Disaster Debris Management and Recovery for Housing Stock in San Francisco, CA

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Abstract

In the wake of the next large-scale earthquake in the City of San Francisco, an expected 85,000 households are expected to become uninhabitable and beyond repair, leaving thousands of residents with immediate needs for shelter. Coupled with an overwhelming 6.8 million tons of debris generated, destroyed lifelines and affected livelihoods, recovery planning becomes critical for immediate response and long-term sustainable development of San Francisco.

Learning from recent disasters in Haiti, New Zealand and Japan, this research addresses relevant recovery issues by investigating the effects of a 7.2 magnitude earthquake in San Francisco, particularly the implications on the City's residential housing stock and impacts on the construction and demolition waste stream. Using System Dynamics as the driving methodology, a pre- and post-earthquake scenario is modeled for multi-family, wood-frame housing stock and waste cycles for the City and County of San Francisco to understand the complex nature of post-disaster debris removal and resource management and needs for long-term recovery.

Keywords: Disaster Debris Management, Debris Removal, Post-hazard Waste Management, Debris Recyclability, Emergency Operations, Resiliency.

Summary

Investigations have found that the cause for many unprecedented consequences from large scale disasters within the last decade, such as Tōhoku, Japan, are largely due to the city and state not planning for the aftermath of a catastrophic event of this magnitude – it far overshadowed the expectations and preparedness of the entire nation [1]. San Francisco has taken many resilient-city initiatives, both technical and community-based, as a basis to be able to bounce back efficiently from the next earthquake to shake the Bay Area. Contemporary case studies of 7managing recovery from the string of earthquakes to have struck the Pacific Rim of fire have provided earthquake-prone cities a guide to necessary preparedness protocols. One of the greatest aspects of resiliency that is currently being tested following the Japanese Earthquake of March 2011 is that of debris management, which is evidenced to be a massive impediment to recovery and rehabilitation.

Debris removal is a critical action that must be taken immediately after a disaster. Ambulances are not able to reach injured citizens if roads are blocked, utility companies cannot reach power stations and emergency workers are hindered in reaching those in need of assistance within the core of the stricken community. “Thus, emergency debris-removal work occurs first, usually when crews- and even emergent citizen groups – move debris to the side of the road. Debris-removal work symbolizes, both literally and in reality, key efforts to jump-start the recovery process” [2].

This research focuses on recovery efforts for San Francisco after a scenario 7.2 magnitude earthquake on the San Andreas fault. It offers an innovative perspective on disaster debris management, which perceives the millions of tons of debris to be reintroduced into distressed material supply streams within San Francisco. Using System Dynamics as the methodological driver, the simulated scenarios bridge debris removal and material end-life streams to that of new construction material necessary to refurbish lost housing units. Because a high percentage of buildings in San Francisco are comprised of residential housing units, citizens face risks in housing that may not be robust enough to withstand a large-scale disaster. Such housing vulnerabilities, along with access impediments, must be considered inclusively. Interconnections can be made between variables impacting city-wide hazard mitigation and recovery management for holistic recovery.

In simulating a post-disaster scenario in San Francisco, notions of debris recyclability for new building materials link emergency response stages and long-term redevelopment. Results show that great potential exists in recycling disaster debris, but not without compromising an increased recovery phase. With macro-level improvements as well as grassroots education of local residents and contractors, San Francisco can maintain its tradition of landfill diversion following the next big disaster. Generally, waste management after a disaster is underestimated or wholly neglected; however, waste with potential can be harnessed as usable construction material given a comprehensive pre- and post-disaster management plan for the City of San Francisco. This research is a means to strengthen disaster mitigation and management plans, in order to encourage the “build-back-better” philosophy through self-efficacious recovery in San Francisco.

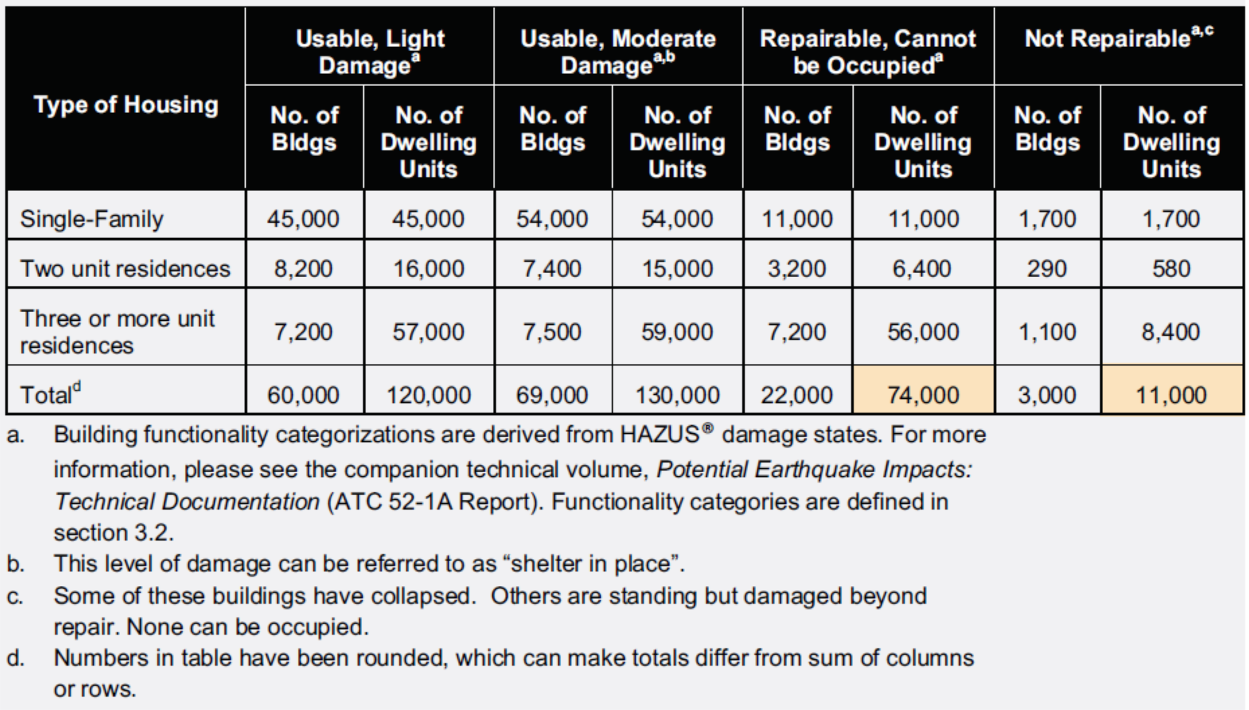
Background and Problem Statement

San Francisco is vulnerable to earthquakes as a peninsula city lying on the Pacific Rim of Fire. The area bordering the Pacific Ocean is subject to constant tectonic plate motion resulting in many of the world’s largest earthquakes, including the Japan and New Zealand earthquakes within the past five years. According to the United States geological Survey, the chance of a 6.7 or greater magnitude earthquake hitting the Bay Area in the next 30 years is about 63%, with a 99% probability of such an earthquake affecting greater California [3].

Housing

“A major earthquake will cause significant damage to the region’s housing. Initially, displaced residents may stay in their homes, even if they are damaged, move in with relatives or friends in undamaged housing, whether in the Bay Area or outside the region, or move to a shelter. Ultimately, the return of displaced residents to their communities is critical to ensuring the long-term viability of the region" [4]. Currently, 75% of San Francisco's housing can be used as shelter-in-place for its residents, with nearly 13,000 residents of a total 750,000 needing temporary or interim shelters. San Francisco's recovery plan timeline estimates that these residents can spend up to three years in alternate housing while homes that were completely destroyed are replaced. With the assumption that residents will want to return to their neighborhoods and will not prefer to re-locate away from their neighborhoods, schools and jobs, it becomes exigent for San Francisco to repopulate quickly, making housing refurbishment a high priority.

The Community Action Plan for Seismic Safety (CAPSS) project reports that residential buildings are expected to suffer significant damage following a 6.7+ magnitude earthquake. From Table 1, about 25,000 residential buildings and 85,000 (74,000 "Repairable, Cannot be Occupied" and 11,000 "Not Repairable") residential units out of a total of San Francisco's 330,000 total dwelling units would not be useable after the 7.2 magnitude earthquake. Thousands of units would necessitate demolition, meaning that many people would be displaced until housing is reconstructed [5]. Consequently, this research focuses on damages to residential housing due to shaking and ground failure, but does not include impacts from fire. Although many earthquake scenarios could be examined, a 7.2 magnitude is used as a control case as it would produce a level of shaking in many parts of San Francisco that corresponds to the level of shaking that the building code requires new structures be designed to resist without major structural damage [6].



Type of Housing	Usable, Light Damage[a]		Usable, Moderate Damage[a,b]		Repairable, Cannot be Occupied[a]		Not Repairable[a,c]	
	No. of Bldgs	No. of Dwelling Units	No. of Bldgs	No. of Dwelling Units	No. of Bldgs	No. of Dwelling Units	No. of Bldgs	No. of Dwelling Units
Single-Family	45,000	45,000	54,000	54,000	11,000	11,000	1,700	1,700
Two unit residences	8,200	16,000	7,400	15,000	3,200	6,400	290	580
Three or more unit residences	7,200	57,000	7,500	59,000	7,200	56,000	1,100	8,400
Total[d]	60,000	120,000	69,000	130,000	22,000	74,000	3,000	11,000

a. Building functionality categorizations are derived from HAZUS® damage states. For more information, please see the companion technical volume, *Potential Earthquake Impacts: Technical Documentation* (ATC 52-1A Report). Functionality categories are defined in section 3.2.

b. This level of damage can be referred to as "shelter in place".

c. Some of these buildings have collapsed. Others are standing but damaged beyond repair. None can be occupied.

d. Numbers in table have been rounded, which can make totals differ from sum of columns or rows.

Table 1 – Building Damage, San Francisco. Cited from CAPSS Report 52-1, Table 15

Debris

As with any natural disaster, including earthquakes, hurricanes, tsunamis and tornados, a key recovery issue is managing the bulk debris that is generated in the wake of the catastrophic event. A reoccurrence of the 1906 earthquake on the San Andreas Fault would generate 50 million tons of debris in the Bay Area, much of it construction and demolition debris from damaged structures [7]. The California Action Plan for Seismic Safety projects 6.8 million tons of debris generated in the City and County of San Francisco alone, making debris removal in the 46.87 square mile of land critical for immediate response [8].

Disaster debris recycling is an environmentally responsible approach to manage building debris following an earthquake. Its viability depends on several factors:

- "The existence of established local debris processors and infrastructure;
- The existing recycling programs and reduction strategies;
- The distance between the disaster area and the debris processors and infrastructure;
- Market demand for debris on a product basis;
- The quality of the debris, which is a function of the type of disaster, demolition techniques and handling;
- Local re-usability and recycling policies, especially for particular material specifications;
- The sorting facilities or the ability to provide separate collection and transportation from non-inert debris" [9].

Processing prior to the recycling of debris includes de-nailing and chipping for wood, removal of mortar for bricks, crushing for concrete, and grinding for gypsum. More information of debris processing a can be found in Appendix A. Prior to processing, it is necessary to screen the material for hazardous household waste or other non-recyclable products such as asbestos. Other types of debris to be screened are vegetative debris, putrescible waste and e-wastes, to name a few. This report treats disaster debris as analogous to construction and demolition debris, and therefore excludes the previously mentioned categories since these cannot be easily recycled, if at all, and must be treated in other ways when attempting disposal. In addition, not all disasters produce the same class of debris. Hurricane debris is different from earthquake debris (excluding conflagration) since the former is typically adulterated by water deposits, which tend to cause bacteria growth rendering much of the debris non-recyclable. Earthquake debris is primarily inert debris such as concrete and steel, and heavily resembles construction and demolition wastes [10].

