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Simulating Post-disaster Temporary Housing Needs for Displaced Households and Out-of-town Workers

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Residential damage from major disasters often displaces local residents out of their homes and into temporary housing. Communities tend to rely on out-of-town contractors for post-disaster housing recovery, and these contractors also need temporary housing. The conflicting housing needs from the displaced residents and out-of-town contractors create pressure on the local available housing stock. Thus, it is important for communities to prepare for a surge in demand for temporary housing to minimize the impact on the local residents and to expedite housing recovery efforts. Computational models can support recovery planning. However, existing models do not account for temporary housing needs when simulating housing recovery. This paper introduces a simulation framework to estimate the workforce demand and the joint temporary housing needs of reconstruction contractors and displaced persons. The framework is applied to a case study on the housing recovery of the city of San Francisco after hypothetical $M6.5$, $M7.2$, and $M7.9$ earthquakes. The earthquakes are expected to cause damage to about 10,000, 17,000, and 40,000 homes respectively. A shortage of contractors is shown to bottleneck the housing recovery in the community if no out-of-town contractors are recruited. We identify a peak demand of 2,000, 4,000, and 11,000 contractor crews following each earthquake, whereas the estimated local workforce is 1,000 contractor crews. These results highlight the need to plan for a shortage of temporary housing during the recovery phase. The framework is also used to provide insights on how to balance the housing needs of the displaced households and temporary contractors with minimal impact to recovery speed for the community.

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INTRODUCTION

In the aftermath of disasters such as earthquakes, once emergencies are attended to, restoring some sense of normalcy becomes a priority. In this phase, providing the conditions for displaced persons to return home is a priority since normalcy cannot be restored without places to live (Comerio, 2014). Occupants of lightly damaged homes may shelter in place while their homes are repaired (Force, 2012). Conversely, those whose homes are heavily damaged or destroyed require temporary housing. Post-disaster housing reconstruction is often assisted by out-of-town workers who also need temporary housing. Thus, the temporary housing needs of displaced populations conflict with that of out-of-town workers (Le Masurier et al., 2006). Investigations of the impacts of earthquakes in the San Francisco Bay Area have identified the conflicting needs for temporary housing as a potential problem for recovery (California Emergency Management Agency, 2011, Section 5.3.1). In this study, we present a framework to simulate the housing needs of the population impacted by an earthquake and the housing needs of workers needed to expedite housing reconstruction. The goal is to identify strategies to attract out-of-town workers into the community and expedite recovery without stressing out the local housing market and forcing the local residents into poor temporary housing conditions.

Temporary housing plays a pivotal role in the early disaster recovery (Félix et al., 2013), allowing the partial restoration of household routines with the understanding that more permanent housings will be eventually secured (Quarantelli, 1982). Traditionally, temporary housing is sought from vacant rental units, trailers, or with family or friends. More innovative solutions include pre-fabricated modular homes (INC., 2009), the construction of multi-family complexes, (Chang-Richards et al., 2013), or even the use of boats moored along the shoreline (Force, 2012). Providing temporary housing for the displaced population can reduce post-disaster population losses. With this goal in mind, communities have developed plans to house displaced residents within municipal boundaries, ideally within their own neighborhoods (Lee and Otellini, 2016). Thus, a significant demand for temporary housing is expected in the housing reconstruction period following a large-scale disaster.

Displaced local residents are not the only ones in need of temporary housing after a disaster. After a disaster, it is unlikely that the local workforce will suffice the demand for construction workers. Insufficient local workforce supply challenged post-disaster housing recoveries after several disasters in the past decades (Barenstein, 2006; Chang et al., 2011; Chang-Richards et al., 2013, 2014; Bilau et al., 2015,?; Bothara et al., 2016). More recently, after the Texas winter storms in February 2021, the state's long-standing lack of plumbers significantly delayed the recovery efforts (Agnew, 2021). Thus, to expedite housing reconstruction communities often rely on the recruitment of out-of-town workers. A survey of 36 construction companies working on the post-earthquake reconstruction in Christchurch identified that 29 hired out-of-town workers (Boiser et al., 2011). Recruiting out-of-town workers often leads to the escalation of rental prices. This may force a portion of the displaced residents out of the rental market. Moreover, unappealing housing conditions limits the community's ability to attract and retain the needed workforce (Center et al., 2009). The competition for temporary housing sparks conflicts between out-of-town workers and local residents (Fletcher et al., 2007).

The Federal Emergency Management Agency highlights the need for emergency managers and planners to maintain awareness of current housing stock within their jurisdiction and identify temporary housing needs prior to an incident (FEMA, 2020). However, the rare nature of large-scale disasters makes it hard to plan for them using empirical knowledge alone. In this context, computational simulations are a powerful tool to support planning. Some scholars have proposed simulation models for and highlighted the relevancy of pre-planning for workforce demand Alisjahbana and Kiremidjian (2021); Costa and Haukaas (2021). However, these models focus on simulating the allocation of the existing workforce. What has not been addressed is the constraints on increasing the local workforce due to limited temporary housing which is also needed by the local residents. To address this gap, this paper introduces a simulation framework to estimate the workforce demand and the joint temporary housing needs of reconstruction workers and displaced persons. The goal is to identify strategies that can increase the communities' recovery speed by bringing out-of-town workers without further stressing the local housing market. These strategies are assessed quantitatively and qualitatively in the context of the city of San Francisco later in the case study section.

TEMPORARY HOUSING DEMAND AND SUPPLY

Figure 1 contains three subplots which introduce key concepts in this study. At the top, the horizontal bars represent the housing recovery processes for four individual households. The households are numbered from one to four. Due to earthquake damage, these households are displaced from their homes until they can repair them. According to the REDi Framework, buildings may need to be inspected, assessed by an engineer, obtain a permit, and obtain financing to be repaired (Almufti and Willford, 2013). In Figure 1 these steps are grouped under 'impeding factors.' Once these steps are completed, the homeowners seek to hire a contractor crews to conduct repairs. If the demand for contractors exceed the supply, homeowners must compete for the scarce worker crews. The details of this simulation are discussed later. At the center plot, a timeline of the demand for contractors is presented. At time t_1, household H1 completes all the steps needed to hire a contractor. The same happens to household H2 at time t_2. In this simplified example, only two contractor crews exist in the community. Thus, when household H3 is ready to hire a contractor, at time t_3, it is not able to. At t_3 the demand for workers exceeds the local supply. Sometime later, at t_4, H2 completes the repairs and is back at home. At this time H3 can finally start repairs and the supply-demand equilibrium is reached again. However, at t_5, household H4 is unable to hire a contractor crew because all crews are currently allocated to other buildings. The workforce deficits at t_3 and t_5 may attract out-of-town workers into the community. Similarly, the community may intentionally bring in out-of-town contractors to improve its recovery process. The out-of-town workers demand housing, and their needs may be in conflict with those of the local residents. The bottom plot shows the demand for temporary housing in the community over-time. In the example, the number of households displaced by the earthquake is less than the available temporary housing in the community, e.g., vacant rental dwellings. However, if out-of-town workers are recruited at t_3 the availability of temporary housing is no longer sufficient. Figure 1 highlights the need to account for the housing needs of displaced persons and out-of-town workers when planning for recovery.

