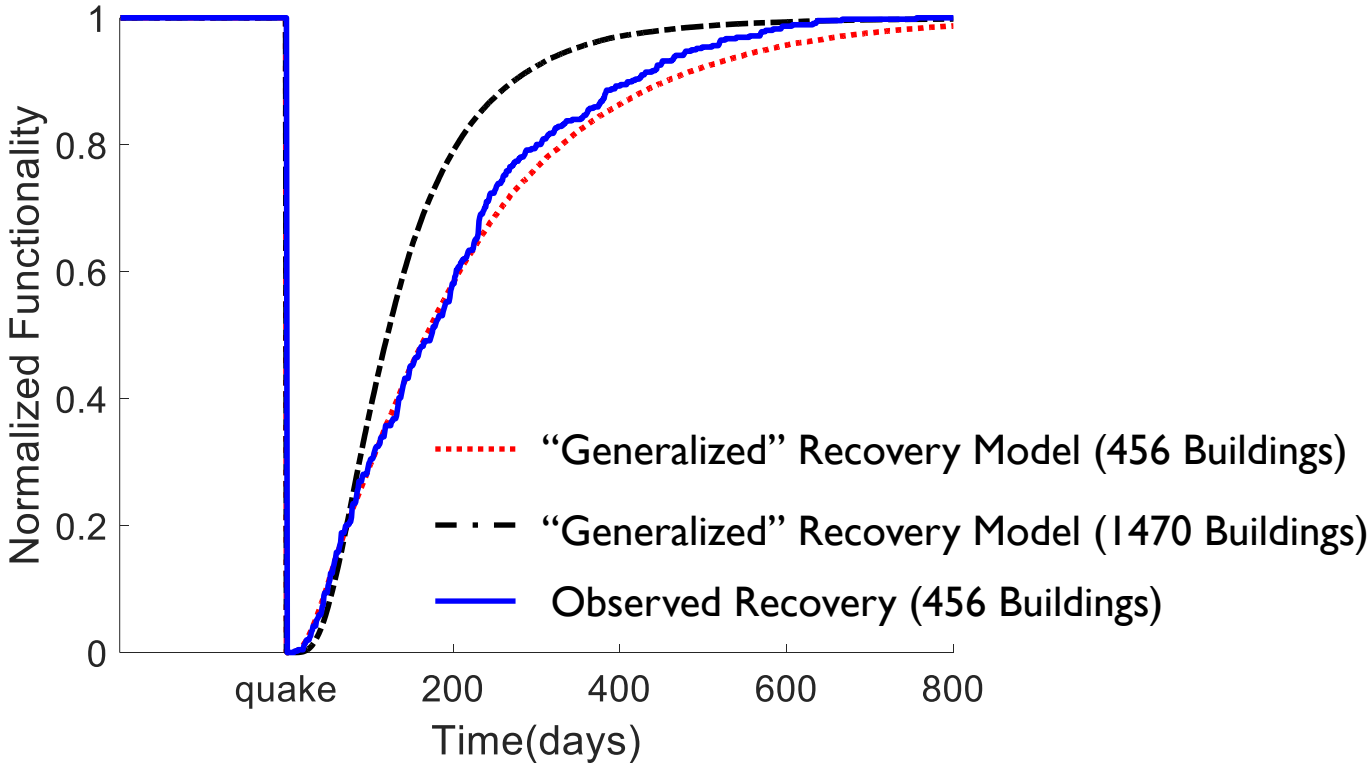


Validation Study

5) Develop statistical model for estimating time-to-permit and repair time based on damage, building attributes (e.g. building age, property value) and socio-demographic data (e.g. mean household income, percentage of owner-occupied buildings).



Validation Study: *6) Generate empirically-based recovery trajectory for 1470 buildings using generalized model from step 5*



The End

Presenter Contact Information
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