Material Recyclability and Markets

Recycling is a desirable option for waste management and is practical if it is the alternative that minimizes the environmental impact as a whole, including the new recycling product life [11]. Information from the San Francisco Debris Management Plan estimates that woody debris will be the predominant material generated from destroyed housing [12]. Thus, for purposes of debris processing and planning, understanding the second life products of disaster debris is important for the feasibility of recycling. Addis has described recyclability potential of timber, concrete and steel comprehensively, as cited below [13][14].

Timber/Woody Debris: "Timber can be used in a wide variety of construction components and building elements and is used in many different forms, varying from substantial structural timbers that may be hundreds of years old, to modern products such as chipboard and medium density fiberboard (MDF), which are made from small particles of timber bonded with resin glue. The function of timber products also ranges widely from substantial beams and roof trusses to finishing elements. The opportunities to reuse timber in construction vary greatly according to the type of timber product and its intended use. Softwoods are highly susceptible to damage in the deconstruction or demolition process, either through the breaking of slender lengths of timber or surface damage and implementation. Nevertheless, reclaimed timber does present many opportunities for reuse and recycling depending on its form. Timber can be:

- Sold by length of volume for reuse as structural or non-structural timber;
- Reused for making formwork for concrete construction;
- Recycled to make chipboard for use in furniture or kitchen manufacture;
- Recycled as wood chippings and used as soil improver.

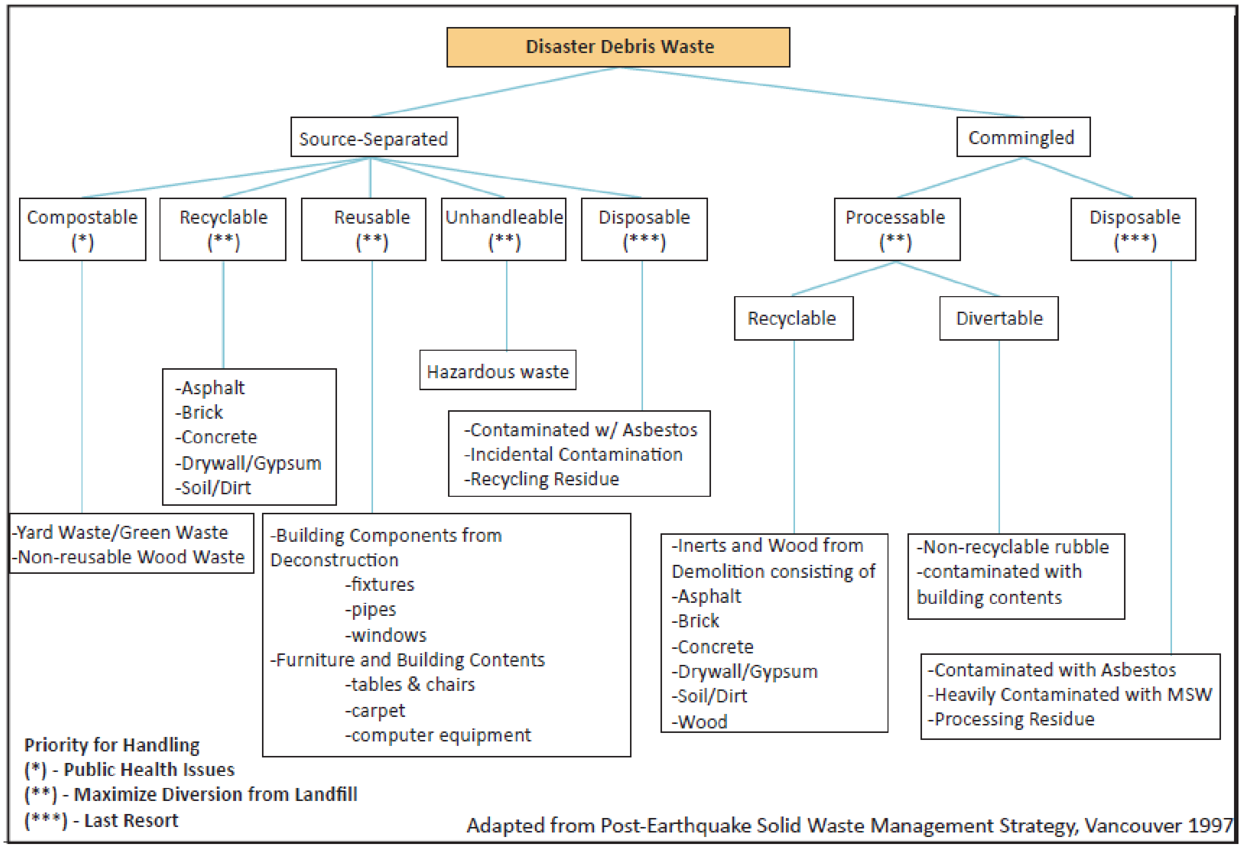
While there is a ready market for clean, used timber, contaminants that can easily become mixed with the load will result in the timber being rejected as recyclable. The effort required to selectively separate timber from all its contaminants may be deemed too expensive to justify the returns.

There exists a growing market for chipped timber, however, it is highly sensitive to market forces – as supplies increase, demand can quickly be satisfied resulting in a rapidly falling price for the raw material. The waste timber is separated from other waste streams and collected from demolition and construction sites. After delivery to factories where it is reduced to chips of various sizes, it is used to make a range of ‘forest products’ including chipboard, MDF, and hardboard, and can be used as mulch or bio-fuel. Some materials like MDF can only be made from post-industrial waste, others from post-industrial or post-consumer waste. The environmental disadvantage of this process is the relatively high environmental impact of the resins used to bond the wood particles. Such forest products are used mainly for non-structural purposes. Following an earthquake scenario, salvaging timber is not as likely as the chipping and processing for second life, the latter a driving assumption of this case.

Concrete: The major use of recycled crushed concrete as an aggregate replacement (recycled aggregate or RCA) in buildings is for making low strength in-situ concrete, typically replacing 20% of the gravel aggregate, such as for concrete slab foundations of houses and ground-level car parking areas. RCA can also be used to make precise concrete blocks and other lightly loaded units. Pulverized fuel ash can be used to replace around 20% cement used in concrete.

Steel: There is a wide-established recycling market for most steel goods. The scrap value of iron varies according to the particular alloy. Ordinary mild steel is a little less expensive than stainless steel. All prices are highly depending on market conditions. There are clear environmental benefits in reusing steel beams and columns since energy is saved twice, first in the energy that would be needed to treat the steel in a furnace, and second in the energy saved by not needing components made from new steel [15].

Figure 1 shows sample post-earthquake disaster debris waste classification [16].



Adapted from Post-Earthquake Solid Waste Management Strategy, Vancouver 1997

Figure 1 – Sample Post-earthquake Disaster Debris Waste Classification

Challenges of Disaster Debris Recycling

Though the benefits of recycling debris seem obvious from an environmental standpoint, problems do exist in actualizing recovery of the disaster debris. These include the following:

- "Transportation and installation of the recycling plants and other necessary equipment;
- Local conditions such as climate, infrastructure, building culture, etc.;
- The absence or the lack of skilled local labor;
- The urgency of the site clearance which may lead to the temporary disposal of the debris mixed with other waste;
- The covering of mixed debris with earth, lime, etc. to avoid epidemics. This makes the debris unsuitable for recycling;
- Political, social and cultural barriers for the acceptance of the idea of recycling disaster debris" [17].

In San Francisco, a prevailing challenge is the lack of space for staging and recyclability, which must be accounted for in drafting a debris plan. Also important is that an expected 7.2 magnitude earthquake will not be isolated to the City and County of San Francisco, but will affect the greater Bay Area, thereby inundating landfills, staging and transfer sites throughout the region. Another challenge is the number of waste managers and industries that could potentially support the meticulous processes of debris sorting, processing, reprocessing and supplying. According to the CAPSS Report 52-1, 11% of the Bay Area works in construction [18], an occupation that is vital to the success of implementing the disaster debris recycling trajectory. If local contractors are not convinced or willing to leverage locally supplied recycled products into new construction, and if externally contracted workers are equally biased, the chances of re-inserting recycled products into construction streams becomes unfeasible.

However with forethought, substantial city-wide dialogue, and industry buy-in, understandings can be made and plans drafted such that these issues are addressed prior to the next earthquake. Though it is impossible to accurately predict outcomes following a disaster in an urban environment, involving stakeholders, analyzing variables of influence, and implementing mandates for sustainable reconstruction can provide for an integrated approach to recovery.

Hypothesis

Debris clearance is a large priority in the aftermath of an earthquake, second to life safety. How debris is managed lays the foundation for infrastructure and development patterns. *This research posits that disaster debris recovery can potentially supply the majority of building materials as required for reconstruction, while simultaneously diverting reusable material from landfills. Regional reprocessing of disaster debris will also stimulate local economies in producing new materials with the benefits of self-efficacious recovery and environmental protection.* Although San Francisco's Ordinance 27-06 mandates 65% of its construction and demolition debris to be recovered in all contracted projects, the danger of a moratorium on such a mandate following an earthquake would guarantee dumping potentially useful material. Maintaining such a directive and providing incentives to producers and buyers for recycled content building products will create a second life for disaster debris. Reprocessing such material has the capability to foster sustainable construction, to stimulate local industries and refurbish lost housing, but not without compromise in housing recovery time. Recovery in this research is determined as the refurbishment of all 85,000 housing units that are deemed uninhabitable following the earthquake. Housing is used as a proxy for overall recovery.

To test this hypothesis, the study is interested in understanding flows of material through San Francisco following an earthquake. Only the effects of shaking and liquefaction on residential single- and multi-family housing is considered since these make up the largest percentage of buildings in San Francisco. To reiterate, the material flow under examination is that of construction and demolition only, which is analogous to inert disaster debris. Figure 2 is a snapshot of the research scope, with the specified inclusions and exclusions that narrow the study.