Two important concepts are introduced in Figure 1. First, it is demonstrated how the competition for resources can exacerbate socioeconomic disparity in the housing recovery. The dashed boxes indicating a waiting period are a consequence of a household entering the competition for resources late due to the inability to raise funds quickly, for example. Thus, if the housing recovery is bottlenecked by the availability of contractors, the household with lower socioeconomic status are subjected to longer recovery processes. Second, in Figure 1 the demand for contractors and temporary housing exceeds the local availability at some, but not all times. Thus, insights into the demand for workers over time may help identify the number of out-of-town workers needed to reduce the waiting period for households and which has a minimal adverse effect on the local housing market. In this study, the fraction of the total demand for contractors that balances the need to speed up recovery and which has minimal impact on the total temporary housing needs is called the 'target ratio', R_{target}, that is

$$R_{target} = \arg\min \Big(T \Big) \qquad \text{subject to } D < A \tag{1}$$

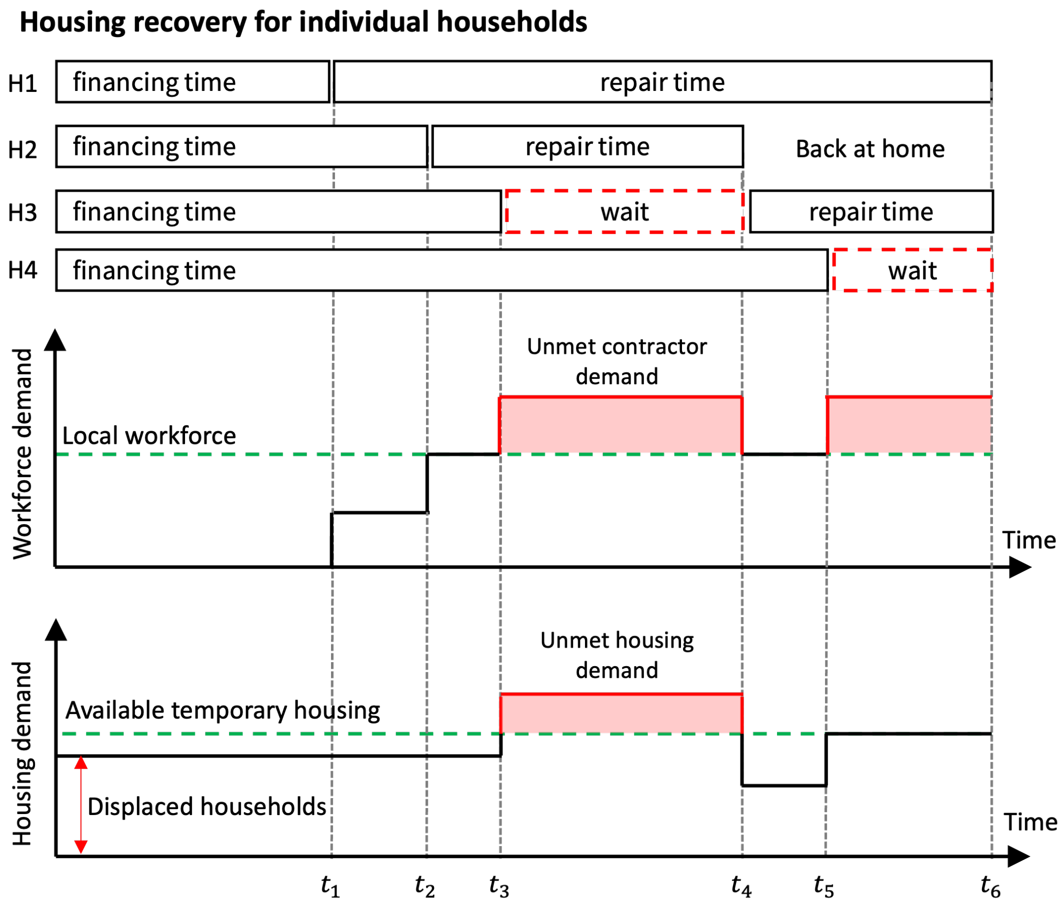

Figure 1. A schematic representation of the demand for contractors and temporary housing over time.

where T is the time to recover the community's housing stock, D is the demand for temporary housing, and A is the community's capacity to accommodate displaced residents and out-of-town workers. When communities establish housing recovery goals, e.g., re-house all residents within four years, they implicitly set R_{target}. That is, R_{target} represents the minimum contractor supply-demand-ratio needed to achieve the recovery goal. The target ratio is used to determine the number of out-of-town workers needed over time, $C_{oot}(t)$, as

$$C_{oot}(t) = R_{target} \times \Big((C_h(t) + C_a(t)) - (C_w(t) + C_a(t)) \Big) \tag{2}$$

where $C_a(t)$ is the number of workers currently allocated to housing reconstruction, C_h is the number of households waiting for a contractor crew to become available, and $C_w(t)$ is the number of workers waiting to be allocated. The total demand for temporary housing should account for the housing needs of the displaced population, $H_d(t)$. That is

$$D(t) = C_{oot}(t) + H_d(t) \tag{3}$$

A shortage of temporary housing is identified if $D(t)$ exceeds the post-disaster available temporary housing stock.

OVERVIEW OF SIMULATION FRAMEWORK

To assess the demand for contractors and temporary housing, we expand a framework of models previously developed by the authors (Costa et al., 2020). Figure 2 summarizes the inputs, outputs, and models involved in this framework. The framework is evaluated from left to right, starting with the assessment of the earthquake hazard. Data on earthquake sources, potential rupture patterns, and soil conditions are inputs. The Regional Risk and Determination Tools developed by the SimCenter (Deierlein et al., 2020) are used to estimate the intensity of the ground motions across the region of interest and generate ground motion maps. Next, an exposure portfolio is constructed using Census data and the methodology described in the HAZUS Inventory Technical Manual (FEMA, 2019). The methodology allows us to estimate the structural type, code design level, and replacement cost for buildings of interest. In the following, damage to each building is assessed using the estimated ground motions and fragility functions FEMA (2015). The damage assessment also allows the repair cost and repair time to be estimated. Maps of the earthquake immediate impacts are the outputs of this step.

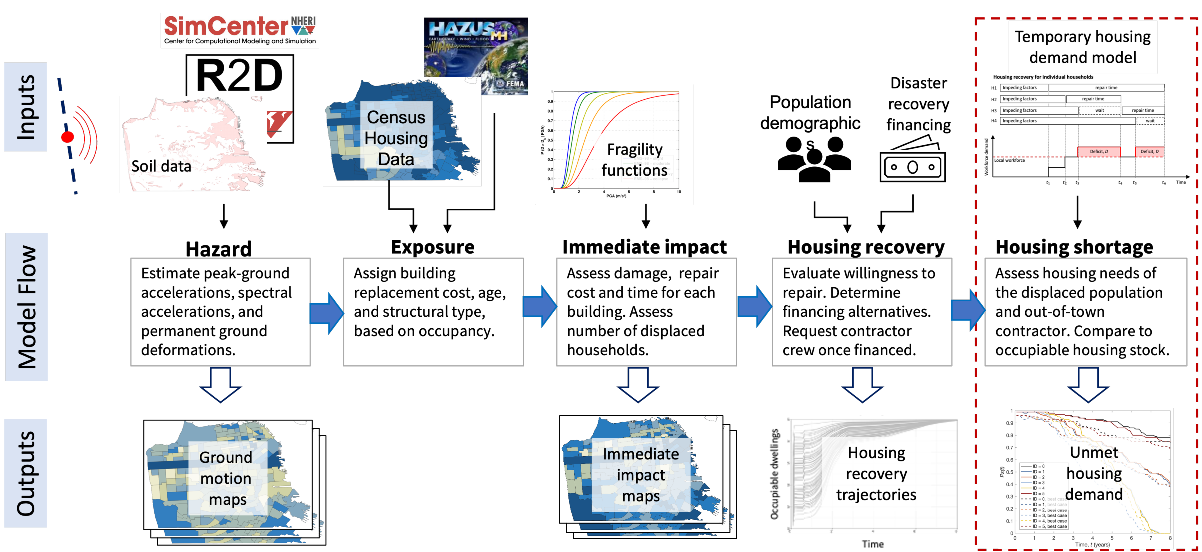

Figure 2. Overview of the simulation framework. The main inputs are publicly available data sources, e.g., Census and USGS. The framework has five main steps which are evaluated sequentially and produce intermediate outputs. The new models developed in this work are highlighted on the far-right.