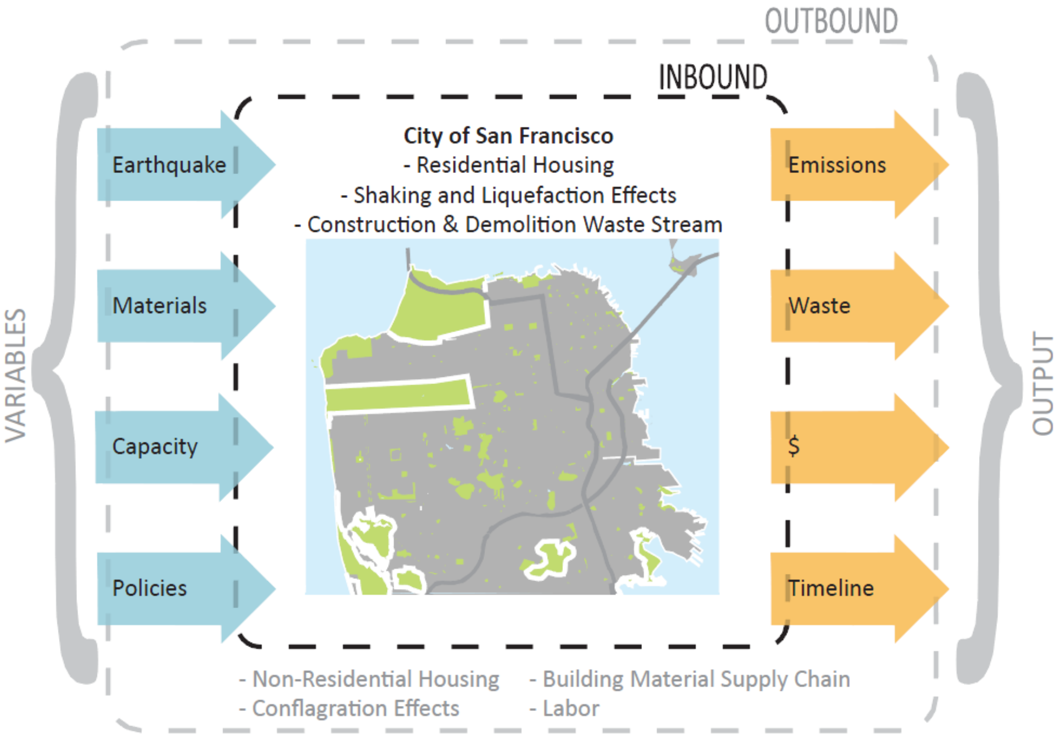


Figure 2 – Research Snapshot

System Dynamic for Post Disaster Material Flow Analysis

Few studies have used System Dynamics to evaluate post-disaster environmental, social and material recovery for communities, either in the emergency phase or in a long-term development. However, system models are becoming increasingly valuable for understanding complicated post-disaster contexts and behavior of factors.

Disaster recovery research has explained the utility of applying System Dynamics to conditions of reconstruction. “Systems theory relies on the idea that several sectors, or systems, interact to produce a disaster event. For disasters, three systems emerge as important: the built, physical and human systems. A misfit of these sectors will result in stronger possibilities for damage. From a systems perspective, disasters occur when the connections among the natural, built, and human systems are disrupted. How we rebuild our physical environment to withstand such hazards matters. Equally important, we must connect the physical environment with the potential human and environmental impacts” [19].

Precedent Analyses

Examples of past research that have pursued dynamic modeling of post-disaster scenarios have been able to present policy analyses mitigating post-disaster effects of an encountered hazard. Investigations following the 2003, 6.7 magnitude earthquake which struck the city of Bam in southeastern Iran are interested in dynamic behavior of disaster management in the country. Ramezankhani and Najafiyazdi conducted the first dynamic analysis of disaster management in Iran, focusing on several factors following an earthquake that lead to the demise of nearly 45,000 inhabitants [20]. The research considered eight block cases, each with its own dynamic model, and all interrelated in the post-earthquake scenario. This work focuses heavily on post-disaster emergency relief and humanitarian logistics, and offers useful management goals by comparing original-case and best-case scenarios.

Another related research is that on the Taichung City earthquake in Taiwan conducted by Ho, Lu and Wang, a 7.3 magnitude quake that occurred in 1999. This work also pursues a multi-level simulation with several subsystems linked in an intricate feedback structure to gain insight on an urban disaster prevention system in Taiwan. Interestingly, debris management is mentioned topically and is included in the broader “Environmental Protection” subsystem [21]. The authors investigated the effects of debris from damaged buildings as a constituent of pollution to the water resources in Taichung City, and therefore, map the refuse and water streams simultaneously to test outcomes.

Post-disaster reconstruction is complex mainly because accurate estimation of reconstruction processes and materials are difficult to ascertain. Quinn appropriately uses systems methodology to identify the material, labor and energy inflows required to restore housing in New Orleans after Hurricane Katrina devastated the city in 2005 [22]. This research explores a full life cycle approach of housing construction to destruction in order to analyze resource requirements for rebuilding New Orleans. Particularly valuable for this study are the observations on demolition and deconstruction strategies, housing construction processes and landfill tipping policies, which are befitting precedence for the San Francisco case.

Though this research utilizes methodologies of previous studies on systematic disaster analysis, it departs from them in its projection of San Francisco’s recovery for an earthquake that has yet to happen, with over 63% chance of occurrence within the next three decades. The benefit is the application of results to anticipatory planning by lending itself to disaster managers for improved preparedness.

Modeling an Earthquake in San Francisco

The causal loop diagram (CLD) with defined boundary captures the question of the recycling potential of disaster debris to feed construction of debilitated housing stock. Figure 3 illustrates factors that influence housing demand, which effectually cycle to increase demand for housing. For example, an external force of a disaster will presumably hurt housing stock, increasing demand for new housing. Subsequently, a push toward reconstruction will require more material, increasing material needs as housing is reconstructed, and finally, the desire to build back communities and housing in an improved manner will again relate back to housing demand. This reinforcing loop will be considered virtuous in the way it has been described, but also work in the opposite direction, decreasing housing demand if no exogenous factors are inciting the system. Each variable has a subset of information creating more depth into the model. For example, “Housing Stock” in Figure 3 will have components of construction rate and delays that impinge on the “virtuosity” of this cycle.

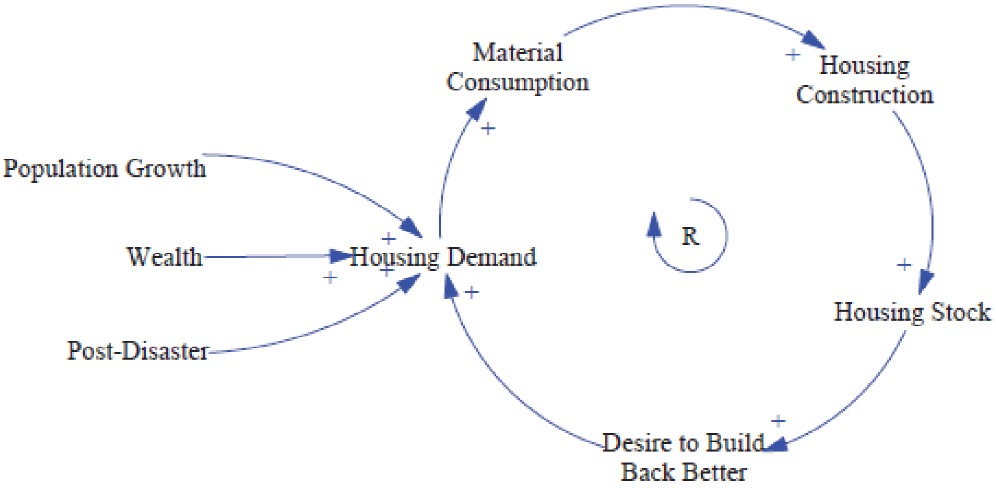


Figure 3 – Research Causal Loop Diagram

Focusing mainly on the factors of housing stock and material consumption, two stock and flow models have been generated respectively and connected via causal links, shown in Figure 4. *This dynamic model seeks to test the implications of reprocessing disaster debris material as new material for construction of a weakened housing stock, specifically in terms of overall delays and accumulations.* The housing stock model diagrams housing unit construction to end-of-life streams, where the material flow model specifically monitors construction and demolition waste streams in San Francisco, under which disaster debris will be included. The connectors between the seemingly independent streams link destruction of housing to construction and demolition debris generated, and recycled content product materials being sold as construction materials for refurbishing homes. The earthquake impulse is the consequential exogenous factor stimulating the housing recovery reinforcing loop. The following section will explain a comprehensive model that includes all influencing variables and detailed descriptions of important stock and flow structures.

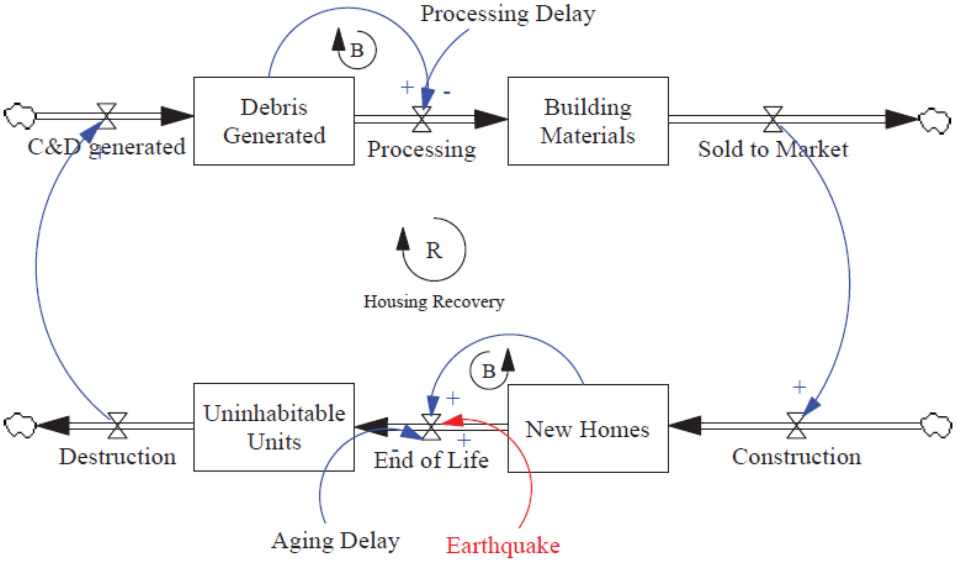


Figure 4 – Research System Models

Recycled Content Products and Imported Building Materials

A leading concern for San Francisco's recovery is how and where construction material will be acquired following a disaster, when building materials will be in great demand. It is assumed that San Francisco traditionally purchases imported construction material, either from outside the country or outside the locale, for its building construction needs. Contrarily, recycled content products (RCPs) are assumed to be locally processed, generating local revenues and local demand for housing construction. Causal loop diagrams explain the notions and assumptions of RCPs versus imported products (Figures 5-6).

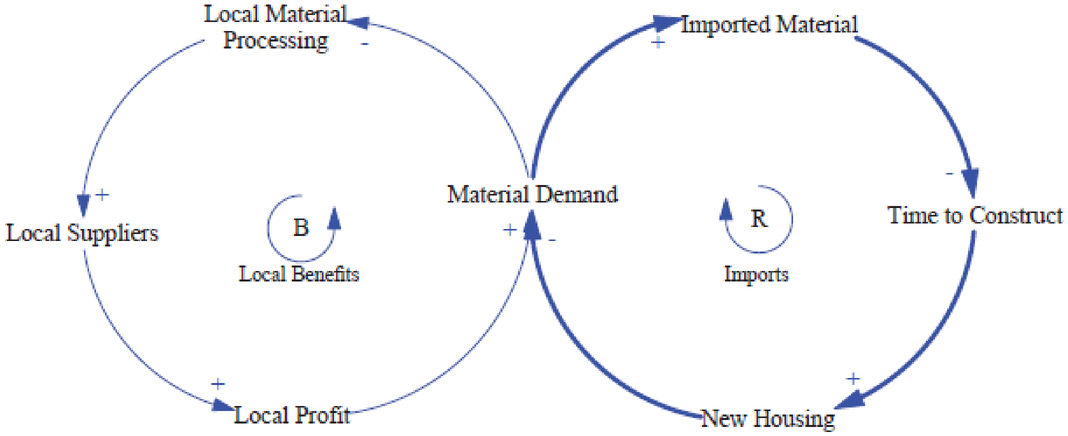


Figure 5 – Causal Loop Diagram, Imported Materials

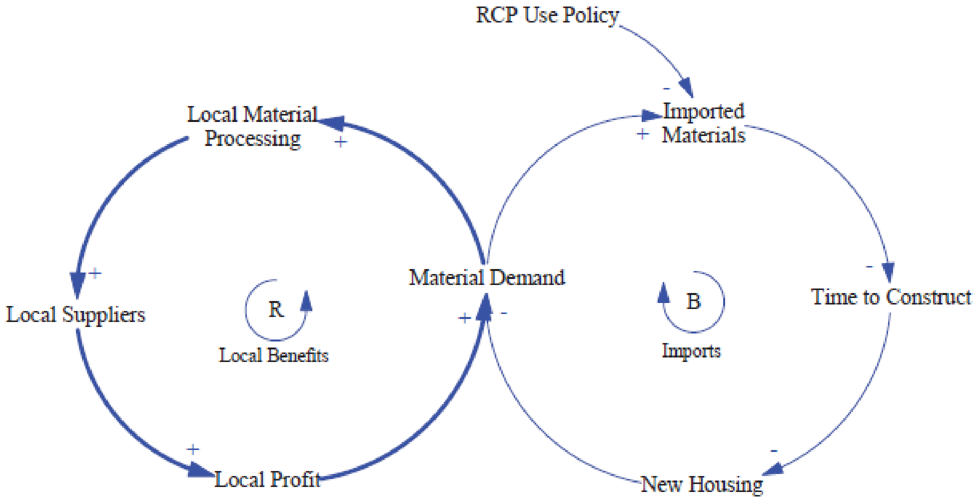


Figure 6 – Causal Loop Diagram, Recycled Content Products

In the CLDs above, the reinforcing cycle show that the use of imported material goods decrease the time to construct, since this is a familiar method of acquiring building products, and eventually increase new housing and material demand. However, it prevents damaged local economies from benefiting through economic stimulus by means of production and supply chains manufactured regionally. Therefore, decreasing the amount of imported materials and increasing the RCP inventory shifts power to the local economy, but not without the cost of a slower recovery. The benefit for providing more jobs, being eco-responsible and stimulating growth in a damaged city may provide enough incentive to tolerate a longer recovery period.

It should be clarified that not all disaster debris is recyclable, meaning that some percentage will always be either unrecyclable or lost in processing or maneuvering. For this research, a maximum percentage of recyclability is calculated to be 72.5% (Appendix A). Material that is not salvaged or reprocessed is then dumped to landfill. Also, care must be taken to separate materials containing household hazardous waste, asbestos, treated wood and lead-based paint for reasons of contaminating mixed and recyclable debris material. In the simplified models used for this study, debris handling is described to have two immediate end-life options, either these are sent to landfill or sent to be reprocessed as new material. However, some debris material can be used as fuel, which has historically been a viable alternative of waste management. Urban woody debris is oftentimes chipped and used as biofuel, creating opportunity for waste-to-energy streams. For the purposes of a simplified study, this option for waste management is defined to be beyond the scope of research.

System Dynamics Analysis of San Francisco

A conceptual understanding of the simulated model begins with a CLD that links end-of-life housing units to debris to new housing in virtuous or reinforcing loop. Adding the exogenous factor of the 7.2 magnitude earthquake can accelerate these trends increasing new housing, contingent on several other factors further detailed in the driving system dynamics models. The simplified CLD shows potential for positive growth of housing using recycled content products for building materials to arrive at pre-disaster habitation levels. Each variable within has its own set of influencing variables. For example, “New Housing” is also affected by construction rates, construction delays, and contractor availability, for example. These inherent factors impede the “virtuosity” of this reinforcing loop, causing delays and complexities to the system at large (Figure 7).

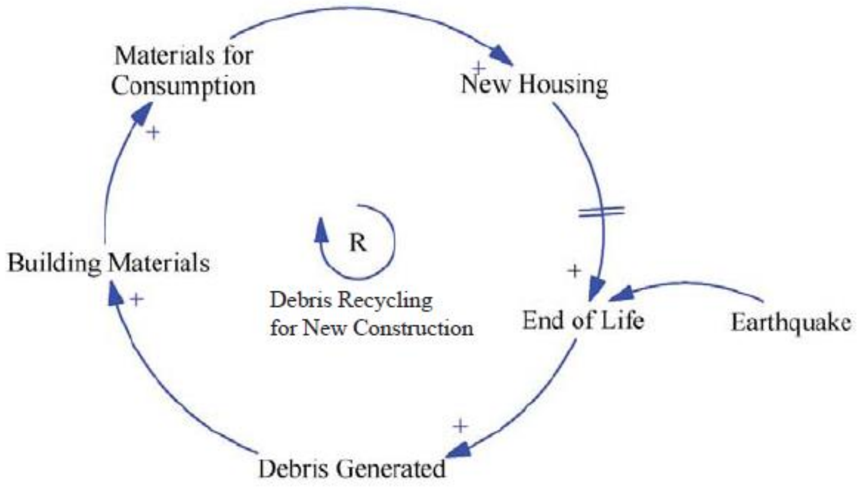


Figure 7 – Causal Loop Diagram of Simulated Systems

Driving Models

Two driving System Dynamics models exist in simulating the hypothesis; housing units and construction and demolition waste. These two streams are essential in understanding debris removal and material use conditions, as well as residential housing recovery. Boundaries have been established in defining the model, and the perceived critical endogenous and exogenous variables have been included. The following is a visual and verbal description of the model with its various components. Using these models, a pre-earthquake equilibrium set of data is examined, along with a system impulse by an earthquake disruption. In order that results are comparable, control variables are set with values and explanations illustrated here for the base case models.