Once the conditions of each building in the community are known, recovery is simulated. We associate one household to each building. The household is described by its socioeconomic status, e.g., tenure status and income, which are determined using random sampling based on Census data. The demographics of the household allows us to determine the financing alternatives available to the household. We employ the model of Alisjahbana et al. (2021), with modifications, to simulate recovery financing. This model was developed considering post-earthquake housing recovery financing for a household in San Jose, California. Four funding sources are included: earthquake insurance, bank loans, Small Business Administration (SBA) loans, and Community Development Block Group for Disaster Recovery (CDBG-DR) grants. Alisjahbana et al.'s model provides an estimate of the time needed for a household to obtain full financing for its repairs. For households that depend on public funds, the financing time is often the most relevant impeding factor. The competition for the limited contractors is simulated using the concepts introduced in Figure 1. The output of this processes are housing recovery trajectories for the community which are obtained by computing the housing recovery time for individual buildings and aggregating across the community.

The novel models developed in this communication are highlighted on the right-hand side of the Figure 2. We introduce models to assess the demand for temporary homes from the displaced population and the demand for out-of-town contractors on each time step of the simulation. These models allows us to evaluate the potential for temporary housing shortages, and determine the unmet demand. The following section provides details about the computer implementation of these models and the calculations involved providing readers with the understanding needed to implement the same models into their own housing recovery models if desired.

AGENT-BASED HOUSING DEMAND SIMULATION

This section provides technical details of the implementation of the framework of models in Figure 2. All models are implemented using the object-oriented paradigm. These models have attributes (i.e., input parameters), actions (e.g., calculations they perform), and communicate with other models (i.e., provide outputs). Some models have simple actions and we call these 'objects', e.g., the Hazard Object simply outputs the ground motion intensity at the location of each building. Other models represent entities with complex behaviors. We call these 'agents' and they can respond to inputs from other models. Figure 3 shows the interactions between the main agents: households, local and out-of-town contractors, and the local housing authority. The Household Agents start most of the interactions in the framework. There are many Household Agents and each "has-a" Building. The "has-a" represents a composition relationship in object-oriented programming (Deitel and Deitel, 2006). The Hazard Objects provide the ground motion intensity estimates to the Building Objects, which in turn evaluate damage and inform the Household Agents. The Household Agents leave the building if significant building damage is observed. Displaced Household Agents seek financing and procure resources, e.g., contractors, to conduct housing repairs. Contractors are initially sought from the Local Contractor Agent. If the demand for contractors exceed the local workforce (C_b), the unmet demand for workers is informed to the Out-of-town Contractor Agents. The displaced Household Agents also inform the Housing Authority Agent of their need for housing, indicate as (+) in Figure 3. The Housing Authority Agent may decide to build new housing to accommodate displaced households and increase the local housing availability. The local housing availability is also communicated to the Out-of-town Contractor Agents. The demand for contractors and temporary housing availability will inform the decision of the Out-of-town Contractor Agents to come or leave the community. When a Household Agent receives contractors it repairs its building and eventually returns home. At this point it updates the Housing Authority Agent indicating it no longer needs temporary housing, shown as (-) in Figure 3.

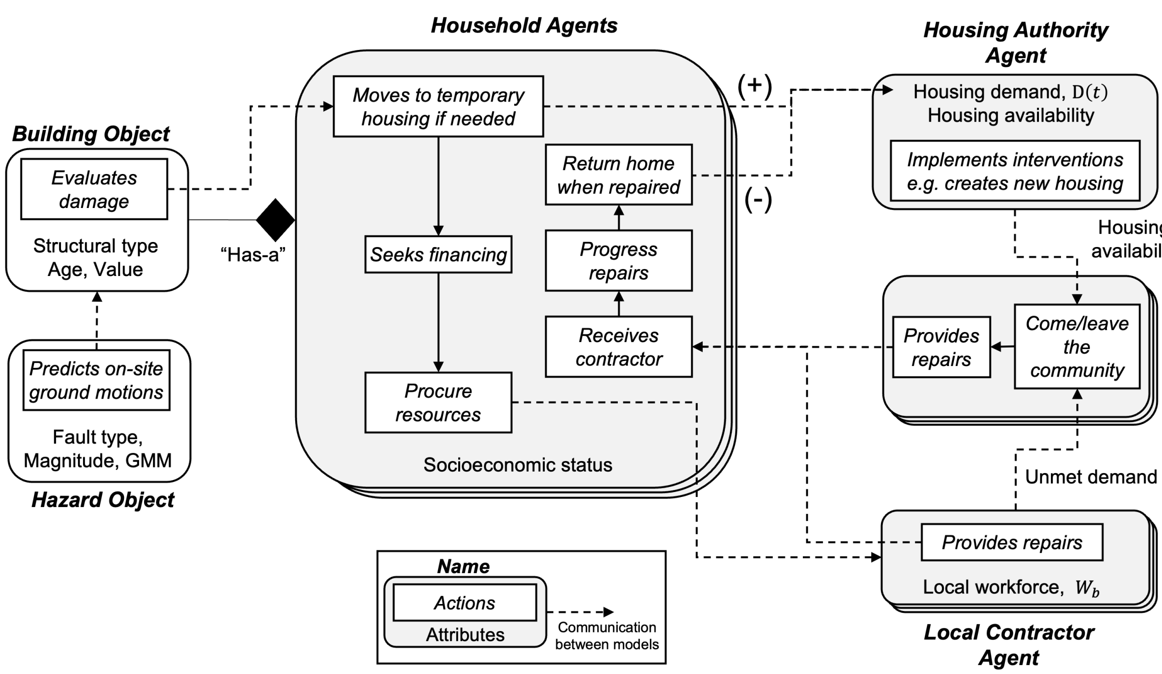

Figure 3. Implementation of the object-oriented agent-based simulation framework.