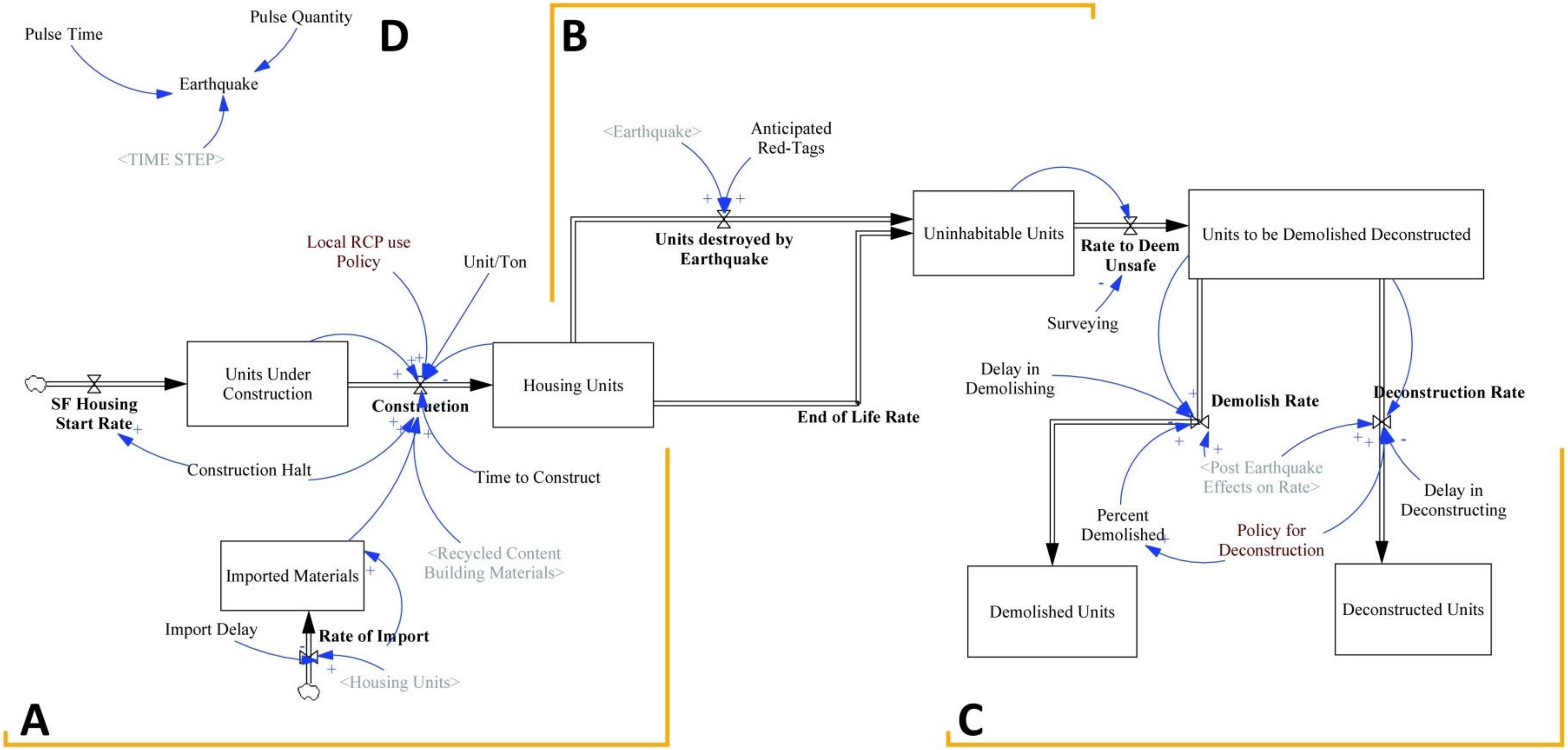


Figure 8 – Base Case Model 1, Housing Unit Driving Model

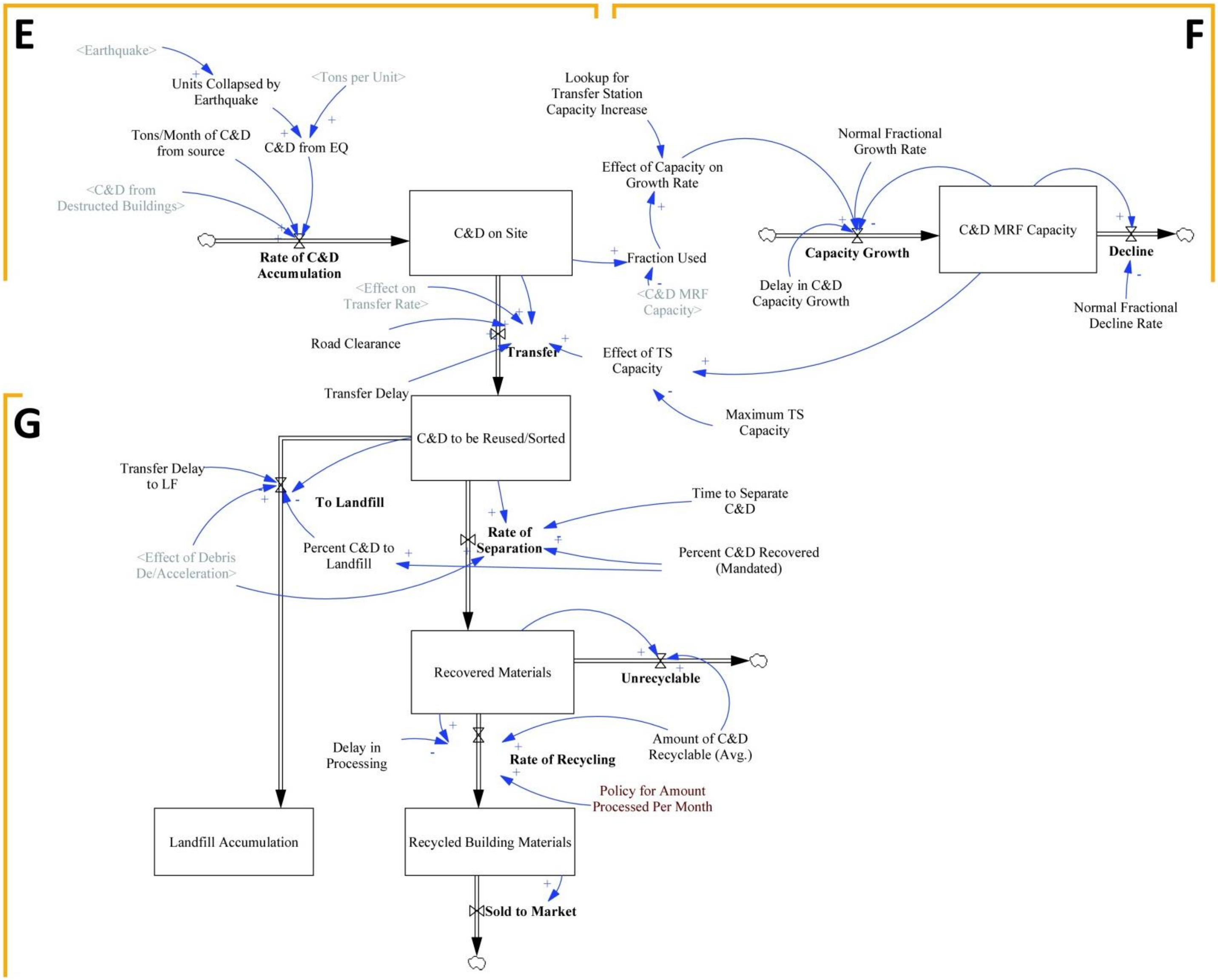


Figure 9 – Base Case Model 2, Construction and Demolition Waste Streams Driving Model

Housing Units Base Case Model Description (Figure 8)

A. Representation of housing construction, with variable labeled "Local Recycled Content Policy Use Policy" for using specific amounts of imported material versus recycled content building products. Construction halt is the stopping and slow progression of residential construction following the earthquake.

B. End-of-life streams for housing, whether caused by "act of God" or old housing age.

C. Representation of "destruction" stream. These include a surveying process by which a unit is deemed safe or unsafe, and two consequential flows for destruction – that of demolition and that of deconstruction. Policy for deconstruction is a percentage of units that are deconstructed, the rest assumed to be demolished.

D. The earthquake pulse is an 85,000 housing unit decrease from 330,000 units at month 12.

"Local RCP Policy" is the construction flow representing the lever that adjusts between imported, virgin materials (traditional construction) and Recycled Content Building Materials (debris reprocessing). The latter variable is possibly the most essential in analyzing the hypothetical situation, that of sorting and processing debris as new building materials for housing refurbishment. "Local RCP Policy" is set as a percentage representative of the amount of material that is imported for building construction. In providing a control mode that other variables can be tested and compared against, an RCP policy measure of 25% is maintained, meaning 25% of the construction material is imported and 75% is recycled content from debris matter. Assuming that some amount of imported material is required in all cases, 25% represents that control value of imported building construction material, with trials of higher and lower values in additional simulation runs. The upper and lower bounds observed for "Local RCP Policy" are 75% and 10%, respectively.

"Policy for Deconstruction" is also a percentage representing the amount of units to be deconstructed, versus those that will be demolished. This is set at a control mode of 40%, indicating that more units will typically be demolished. This value is an approximation based on the density of San Franciscan neighborhoods and city demolition requirements for compacted and careful tear-downs of buildings [23]. These tend to resemble deconstruction techniques more than traditional, demolition-ball destruction methods.

Construction and Demolition Waste Stream Base Model Description (Figure 9)

E. Accumulation of Construction and Demolition waste on site. Within this micro-stock and flow are included construction and demolition generated from building collapse debris and that from demolition and deconstruction of units. A constant flow of construction and demolition from source is estimated to be 5,760 tons per month [24], and is varied post-earthquake as one assumes that normal C&D generating processes will be stymied or slowed in an extreme condition after a disaster.

F. Capacity growth and total Construction and Demolition/Materials Recycling Facility Capacity stock and flow stream for five transfer stations of concern. The amount of C&D Capacity varies as the model is affected by pulses and policies, and is useful in determining necessary capacity and processing requirements for debris removal. As can be noted, an increase in C&D Capacity increases the amount of debris transfer since it is understood that debris transfer possibilities are accelerated as space for debris staging and processing, as well as labor, is increased. This effectively speeds up recovery time, but my nominal amounts.

G. This portion of the model describes the transfer and processing of debris and its ultimate destination – landfill or to recycled content material supply chains. The RCP materials are then used as construction material in the Housing Units model, and behave as a nexus between the two driving models.

   Two important elements within the site-to-sorting station transfer rate are “Road Clearance” and “Transfer Delay”. Road Clearance is the amount of road impediment due to the debris generated after the seismic disruption. In its equilibrium state, the Road Clearance = 1. Based off of GIS calculations and Associated Bay Area Governments (ABAG) data, the total road mileage that is affected due to the earthquake nears 25% [25]. From the Loma Prieta earthquake, it is noted that on average, it took 134 days to clear the roads. However, since the 7.2 magnitude San Andreas earthquake is expected to generate far more debris than the Loma Prieta, this value has been increased to a year’s worth of clearance time.

   Transfer Delay is the amount of time it takes for trucks to deliver debris to staging/material recycling facilities from sites of construction or demolition and debris. It is estimated that it takes about two months to transfer 20,000 tons of material [26].

   Also detailed in this segment is the fact that all recycled materials are not inherently recyclable. Calculations show that about 72.5% [27] of recovered construction and demolition debris can be recycled as building material, the rest having potential as biofuels or for landscaping and siting purposes.

“Policy for Amount Processed per Month” in the C&D waste stream model accounts for the percentage of recovered material that can be processed per month. This is a function of the kinds of eco-industrial businesses suitable for reprocessing in the San Francisco Bay Area, and is set at a control value of 40% for the base earthquake scenario. This assumed value is based off the City’s existing high material diverting capability.

Another influential exogenous factor is “Percent C&D Recovered (Mandated),” which denotes a 65% required recovery rate for all construction and demolition waste streams as per San Francisco Environmental Code Chapter 14 and C&D Debris Recovery Ordinance [28]. In order that the hypothesis maintains any validity, *this mandate must remain true throughout the time frame in question.* Without preserving or increasing the 65% diversion rate, no recycled content processing is possible, disabling the premise of the research question. This leads to an important point on the relaxing of various ordinances, policies, and norms in a post-disaster setting, which greatly influences how recovery is managed and the city is rebuilt.

The time frame for simulating both models is 120 months, with the pulse occurring at month 12. Not included in the models are lookup tables that provide conditional output based on a specified input. For example, in the Housing Units model, “Lookup for Transfer Station Capacity Increase” outputs a value between 0 and 16 when the “Fraction of Construction and Demolition waste to Transfer Station/MRF Capacity” reaches a specific value. This output number behaves as a multiplier captured in “Effect of Capacity on Growth Rate,” which is factored into the growth rate of the Transfer Station/MRF total capacity, thereby affecting the aforementioned fraction of debris to capacity. As the growth rate increases, the fraction used decreases, providing an embedded balancing loop within the model. This loop provides information to the Transfer Station/MRF Capacity required to process the influx of debris for five transfer stations of concern. It also allows simulation of recovery times if such capacity is locked to a certain number of tons if, for example, capacity growth is considered unrealistic [29].

Results and Recovery Forecast

Performing numerous simulations of the base model with policy alternatives described earlier, graphs and descriptions are provided to quantify the effects of possible scenarios. To reiterate, complete recovery is described in terms of reaching the pre-earthquake housing state of 330,000 units, compared by the time for such recovery. Also evaluated is the amount of landfilled material versus recovered material, which will consequently service as building material following processing. The overall results indicate *6.8 years of recovery following a 7.2 magnitude earthquake, with the benefit of 1.5 million tons of debris being diverted from landfill.* Comparing the extreme cases, a larger percentage of locally supplied recycled material for construction slows total recovery by two years while saving more than three years of landfill space [30] and upwards of 1.6 million tons of potential usable debris from being disposed.

Base Case Model Experiencing No Earthquake

Under normal conditions, San Francisco would experience a normal growth rate of housing and near stable transfer station/MRF capacity (Figure 10). A growth of about 0.89% in housing units occurs over the 10 year period examined, reaching 332,960 residential units. However, due to the in-built balancing loop formed, the transfer station capacity is shown to decrease significantly. Realistically, however, square footage of the material recycling facilities would not be decreased, but would rather stay constant or increase slightly given reasonable economic and space circumstances. The equilibrium level for five transfer stations is estimated to be 367,500 tons of storage and processing capacity per month (Figure 11).

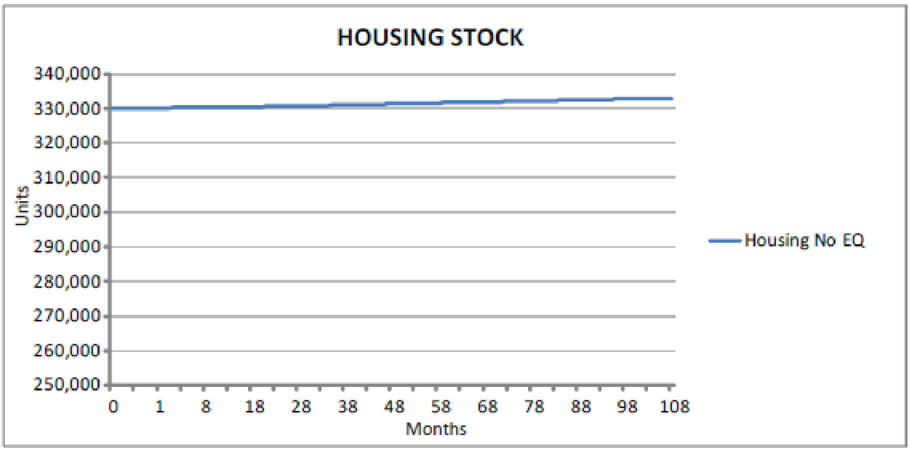


Figure 10 – Housing Stock in Equilibrium Case

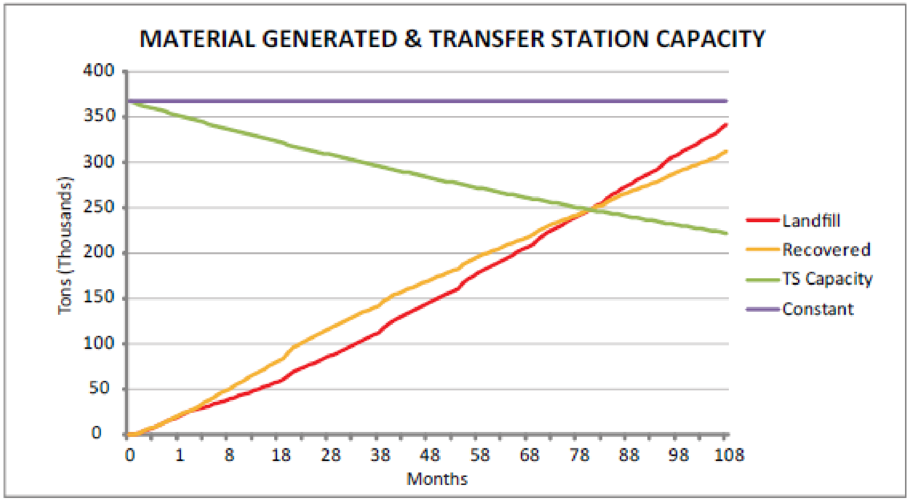


Figure 11 – Landfill and Recovered Material versus Storage and Processing Capacity

Base Case Model Experiencing Earthquake

With an earthquake pulse resulting in a deficit of 85,000 housing units, a 25% imported material rate results in a 6.8 year, or 82 month recovery period, as indicated by the blue line on Figure 12. Varying the imported building material rate to a higher and lower value presents differing recovery times. As imported material rate is increased, a faster housing refurbishment time is observed since it is a conventional method of acquiring construction materials. It is assumed that local processing of material is limited in and near San Francisco, and phase of learning and implementation by local producers following the earthquake will slow the RCP supply chain, further escalating the recovery period. Figure 13 shows “Construction Rate” as a flow from the Housing Units model, indicating the rate of change between housing starts to completed housing units. As can be noted, an increased import rate intensifies construction rates, as well as further decreases total recovery time.