HOUSEHOLD AGENTS

The main attributes of the Household Agents are socioeconomic data. Their tenure status (i.e., renter or owner) and income bracket (i.e., low, moderate, or high) are used to determine the households access to housing recovery financing using Alisjahbana et al. model. These demographics are sampled from the distributions in each census block group, but correlations between demographics are not directly simulated. For example, if 50% of the households are renters in one block group, and 30% have a low income, the probability that a household is a renter and has a low income is $0.5 \times 0.3 = 0.15$. This approach partially captures the spatial correlation that exists between demographics at the block group level. The main actions of the Household Agents are related to temporarily moving out of and back in to their buildings. We assume that buildings severely and completely damaged require substantial repairs and may not be safe. Past events have demonstrated the safety concern may not be sufficient for households to leave their damaged homes. Accounting for this factor is outside of the scope of this study and we assume that the occupants of severely and completely damaged buildings seek temporary housing. For completely damaged buildings, reoccupancy is reestablished when the building is fully repaired. For severely damaged buildings 50% of the repairs need to be completed before the building is reoccupiable (FEMA, 2015, Table 15.11). The destination of displaced households is not tracked (Sutley and Hamideh, 2020, e.g.,). We assume that ideally they would be in a temporary home similar to their pre-disaster home and thus contribute to the community's housing demand.

LOCAL CONTRACTOR AGENTS

The Local Contractor Agents represent the contractors that exist in the community prior to the earthquake. These contractors are assumed to be available immediately after the disaster and to remain in the community during the reconstruction processes. In communities with high living costs, it is likely that many contractors that work in the city live in neighbor communities. These neighboring communities are also likely to be impacted by the earthquake. It is outside of the scope of this work to determine if these workers will have enough incentives to continue commuting to the community of interest after a disaster or work on nearby sites. Hence, our baseline assumption is that they will not. Thus, the Local Contractor Agents are comprised of workers who live within the community of interest. We estimate the number of local contractors using data from the ArcGIS Business Analyst (ESRI, 2021). For San Francisco, about 3,000 persons work the single-family construction and repair sector. We assume a contractor crew is comprised of three persons, hence, we estimate 1,000 local contractors exist in San Francisco.

OUT-OF-TOWN CONTRACTOR AGENTS

The Out-of-town Contractor Agents respond to inputs from the Local Contractor Agents and the Housing Authority Agent. These outputs reflect how favorable to labor and housing market in the community are, respectively. The actions of the Out-of-town Contractor Agents are defined by the workflow in Figure 4. On each time step of the simulation, they evaluate the community's need for out-of-town contractors to assist to assist with housing recovery, $C_{oot}(t)$, introduced in Equation 2. If $C_{oot}(t) > 0$, out-of-town contractors are needed. Before the $C_{oot}(t)$ new workers come into the community they check how favorable the housing market in the community is. The expected number of temporary housing units in the community ,$A(t)$, is

$$A(t) = max(V(t) - D_h(t), 0) \tag{4}$$

where $V(t)$ is the expected number of vacant housing units discussed later, and $D_h(t)$ is the housing demand by the displaced population. If $A(t) = 0$, the housing market is not attractive and out-of-town contractors are not attracted to the community. Conversely, if $A(t) > 0$, $max(C_{oot}(t), A(t))$ come into the community and the number of workers available increases by $max(C_{oot}(t), A(t))$. At the same time, $A(t)$ decreases by $max(C_{oot}(t), A(t))$. This process is shown on the left-hand side of Fig. 4. Conversely, when $C_{oot}(t) < 0$ a portion of the out-of-town workers is assumed to leave the community. This simulates the situation observed in previous disasters in which, as the demand declines, construction companies are no longer able to afford to retain the out-of-town workers. This process is shown on the right-hand side of Fig. 4. The number of out-of-town contractors currently unemployed, namely the surplus workers, $C_s(t)$, is assessed as

$$C_s(t) = C_a(t) + C_w(t) - R \times (C_a(t) + C_h(t)) \tag{5}$$

and it is assumed that a fraction L of the surplus workers will leave the community the next time simulation time step, i.e., $C_w(t)$ decreases by $L \times C_s(t)$, and the accommodation capacity $A(t)$ increases accordingly. Note that that only out-of-town workers leave when the contractor supply exceeds the local demand. That is, the total workforce supply has a lower bound equal to the number of local contractors. Moreover, if $R = 1$, $C_s(t)$ is simply the difference between the supply and demand for workers. This guarantees that contractors currently allocated to a building do not leave before they complete their current job.

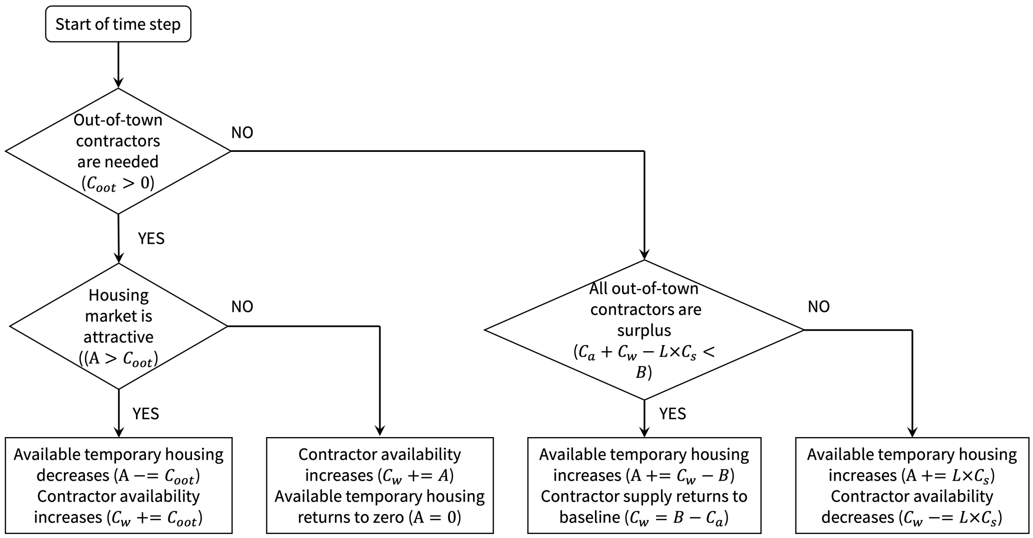

Figure 4. Flowchart of actions taken by the Out-of-town Contractor Agents.

HOUSING AUTHORITY AGENT

The Housing Authority Agent represents the decision makers in the community. This agent keeps track of the housing needs of the displaced residents and out-of-town workers. It is aware of the number of vacant units that exist in the community. Considering temporary housing demand from displaced household and out-of-town workers, $D(t)$, the number of vacant units in the community, $V(t)_i$, and the probability of observing a shortage of temporary housing at time t is

$$P_s(t) = \frac{1}{N} \sum_{i=1}^{N} \mathbf{1}\left(D(t)_i > V(t)_i\right) \tag{6}$$

where **1** is an indicator function that returns the unity if the condition is true and zero otherwise. Note that displaced households may stay temporarily with family or friends. Thus, $D(t)$ represents the maximum housing demand. The number of pre-earthquake vacant units is obtained from the 5-year estimates by American Community Survey (ACS). These homes fall into one of four categories: (1) units currently in the market for rental or sale; (2) secondary and currently empty homes; (3) primary homes which were not occupied at the time of the survey; and (4) other. Category (4) encompasses 18,626 housing units and these are assumed to have the potential of being used by displaced households after an earthquake. The 18,626 include single-family home or an apartments. We assume that vacant rental homes remain available for renting after the disaster, i.e., the owners do not occupy or sell them. The ACS data do not allows for the spatial distribution of these homes to be determined. Moreover, this spatial distribution can significantly change over time. Hence, we do not estimate the ground motion intensity at the sites of these buildings to determine their post-disaster inhabitability. Rather, we assume that if 20% of the occupied housing portfolio is damaged an equal percentage of the vacant portfolio is also damaged. We also assume that buildings that were vacant before the disaster will not be repaired before the buildings that were occupied.