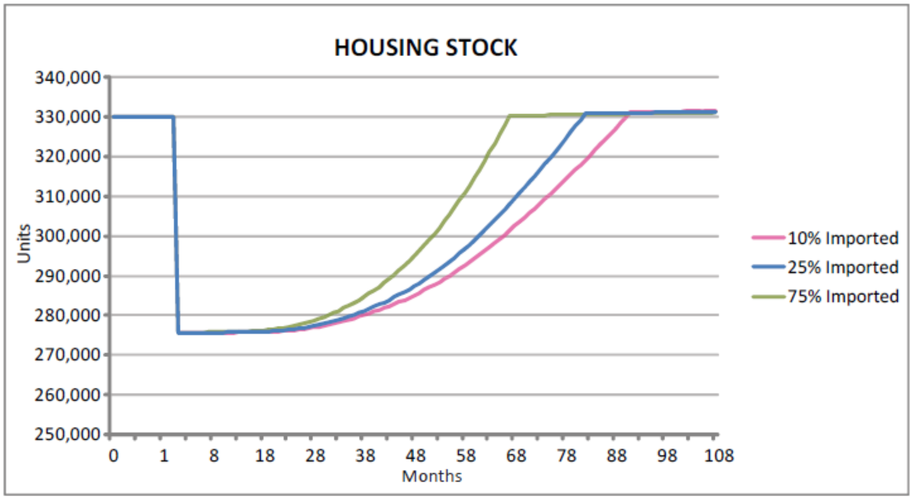


Figure 12 – Housing Stock with Effects of Earthquake

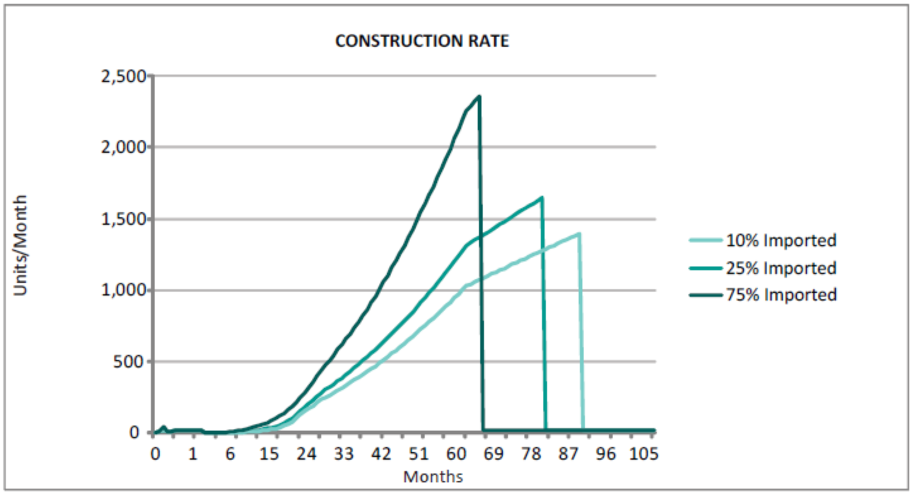


Figure 13 – Construction Rate with Effects of Earthquake

Effects on the internal balancing loop for transfer station capacity outputs an increase of 70,000 tons/month of transfer station capacity required to achieve the subsequent results. Therefore at the point of recovery, the throughput capacity reaches a value of 445,500 tons per month of processing function in order that a 6.8 year period is realized for the control case, a 21% increase from the original capacity. It is noticed in the Transfer Station graph (Figure 14) that the amount of imported versus RCP material used does not affect the total MRF capacity requirements. This is due to the delay in the processing of RCP to its actual implementation to the construction stream. In addition, the decision to deconstruct versus demolish affects the landfill, recovered material and transfer station streams directly. Transfer station capacity value will change based on which factors are variegated.

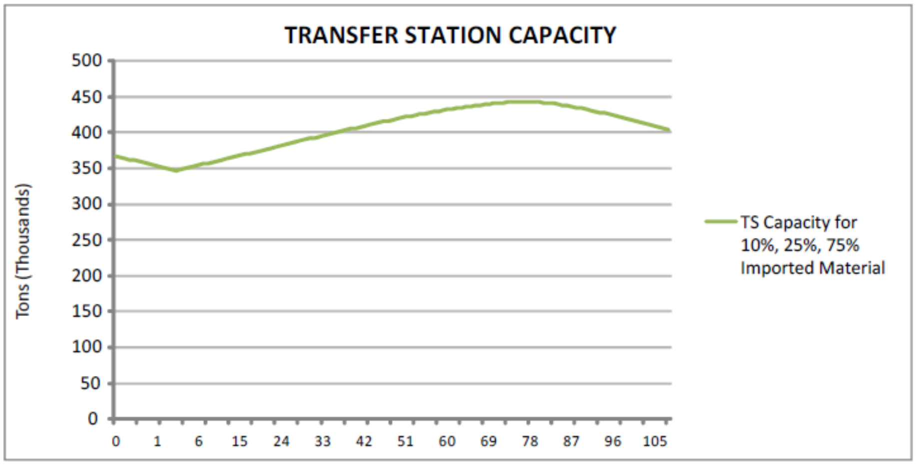


Figure 14 – Transfer Station Capacity with Effects of Earthquake

The usage of recycled content products diverts nearly 1.5 million tons of debris from landfill at the month of recovery, as shown in Figure 15. Much material still enters the landfill since bounded processing capacity and delays limit total divertability, totaling about 1.1 million tons of debris as refuse. The tradeoff for a greater recovery period comes with the benefit of nearly 3 years of landfill space that is conserved with RCP methods [31], saving nearly $6.6 million dollars in landfill contracting [32][33]. In addition, local markets of recovered content products will serve to generate income in order to lessen the economic impact on the City after disaster strikes, while simultaneously providing materials for recovery. An empirical justification of "building-back-better" is shown in Figure 12. To ensure environmental protection in the recovery phase alongside the rebuilding of quality housing stock, a compromise in recovery time must occur to allow necessary time for preparation and planning of reconstruction.

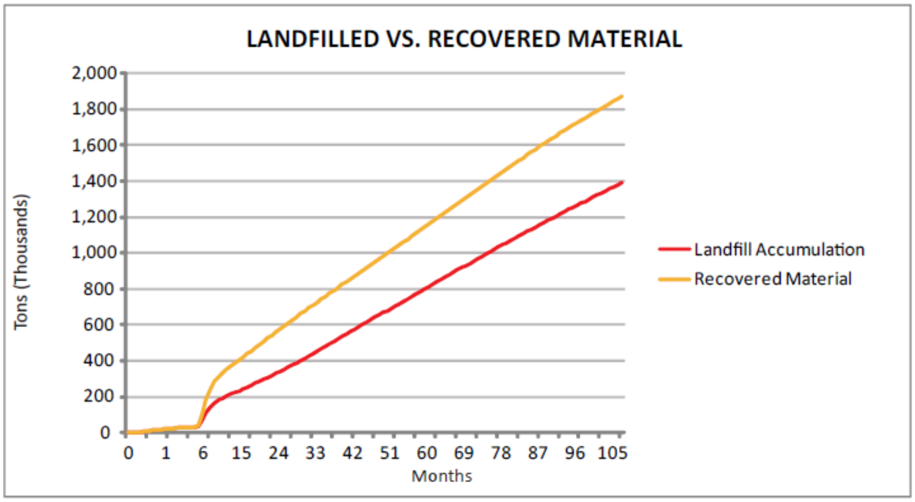


Figure 15 – Landfilled Material and Recovered Material following Earthquake

Furthermore, the inertia of recovery within the first several months can be attributed to the learning and implementation of a new means of acquiring construction material via debris reprocessing. This is so that local suppliers and waste managers can begin producing construction materials within their respective industry, which is assumed to be non-conventional in ordinary circumstances. If most material today is being imported into the region, then a shift in processing RCP material in the Bay Area requires a steepened learning curve before results of higher RCP content can be witnessed.

Conclusions

Results from the control case described previously show clear incentive for harnessing the potential of debris as material for new construction. Comparing the extreme cases of 75% import rate to a 10% import rate shows an increase in recovery of nearly two years (5.6 years versus 7.6 years, respectively). In spite of this, the compromising housing recovery delay is befitted with the enormous tonnage of debris that is recovered for use, reaching upwards of 1.6 million tons of material diversion.

An important caveat exists in achieving any material recovery, which relies upon the mandated ordinance for landfill diversion. San Francisco’s Ordinance 27-06 requires contractors to recover at least 65% of materials created on construction and demolition sites. This research envisions that this and similar directives are kept in place, or optimistically increased, in times of post-disaster recovery, wherein they may otherwise be relaxed or jettisoned entirely. Without such a regulation, hopes for landfill diversion are dismal and possibility for material extraction from debris is difficult.

It is also important to comment on the economic, social and environmental benefits of reprocessing debris for building construction materials. As is noted by the Community Action Plan for Seismic Safety [34], economic impacts from a 7.2 magnitude earthquake will result in direct costs of nearly $14 billion dollars in housing, property, material damage and loss. Secondary economic hardships would also ensue, resulting in many residents being out of work until relocation and business restoration is managed. Though difficult to estimate explicit secondary losses in terms of employment deficits, instating a holistic materials recovery program will assist in boosting economic conditions and reviving local industry.

Environmental benefits from landfill diversion include reduction in caustic methane emissions from landfill sites, decrease in space required for landfilling, provision of added building allotment for commercial or housing needs, and greater utilization of resource value salvaged from solid waste. Based on the results of this research, calculations show the economic benefits of reliance on MRF for C&D waste management versus resorting to landfilling as the only means of debris removal. A 70,000 tons/month MRF capacity growth is suggested for material recovery; this results in a savings of about $4.4 million dollars as compared to contractual costs for increasing ears of landfill space [35].

Another important measure of landfilling is the amount of CO_2 emissions resulting in truck transport to Altamont landfill in Livermore, CA, a nearly 100 mile round trip over the Bay Bridge from San Francisco City. More than 73,000 truckloads would be necessitated to move all debris to landfill if recovery is implemented, about 1000,000 truckloads less than if diversion is ignored. This diversion not only avoids overall tipping costs of about $120 million (estimated at $80/ton), but also controls the amount of CO_2 emitted by a near 63,000 ton reduction in noxious truck fumes, which is 23 times more emissions than a material recovery scenario [36]. These drastic increases in cost trickle down to the resident level while emissions affect the aggregate health of citizens, proving an unsustainable recovery. Though increased practice of material recovery following a disaster will not entirely remove the described negative impacts, it does afford greater economic and societal advantage when compared to total landfilling of debris.

Insights

The results provide useful information on prevalent variables considered endogenous to the system. Some of these aspects should be interpreted with detail, including the transfer stations and retrofit policies.

Results from the transfer station sub-system modeled within the larger stock-flow structure allow for interpretation of values to realistic suggestions. Transfer station capacity requires a 21% increase to stage and process construction and demolition debris only. Since construction and demolition waste comprises only 12% of California's landfill content, the projected capacity increase will not be sufficient for the other types of debris that will be generated. Therefore, discussions about regional provisions for staging and processing are critical for material that is to be recovered, and for those deemed harmful and must be disposed of in other ways.

Additionally, the fact that a relatively large delay (nine months) for transfer station capacity growth has not severely delayed the overall recovery results of the model is a point of interest. This means that even with a slow and steady transfer station capacity growth, a great amount of material can be processed for reuse. The reason for this is that capacity increase is assumed to be coupled with increased labor and machinery for processing. Adding physical capacity alone will not progress the movement and recycling of debris; rather, additional variables of labor and machinery are influential in waste management.

A retrofit policy analysis also attests to the large benefits from retrofitting housing prior to a hazard event (Appendix B). Retrofitting has been a foregoing and prominent means of community resiliency, but is faced with financial and societal complexities which hinder its widespread adoption. Testing the feasibility of retrofitting within the system bounds again prove its viability and necessity in a community that is prone to adverse environmental threats. Retrofitting is shown to cut overall recovery time by nearly two years, which allows potential for greater life safety prior to a disaster event, as well as maintenance of citizens following an earthquake, both indicative of a resilient city.

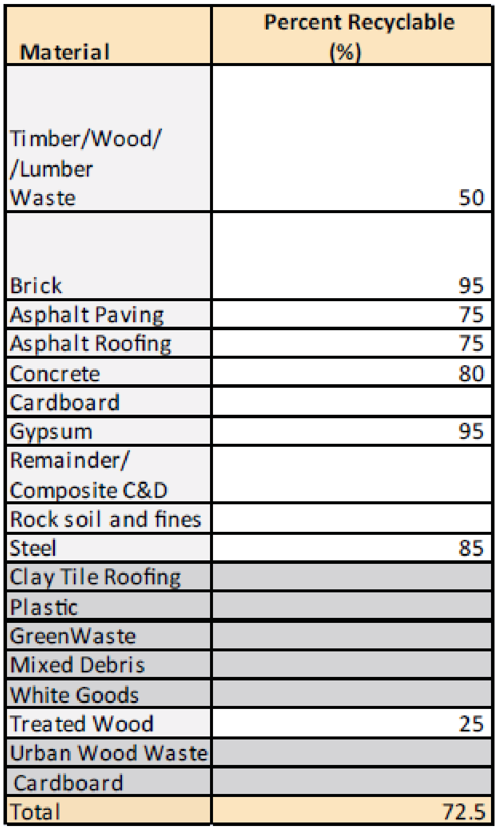
Model Critique

As with any System Dynamic model, the decision of bounding the model must always be questioned and pushed such that feasible insights are not excluded. In this case, the model boundary treats as exogenous the aspects of stakeholders, public decisions and societal concerns, land use and design and supply chain understandings of recycled content materials. For example, the decision of housing is left uncomplicated in this model, but can have large implications in a future recovery scenario. Also, notions of environmental equity are also left exclusive to the model; questions of which communities will suffer from new landfills that must be formed in or near their locales if debris is not diverted must be considered when forming disaster management plans. If intentions to recover material from damaged housing exist, then notions of designing for deconstruction should be studied and perhaps implemented in new construction of housing. This method of design includes parameters of end-life housing removal or destruction, and entails guidelines on how to best recover and recycle material from a home that is no longer of service. An additional iteration would consider these and other variables as inclusive of the model bounds, as they have clear influence for the overall built environment and city recovery scenarios as defined by the scope of research.

Additionally, some results show sharp or precipitous growth/decline rates that may not be fully be realistic. For example, housing construction shows a sharp decline after all homes are refurbished. In the real world, contractors would slow down momentum as they anticipate housing reconstruction nearing its end, and perhaps send labor force to other tasks. In this case, and again for the sake of simplicity, the results are shown to be abridged where they can be contrasted to other variables to understand relatedness. This method of resolution allows for comparison and linkage to other aspects of the model since relative results per variable are the same.

Tradeoff for such exclusions and simplifications are the levels of clarity and focus that the model can bring for early comprehension of the variables of interest and the hypothesis in question. This allows for broader discussions about influential aspects of post-disaster recovery within the regional community. The intention for such model simplification is to reach multiple audiences that are able to add more foreseeable variables and contexts to the impending issue of post-disaster recovery. Thus far, the model adequately provides the results and processes needed for the discussion the author set to simulate. It also speaks to the need of additional research on a broader level, with components that must be linked to the existing model to understand the vast interconnections of variables affecting hazard mitigation and disaster management. The hope is that future iterations constitute vantages beyond debris handling and housing stock refurbishment.

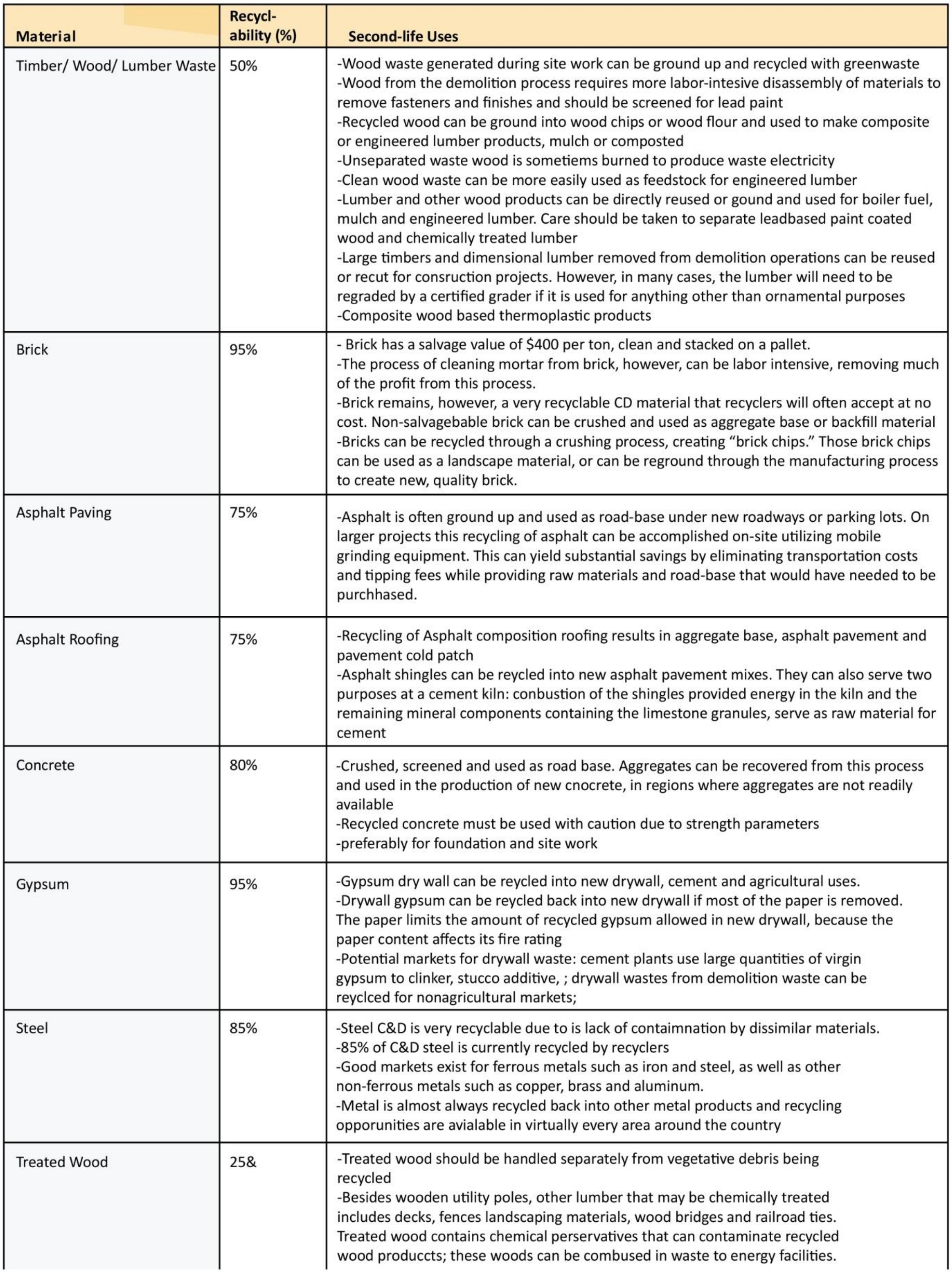
Appendix A – Material Recyclability



Material	Percent Recyclable (%)
Timber/Wood/ /Lumber Waste	50
Brick	95
Asphalt Paving	75
Asphalt Roofing	75
Concrete	80
Cardboard	
Gypsum	95
Remainder/ Composite C&D	
Rock soil and fines	
Steel	85
Clay Tile Roofing	
Plastic	
GreenWaste	
Mixed Debris	
White Goods	
Treated Wood	25
Urban Wood Waste	
Cardboard	
Total	72.5

Table 2 – Simplified Recyclability Rates per Material

Note: Materials with recyclability values are used for this research model. For an expanded list of material recyclability, see Table 3.