In this study, the Housing Authority simply communicates the state of the local housing market to the Out-of-town Contractor Agents to inform their decisions. In future implementations, the Housing Authority Agent may be given the ability to implement interventions to address the housing shortages. Intervention may consist of building new temporary housing or giving priority to a certain group (e.g., local residents over out-of-town workers). The Housing Authority Agent also decides when the intervention should be implemented. For example, if an intervention to build new temporary homes is implemented immediately after the earthquake it may have adverse effects in the progress of housing recovery in the short-term due to it requiring the local workforce.

CASE STUDY

In this case study, the framework discussed in the previous sections is used to simulate housing recovery. The contractor supply-to-demand ratio is indicated by R, i.e., R=1 indicates all demand for contractors is met. Initially, housing recovery is simulated considering only the local availability of contractors. The case study also investigates how different R can accelerate housing recovery but exacerbate the temporary housing needs. The goal of the case study is to identify the R that balances the positive and negative effects of receiving out-of-town contractors for the housing recovery process. We consider the impacts of three earthquakes with magnitudes (M) 6.5, 7.2, and 7.9 on the single-family housing stock in San Francisco. San Francisco's vacancy rate of rental dwellings is relatively low, i.e., 4% as per Census Data in 2019. The low vacancy rate is compound by the city's lack of vacant land to create new temporary housings in the aftermath of a major disaster (Force, 2012). These factors make San Francisco an interesting case study.

The building portfolio for the case study is constructed from Census data using the procedure in FEMA (2019). The case study includes 124,564 single-family houses in the city of San Francisco. The considered earthquake scenarios rupture the northern San Andreas fault which is located west of San Francisco. For each of the three earthquake scenarios, one hundred ground motion and damage maps are generated to partially capture uncertainty in the immediate impact of the earthquakes. Table 1 provides an overview of the impact of each earthquake. As expected, the average number of buildings severely or completely damaged increase with the earthquake magnitude. These buildings are assumed to require major repairs (FEMA, 2015). In the following, we refer to these as 'displaced households.' Although outside of the scope of this study, a portion of these households may opt to stay in their homes despite of their damaged state whereas others may stay with family or friends. Choosing the live in partially damaged homes has been associated with negative physical and mental health Abramson et al. (2015). Thus, we assume that these households would desire to be allocated to a structurally safe temporary housing. Hence, the results in the following represent the upper bound of the number of displaced persons. The last column in Table 1 shows the number of temporary dwellings expected to be available in the community after each earthquake calculated as described in the previous section.

Table 1. Expected impacts of the three earthquakes on the building portfolio.

Earthquake magnitude [M_w]	Structural damage state	Number of buildings	Displaced households	Potential Temporary housing*
7.9	Severe	22,369	39,039	12,800
	Complete	16,670		
7.2	Severe	11,364	16,983	16,096
	Complete	5,619		
6.5	Severe	7,414	10,430	17,214
	Complete	3,016		

*immediately following the earthquake.

For each damage map, i.e., 100 per earthquake, we simulate housing recovery for eight years following the event using 14-days time steps. The recovery time for each building is dependent on its repair time and the delay to start repairs. Repair time is a step function of the damage state. Repair delay measures the time from the event to the moment repairs start. Repair delay is bound by the ability of a household to obtain financing and the competition for contractors in the community. We assume all households will either repair or sell their buildings. Buildings sold are repaired by the new owner, but a delay is incurred by this transaction. There is significant variability in the repair delay. Some households can self-fund repairs and start repairs soon after the earthquake, whereas others have to rely on grants that take years to be disbursed.

Figure 5 shows the median housing recovery curves for the three earthquakes on San Andreas Fault. For each earthquake, three recovery scenarios are considered. The 'baseline scenario' considers that recovery relies solely on the local workforce. The remaining two scenarios are defined in terms of ratio of contractors in the community to the demand for housing repairs, i.e., R. In these scenarios, the high demand for contractors attracts out-of-town contractors. In the 'ideal' scenario as many contractors as needed are available, i.e., R=1, and the availability of contractors does not bottleneck the recovery. This ideal scenario is unlikely since communities may not be able to attract as many contractors as needed. In the 'intermediate' scenario $R = 0.5$, that is, the community is capable to attract contractors to supply about 50% of the demand at any point in time. In this case study, we are interested in evaluating the impact that the out-of-town contractors would have in the local housing market. Hence, we consider that they will come to the community as long as the demand exists. Another assessment could focus on determining the ideal number temporary housing units that need to be created in the community to attract the needed contractors, e.g., emphasizing Eq. **??**. The results show that due to the low availability of local contractors in San Francisco the baseline scenario leads to a slow recovery. The other two scenarios result in similar and significantly better results than the baseline scenario. The change in slope in the curves around the two-year mark is due to some households being reliant on public funding which is slowly disbursed over several years.

Achieving the ideal recovery speed in Figure 5 requires a substantially higher number of contractor crews than those available in the city. Figure 6 shows the number of contractor crews needed over time. The horizontal line shows the local workforce, i.e., 1,000 contractor crews. In the ideal scenario, there is a spike in the demand for contractors within the first two years since the earthquake. The long right tail in the ideal scenario is due to the recovery being bottlenecked by the ability of homeowners to obtain financing. In the intermediate scenario, the peak within the first two years is smaller. However, the right tail is longer. For the $M6.5$ scenario the local workforce is sufficient to supply 50% of the demand at any one point, i.e., the intermediate scenario. For the M7.2 and M7.9 it may take several years for housing reconstruction to not

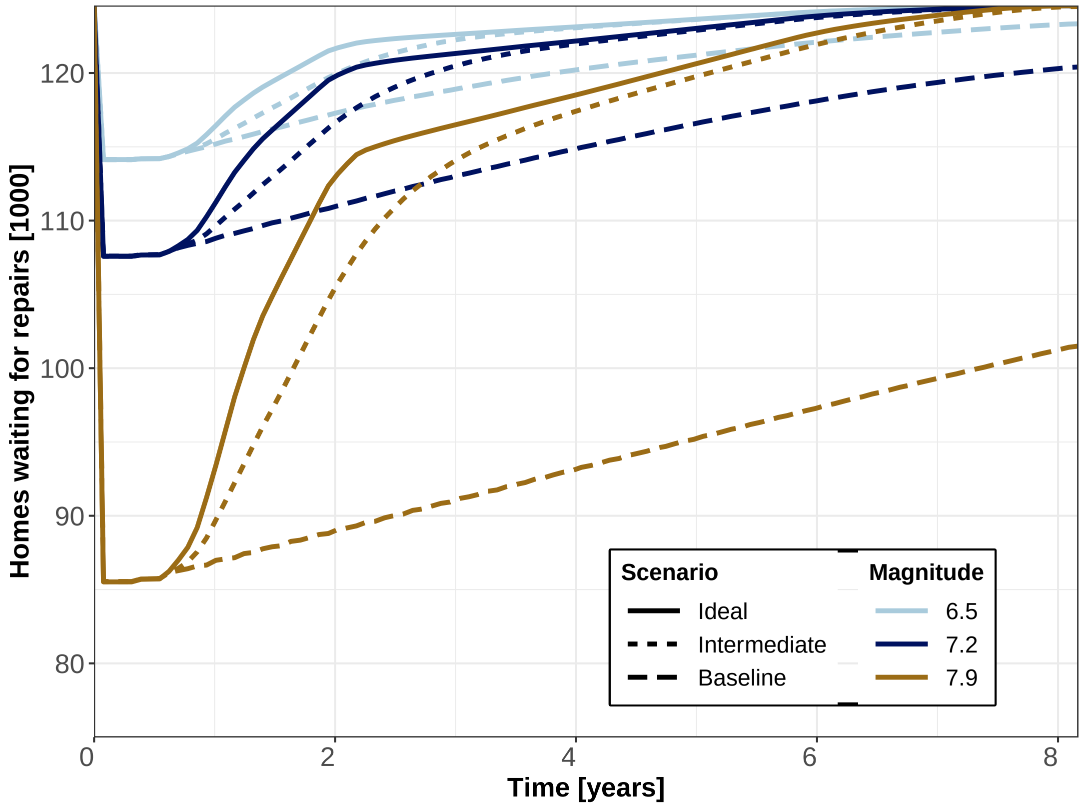

Figure 5. Median housing recovery curves for the three earthquakes on San Andreas Fault: $M7.9$, $M7.2$, $M6.5$. The scenarios represent different contractor supply-to-demand ratios, R's. In the baseline scenario only the 1,000 local contractor crews are available to recover the housing stock. In the ideal scenario R=1, that is, as-many-as-needed crews are available. In the intermediate scenario $R = 0.5$.

355 need support from out-of-town contractors.

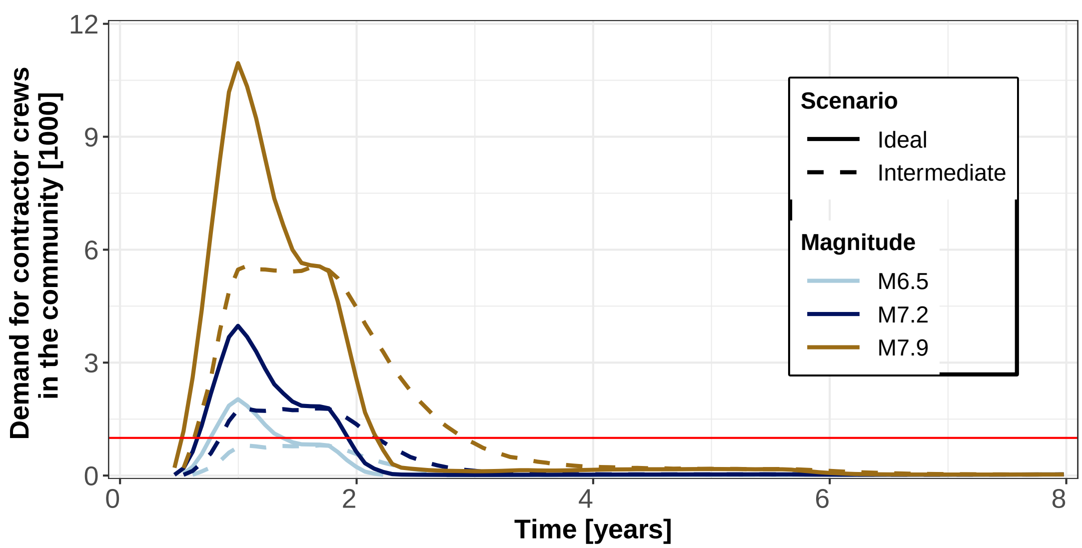

Figure 6. Demand for contractor crews needed to support housing recovery in the community over time.

Figure 6 shows that the ideal recovery process for the community would require a significant number of out-of-town contractors. If these contractors are to be housed within the community, this may significantly impact the post-disaster housing demands. Figure 7 presents the total temporary housing needs in the community. The results at time t=0 represents the needs of the displaced households. Over time, the needs of the displaced households decreases whereas the needs of the out-of-town contractors may increase. The results show that, if out-of-town contractors require temporary housing within the community, their housing needs are not negligible. Figure 7 also shows the temporary housing needs when recovery is not supported by out-of-town contractors, i.e., the baseline scenario. In this case, although the local housing market does not suffer any extra pressure, the bottleneck introduced by the limited local workforce subjects residents to a much longer period of potential displacement. In combination, these results highlight that attracting out-of-town contractors is important but that without the necessary planning it can exacerbate the disaster impact on communities.

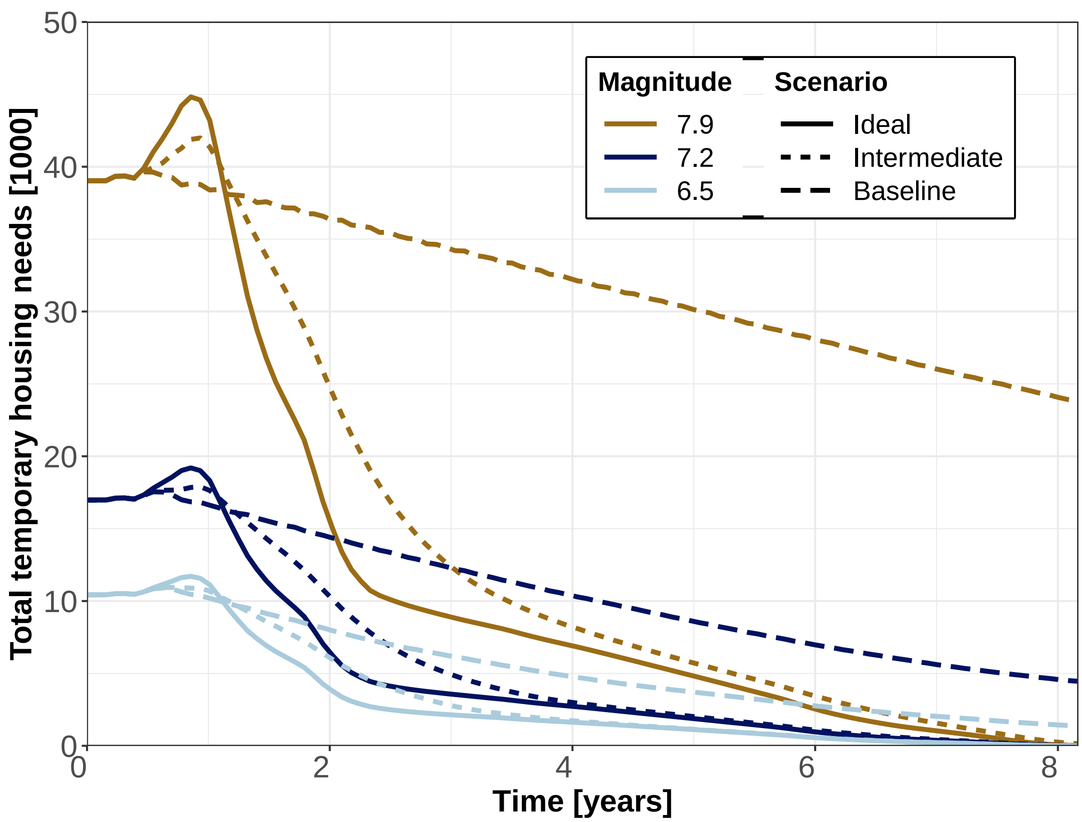

Figure 7. Median temporary housing needs of out-of-town contractors and local displaced residents.