Material	Recycl-ability (%)	Second-life Uses
Timber/ Wood/ Lumber Waste	50%	-Wood waste generated during site work can be ground up and recycled with greenwaste -Wood from the demolition process requires more labor-intesive disassembly of materials to remove fasteners and finishes and should be screened for lead paint -Recycled wood can be ground into wood chips or wood flour and used to make composite or engineered lumber products, mulch or composted -Unseparated waste wood is sometiems burned to produce waste electricity -Clean wood waste can be more easily used as feedstock for engineered lumber -Lumber and other wood products can be directly reused or gound and used for boiler fuel, mulch and engineered lumber. Care should be taken to separate leadbased paint coated wood and chemically treated lumber -Large timbers and dimensional lumber removed from demolition operations can be reused or recut for consruction projects. However, in many cases, the lumber will need to be regraded by a certified grader if it is used for anything other than ornamental purposes -Composite wood based thermoplastic products
Brick	95%	- Brick has a salvage value of $400 per ton, clean and stacked on a pallet. -The process of cleaning mortar from brick, however, can be labor intensive, removing much of the profit from this process. -Brick remains, however, a very recyclable CD material that recyclers will often accept at no cost. Non-salvagebable brick can be crushed and used as aggregate base or backfill material -Bricks can be recycled through a crushing process, creating “brick chips.” Those brick chips can be used as a landscape material, or can be reground through the manufacturing process to create new, quality brick.
Asphalt Paving	75%	-Asphalt is often ground up and used as road-base under new roadways or parking lots. On larger projects this recycling of asphalt can be accomplished on-site utilizing mobile grinding equipment. This can yield substantial savings by eliminating transportation costs and tipping fees while providing raw materials and road-base that would have needed to be purchhased.
Asphalt Roofing	75%	-Recycling of Asphalt composition roofing results in aggregate base, asphalt pavement and pavement cold patch -Asphalt shingles can be reycled into new asphalt pavement mixes. They can also serve two purposes at a cement kiln: conbustion of the shingles provided energy in the kiln and the remaining mineral components containing the limestone granules, serve as raw material for cement
Concrete	80%	-Crushed, screened and used as road base. Aggregates can be recovered from this process and used in the production of new cnocrete, in regions where aggregates are not readily available -Recycled concrete must be used with caution due to strength parameters -preferably for foundation and site work
Gypsum	95%	-Gypsum dry wall can be reycled into new drywall, cement and agricultural uses. -Drywall gypsum can be reycled back into new drywall if most of the paper is removed. The paper limits the amount of recycled gypsum allowed in new drywall, because the paper content affects its fire rating -Potential markets for drywall waste: cement plants use large quantities of virgin gypsum to clinker, stucco additive, ; drywall wastes from demolition waste can be reyclced for nonagricultural markets;
Steel	85%	-Steel C&D is very recyclable due to is lack of contaimnation by dissimilar materials. -85% of C&D steel is currently recycled by recyclers -Good markets exist for ferrous metals such as iron and steel, as well as other non-ferrous metals such as copper, brass and aluminum. -Metal is almost always recycled back into other metal products and recycling opporunities are avialable in virtually every area around the country
Treated Wood	25&	-Treated wood should be handled separately from vegetative debris being recycled -Besides wooden utility poles, other lumber that may be chemically treated includes decks, fences landscaping materials, wood bridges and railroad ties. Treated wood contains chemical perservatives that can contaminate recycled wood produccts; these woods can be combused in waste to energy facilities.

Table 3 – Material Recyclability Methods

Appendix B – Retrofit Policy

This particular policy scenario differs from the four described previously in that it applies a pre-earthquake, mitigative effort to retrofit housing prior to assessing effects from the earthquake shock. The causal loop diagram in Figure 16 demonstrates how retrofitting homes becomes dually beneficial if enough homes are retrofitted to at least a minimum standard [37]. This retrofit scheme is a minimal approach intended to reduce harm to those who live or frequent the building. Collapse would be prevented, and occupants should be able to escape the building safely, but the building might not be repairable or fit for occupancy following the earthquake event [38]. This is determined as the least costly method of retrofit, at an average of $6.60/ sq. ft., adding to approximately $11,000 [39] per housing unit [40]. The retrofitting would result in a 57% reduction of damaged housing; a drop to 49,000 damaged or collapsed residential units versus 85,000 units.

The diagram shows that as retrofit policy is implemented, uninhabitable units are consequently decreased following an earthquake. If more homes are rendered habitable, either green-tagged or yellow-tagged, more shelter-in-place is possible. Shelter-in-place is described as a “resident’s ability to remain in his or her home while it is being repaired after an earthquake – not just for hours or days after an event, but for the months it may take to get back to normal. For a building to have shelter-in-place capacity, it must be strong enough to withstand a major earthquake without substantial structural damage. This is a different standard than that employed by the current building code, which promises only that a building meets Life Safety standards (i.e., the building will not collapse but may be so damaged as to be unusable)” [41].

The San Francisco Planning and Urban Research Association (SPUR) estimates that only 75% of the City’s current housing stock will provide adequate shelter for residents after a large earthquake, slowing overall recovery. SPUR’s projected goal for resilience is that the housing stock reaches a 95% shelter-in-place standard [42]. This goal is augmented by substantial retrofitting, which helps to retain the San Franciscan in the city after an earthquake. A resilient city can facilitate recovery and increase housing construction to restore uninhabitable residences to livable standards so as to regain any displaced residents. This is shown by the right-hand reinforcing loop in Figure 16.

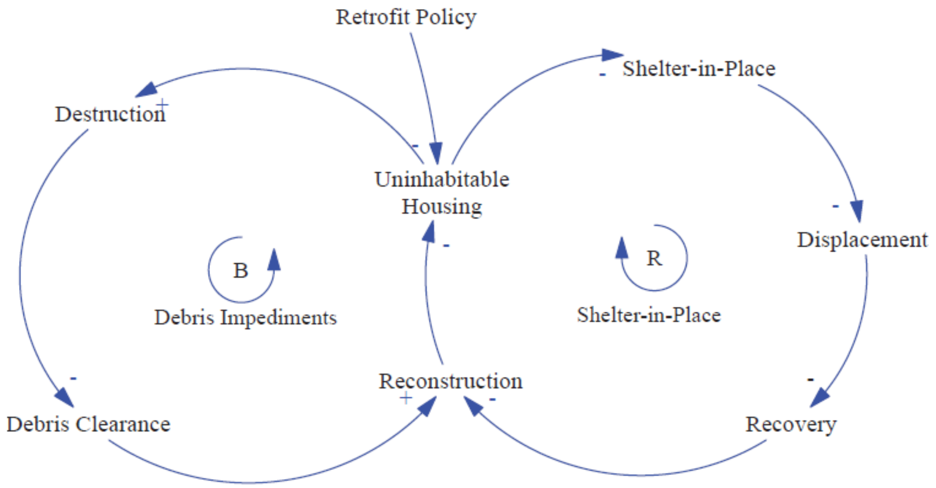
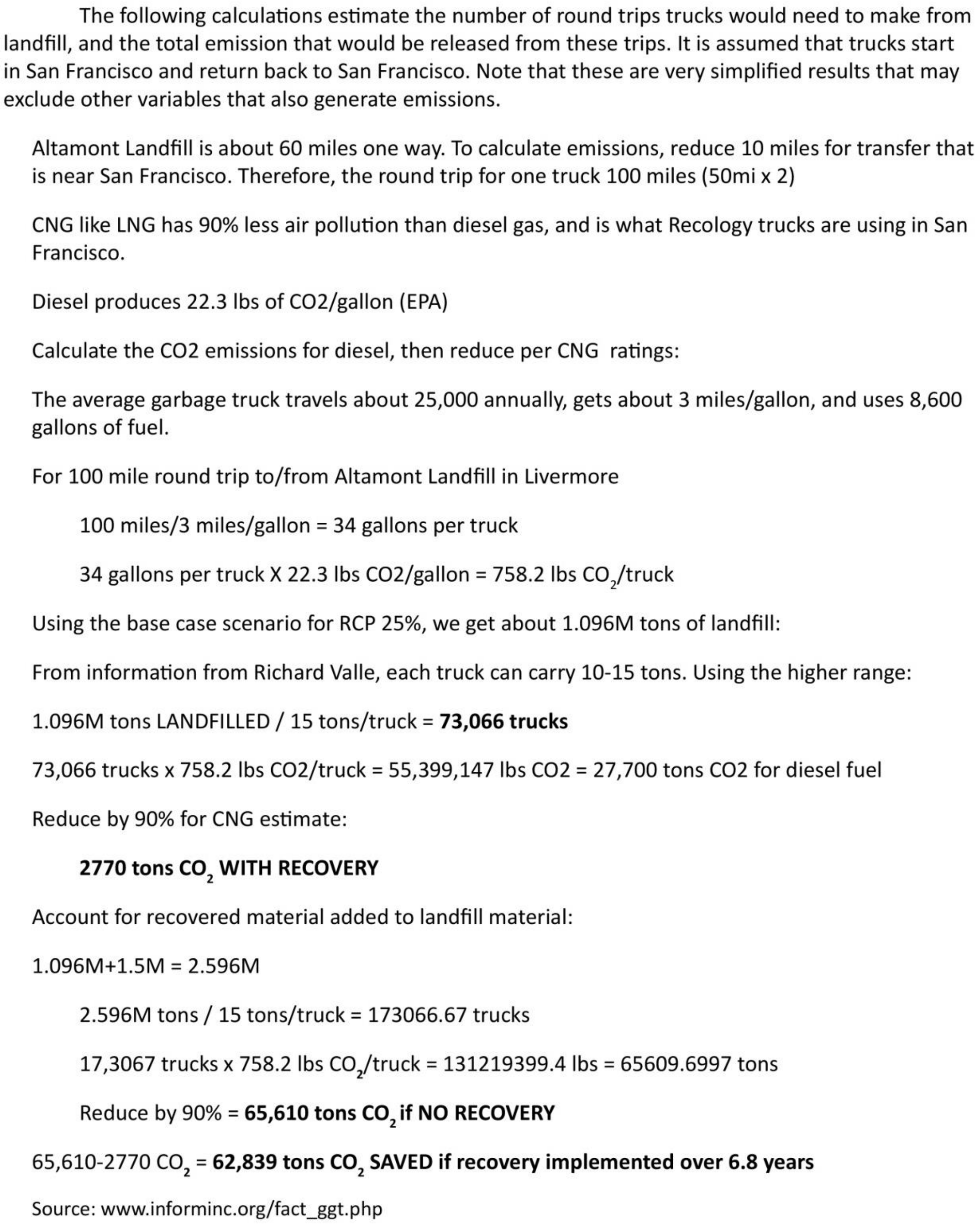


Figure 16 – Causal Loop Diagram, Retrofitting Policy

Appendix C – Emissions



The following calculations estimate the number of round trips trucks would need to make from landfill, and the total emission that would be released from these trips. It is assumed that trucks start in San Francisco and return back to San Francisco. Note that these are very simplified results that may exclude other variables that also generate emissions.

Altamont Landfill is about 60 miles one way. To calculate emissions, reduce 10 miles for transfer that is near San Francisco. Therefore, the round trip for one truck 100 miles (50mi x 2)

CNG like LNG has 90% less air pollution than diesel gas, and is what Recology trucks are using in San Francisco.

Diesel produces 22.3 lbs of CO2/gallon (EPA)

Calculate the CO2 emissions for diesel, then reduce per CNG ratings:

The average garbage truck travels about 25,000 annually, gets about 3 miles/gallon, and uses 8,600 gallons of fuel.

For 100 mile round trip to/from Altamont Landfill in Livermore

100 miles/3 miles/gallon = 34 gallons per truck

34 gallons per truck X 22.3 lbs CO2/gallon = 758.2 lbs CO_2/truck

Using the base case scenario for RCP 25%, we get about 1.096M tons of landfill:

From information from Richard Valle, each truck can carry 10-15 tons. Using the higher range:

1.096M tons LANDFILLED / 15 tons/truck = **73,066 trucks**

73,066 trucks x 758.2 lbs CO2/truck = 55,399,147 lbs CO2 = 27,700 tons CO2 for diesel fuel

Reduce by 90% for CNG estimate:

2770 tons CO_2 WITH RECOVERY

Account for recovered material added to landfill material:

1.096M+1.5M = 2.596M

2.596M tons / 15 tons/truck = 173066.67 trucks

17,3067 trucks x 758.2 lbs CO_2/truck = 131219399.4 lbs = 65609.6997 tons

Reduce by 90% = **65,610 tons CO_2 if NO RECOVERY**

65,610-2770 CO_2 = **62,839 tons CO_2 SAVED if recovery implemented over 6.8 years**

Source: www.informinc.org/fact_ggt.php

A5- Hauling and $C0_2$ Emissions

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