One metric of the impact of receiving out-of-town workers is the probability that the demand for housing will exceed the availability of temporary housing in the community. Especially as San Francisco aims to house the displaced households as close to their original homes as possible (Lee and Otellini, 2016). Considering the post-earthquake availability of temporary housing in the city as per Table 1, Equation 6 is used to calculated the probability of a housing shortage during recovery, $P_s(t)$. It is noted the needs for proper temporary housing are considered not only for people in public shelters, but also for people living with their relatives or friends, and for people who relocate into boats. We consider that those people are unlikely to be satisfied with their current destination, i.e., living with friends or relatives, or boats for several months or even years. We also note that not all contractors need to be housed within the city of San Francisco. Inter-municipal coordination could be made to facilitate the accommodation of out-of-town contractors in neighboring municipalities. Thus, the results in Figure 8 are the upper bound for the probability of housing shortage.

The results in Figure 8 show $P_s(t)$ for the three earthquakes. As the earthquake magnitude increases from 6.5 to 7.2 and then 7.9, the probability of housing shortage immediately following the earthquake, i.e., $P_s(t{=}0)$ increases from 0.20 to close the unity. For the M7.9 earthquake, it becomes evident that new temporary dwellings are needed to support the displaced population. However, for the M6.5 and M7.2, there is a significant chance that if the local vacant housing is available to temporarily shelter the displaced population and financial mechanisms are created to facilitate it, this is an appealing alternative. The results in Figure 8 demonstrate that recovery can be significantly expedited if out-of-town contractors are attracted. Moreover, substantial improvements can be achieved even if the demand for contractors is not fully met, i.e., $R < 1$. As shown in Figure 8, $P_s(t)$ for intermediate and ideal scenarios returns to zero significantly faster than that of the baseline scenario regardless of the earthquake magnitude, highlighting a substantial decrease in the probability of housing shortage when out-of-town contractors are attracted. As expected, $P_s(t)$ of the ideal scenario returns to zero faster than that of intermediate scenario due to out-of-town contractors being available. However, the difference in declining speed between baseline scenario and ideal and intermediate scenarios is much larger than the difference between ideal and intermediate scenarios, which shows that fast declining of $P_s(t)$ can be achieved even when $R < 1$. It is also noted that the peaks in Figure 8 align with those in Figures 6 and 7 since the peaks are directly related to the recruitment of out-of-town contractors.

The framework introduced in this paper can be used to devise a decision tool for communities. To do so, we run new sets of 100 housing recovery simulations considering R=0.25,0.5,0.75,1.0 and M=6.5,7.2,7.9. For each R-M pair, we obtain two metrics. First, we generate one recovery curve, as in Figure 5, and calculate the area above the curve for each R-M pair. This area, with units *households displaced* $\times$ *time*, is often used as a metric of the quality of the recovery

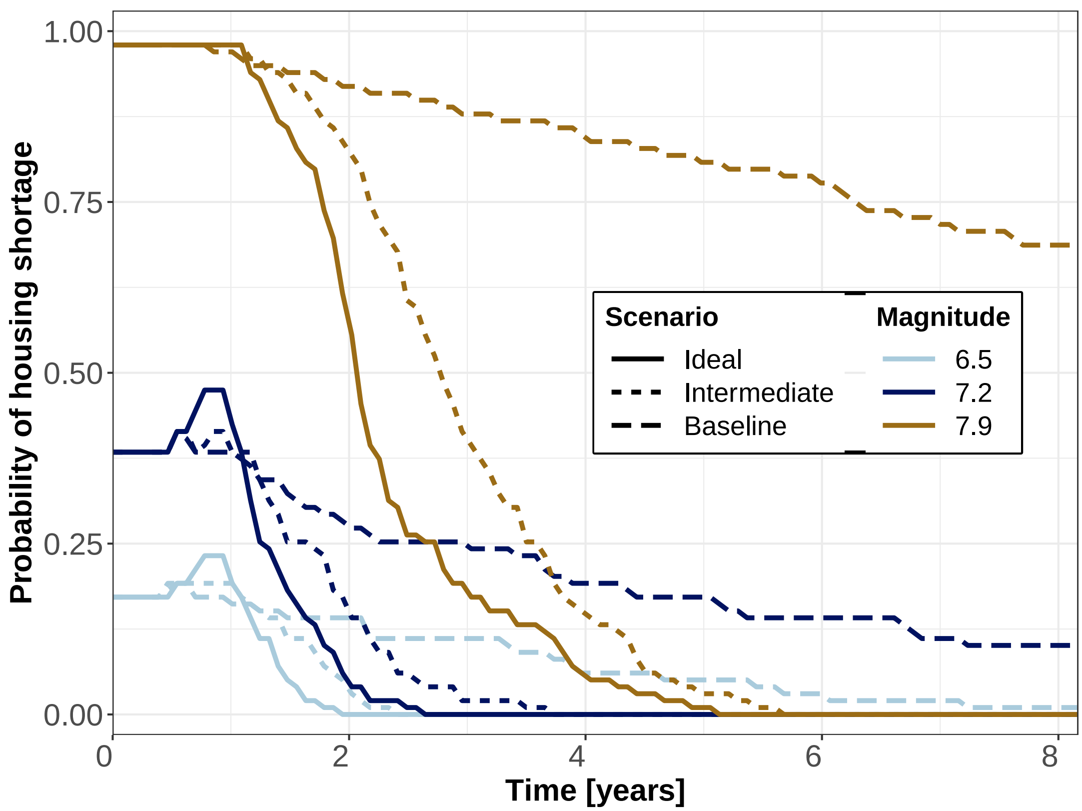

Figure 8. The probability of housing shortage for 100 ground motion maps, $P_s(t)$, for three earthquake scenarios on San Andreas Fault: M7.9, M7.2, M6.5. Thick lines represent cases where the accommodation capacity $A(t)$ is assumed to be infinite, whereas thin lines correspond to cases where $A(t)$ is assumed to be zero.

process - the smaller the area the better the recovery process is. Second, we generate Figure 6 for each R-M pair and calculate the peak demand for out-of-town contractors. This is a metric of the impact on the local housing market of receiving out-of-town contractors. Other metrics were tested, such as the area under the curve in Figure 6. However, all metrics resulted in the same conclusions and the peak demand is a more tangible metric, hence it was chosen. Lastly, the results for each R-M pair are plotted in Figure 9. To facilitate the comparisons, the results are normalized. The ordinate axis is normalized by the peak for R=1 for each M. The abscissa axis is normalized by the results in the baseline scenario. The number of the figure indicate the peak out-of-town contractors associated with the data point. The results indicate that there are small gains in recovery speed, i.e., fewer households displaced per time, from increasing R from 0.5 to 1.0. However, to achieve R=1.0, more than double the number of contractors must be attracted at one point in time. Alternatively, the graph in Figure 9 can be used by communities the estimate the anticipated gains in recovery speed from increasing the available contractors beyond the baseline value. For example, if the community anticipates that it can attract 1,000 contractors during post-earthquake reconstruction, the reduction in the number of households displaced overtime can be interpolated. This provides communities with a simple mechanism for exploring the benefits of recruiting more workers to improve housing recovery.

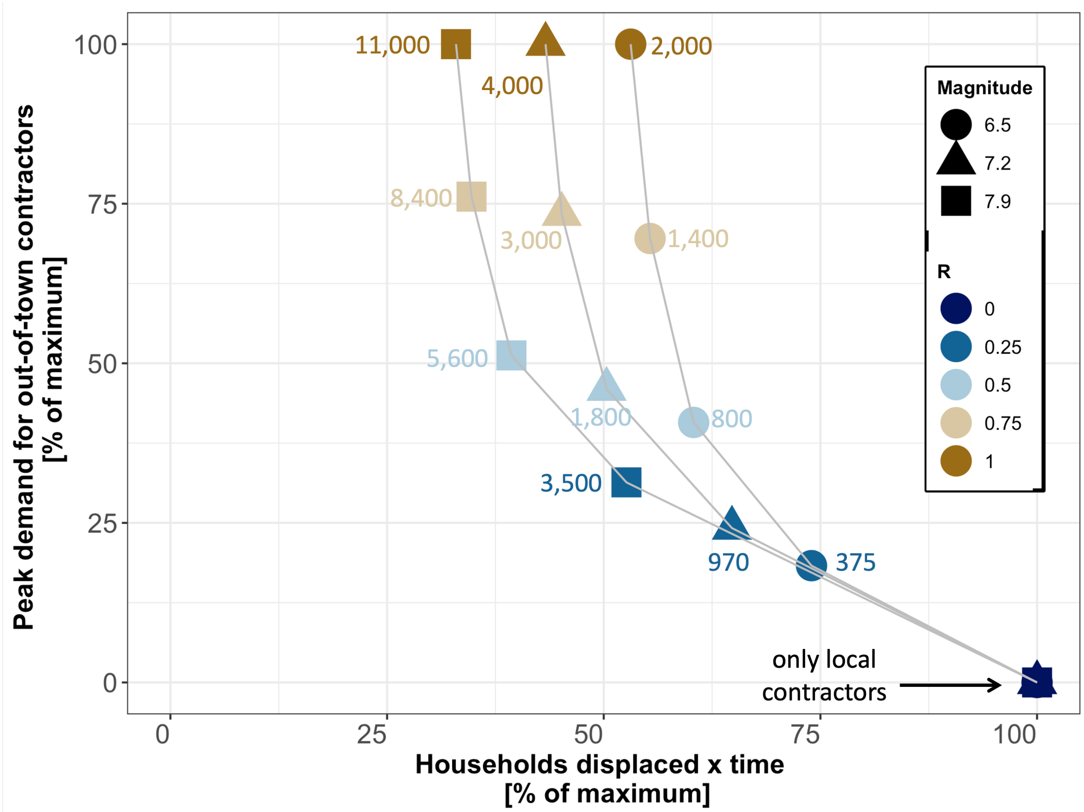

Figure 9. Benefits and challenges associated with receiving out-of-town contractors. The abscissa axis shows the area under the curves in Figure 5 normalized by the baseline scenario. The ordinate axis shows the peak in figure 6 normalized by the peak for the best scenario.

Figure 9 shows that there is a limit to how much housing recovery can be accelerated by having more contractors in the community. That is, at some point other impeding factors become the bottleneck. Thus, to balance the gains in recovery speed and the impacts of having more out-of-town contractors into the community, it is arguably wise to aim for R=0.5. That is, plan to have about 50% of the demand for contractors met at any one point during the reconstruction process. However, if a decision is made to not facilitate the recruitment of as many contractors as possible some household's reconstruction process will be slowed down. It is important to understand who bears the adverse consequences of this decision and take action to prevent this decision from exacerbating pre-existing inequalities. The granularity of the data available for this study does not allow us to investigate the topic further. However, we envision that if such data is available a third axis can be added to Figure 9 in which a metric of socioeconomic disparity is plotted and the R that minimizes the speed-housing demand-disparity surface be chosen.

INTERVENTIONS TO ADDRESS HOUSING NEEDS

The case study results demonstrated that housing recovery after a large earthquake will rely on workers coming from nearby regions. The housing needs of these workers compound to the temporary housing needs of the local displaced population. Thus, a community's capacity to create a competitive housing market and to provide the good working conditions for these workers is crucial to expedite recovery. Past disasters have witnessed differential approaches adopted by communities and authorities to address the temporary housing needs. After Hurricane Katrina, semi-permanent dwellings housed many Mississippian households who lost their homes (INC., 2009). In the reconstruction following the 2008 Wenchuan Earthquake, prefabricated workers' complexes were widely used by construction companies to house the contractors recruited nationwide to fasten the recovery (Chang-Richards et al., 2013). In contrast, NGOs built permanent buildings to house reconstruction professionals after the Indian Ocean tsunami in 2004 (Chang-Richards et al., 2013). Moreover, those permanent building complexes were later repurposed as interim accommodations for NGOs and tourists, showing the importance of considering second-life uses when designing post-disaster housing programs. Given the diverse ways in which post earthquake housing needs can be addressed, it is beyond the scope of this work to provide recommendations regarding the optimal strategy.

CASE STUDY LIMITATIONS AND FUTURE WORK

It is also important to acknowledge the limitations in the case study and to identify future work that addresses those limitations. Only single-family buildings are included due to challenges associated with determining the funding mechanisms and decisions involved in repairing multi-family buildings. In consequence, post-disaster temporary housing needs are likely to be higher, emphasizing the need to plan for it. In addition, we do not account for the temporary housing needs of the homeless population (California Emergency Management Agency, 2011). The case study assumes that out-of-town contractors would contribute to the housing demands in the City. However, contractors could commute to San Francisco from neighboring counties. However, the case study sheds light on the City's inadequate capacity to house the needed out-of-town contractors within its limits without negatively affecting its residents. This emphasizes the importance of coordinating with potential host communities to guarantee its recovery progresses as desired - an issue that has also been raised by other research efforts (California Emergency Management Agency, 2011).

CONCLUSIONS

This paper introduces a modeling framework to estimate the demand for construction contractors after a disaster. An agent-based model is utilized, where households and contractors interact to simulate the recovery. This modeling framework allows the user to explore scenarios regarding the contractor supply-demand dynamics, investigate the expected recovery process if no contractors are brought from out-of-town, and the impact of bringing out-of-town contractors on the local housing market. The framework provides a tool that communities can use before a disaster to identify the need to pre-establish agreements with neighbor communities to host the displaced population or the out-of-town workers that will support its reconstruction. Alternatively, the framework can support post-disaster decisions. It can be evaluated over-time to estimate, given current rate of recovery, the expected demand for temporary housing and out-of-town contractors in the following months, giving communities leeway to adapt.

A case study on the housing recovery of the city of San Francisco after hypothetical $M6.5$, $M7.2$, and $M7.9$ earthquakes on the San Andreas Fault is presented. It is shown that housing reconstruction in San Francisco needs considerably more contractors than its current workforce. If recruited out-of-town and housed within the city, the housing needs of these contractors compounds to the housing needs of the displaced San Franciscans will lead to a temporary housing shortage. Several aspects of the housing recovery are evaluated, providing communities with tangible metrics that can be used to support recovery-enhancing decisions. An example is given on how communities could use the framework to devise a decision tool to balance the overall housing needs while achieving their recovery goals. We show that there is a limit to how much housing recovery can be expedited by attracting more contractors because after some point the bottleneck to recovery is no longer the contractor availability. Thus, this study shows that by pre-planning for the appropriate contractor supply-to-demand ratio, disaster-affected communities can accelerate their housing recovery without exacerbating the housing challenges for the local population.

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