

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

by

Zahraa Nazim Saiyed  
B.A. Architecture  
Minor, Structural Engineering  
University of California, Berkeley, 2008

Submitted to the Department of Architecture in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Architecture Studies

at the

Massachusetts Institute of Technology

June 2012

© 2012 Zahraa Saiyed  
All rights reserved

The author hereby grants to MIT permission to reproduce and to distribute publicly paper and  
electronic copies of this thesis document in whole or in part in any medium  
now known or hereafter created.

Signature of Author: .....

Department of Architecture  
May 24, 2012

Certified by: .....

John E. Fernández  
Associate Professor of Architecture and Director of Building Technology  
Thesis Supervisor

Accepted by: .....

Takehiko Nagakura  
Associate Professor of Design and Computation  
Chair of the Department Committee on Graduate Students



## ADVISORS & READERS

John E. Fernández  
Associate Professor of Architecture and Director of Building Technology

James Wescoat, PhD  
Aga Khan Professor  
Reader

Anjali Sastry  
Senior Lecturer, System Dynamics  
Reader



# **Disaster Debris Management and Recovery of Housing Stock in San Francisco, CA**

by

Zahraa Nazim Saiyed

Submitted to the Department of Architecture on May 24, 2012 in Partial Fulfillment of the  
Requirements for the Degree of  
Master of Science in Architecture Studies

## **Abstract:**

This thesis investigates the potential effects of a 7.2 magnitude earthquake in San Francisco City, particularly the implications on San Francisco's residential housing stock and impacts on the construction and demolition waste stream. The study uses System Dynamics methodology to analyze the feasibility of recycling disaster debris as new construction material to rebuild the diminished housing stock. A meta-analysis identifies capacity requirements for transport and processing material, and seeks to project a time frame for refurbishing lost housing. Simulated scenarios of policy measures provide the basis for recommendations on improving San Francisco's post-disaster recovery as related to debris handling and reoccupation of housing. Results show that an increased use of recycled content products diverts upwards of 1.6 million tons of debris from landfill, with an additional two years of delay in overall recovery. Under this hypothesis, and considering residential housing recovery as a proxy for city-wide recovery, the effects of a large-scale earthquake would require an estimated recovery time of 6.8 years. Future work will address additional influencing variables of economics while honing existing factors within the dynamic model, as well as applications to other vulnerable cities in a domestic and international context.

Thesis Supervisor: John E. Fernández

Title: Associate Professor of Architecture and Director of Building Technology



## CONTENTS

SUMMARY.....	13
INTRODUCTION.....	15
1.0 Background and Problem Statement.....	15
1.1 Motivation.....	17
1.2 Sustainable Cities in Recovery.....	17
1.3 Hypothesis.....	25
1.4 Lessons from Previous Disasters.....	26
1.5 Industrial Ecology.....	27
SYSTEM DYNAMICS FOR POST-DISASTER MATERIAL FLOW ANALYSIS.....	34
2.0 Research Methodology.....	35
2.1 System Dynamics.....	35
2.2 Modeling an Earthquake in San Francisco.....	42
2.3 Debris Management.....	44
2.4 Disaster Debris Recycling.....	46
DEFINITIONS AND METHODOLOGY OF DATA GATHERING.....	55
3.0 Definitions and Methodology for Data Gathering.....	57
3.1 Area of Focus.....	57
3.2 Challenges.....	58
3.3 Description of Housing .....	59
3.4 Road Closures and Transfer Delays.....	63
3.5 Reoccupation on of Housing.....	65
3.6 Material Recycling Facility (MRF) and Landfill Site.....	66
3.7 Demolition and Deconstruction.....	68
3.8 Debris Generated.....	70
SYSTEM DYNAMICS ANALYSIS OF SAN FRANCISCO.....	73
4.0 System Dynamics Analysis of San Francisco.....	75
4.1 System Causal Loop Diagram.....	75
4.2 Driving Models.....	75
4.3 Results and Recovery Forecast.....	80
4.4 Conclusions.....	84
4.5 Insights.....	85
4.6 Model Critique.....	86
POLICY ALTERNATIVES AND SCENARIOS.....	89
5.0 Policy Analysis.....	91
5.1 Sensitivity Tests and Situational Alternatives.....	91
DISCUSSION.....	103
6.0 Discussion.....	105
6.1 Conclusions.....	105
6.2 Future Work.....	111
6.3 Vision.....	112
APPENDIX.....	113
Appendix A: Dynamics and Results.....	115
Appendix B: Housing.....	127
Appendix C: Debris & Waste.....	139
Appendix D: Recyclability.....	147
Appendix E: Delays.....	151
Appendix F: Recovery.....	153
REFERENCES.....	155





## FIGURES

Figure 1A. Pacific Rim of Fire .....	17
Figure 1.1A. Debris generated by Tohoku Earthquake, 2011.....	18
Figure 1.1.1B. Breakdown of Unoccupiable Dwelling Units by Structural Type.....	21
Figure 1.1.3A. Comparison of Debris by Disaster, 1999-2011.....	23
Figure 1.1.3B. Debris on Moscone Center Parcel, Waste Characterization of Debris.....	23
Figure 1.1.3C. Post Disaster Activities Concerning Recycling and Disposal of Debris .....	25
Figure 1.3A. Research Snapshot.....	27
Figure 2.1.1A. Causal Loop Diagram Example, Balancing and Reinforcing Loops.....	36
Figure 2.1.2A. Endogenous System.....	37
Figure 2.1.2B. Exogenous System.....	38
Figure 2.1.2C. Causal Map, Impacts of an Earthquake.....	39
Figure 2.1.3A. Stock and Flow, Debris Accumulation.....	39
Figure 2.1.4A. First Order Delay, Stock and Flow.....	40
Figure 2.1.4B. Exponential Growth Model Behavior, Landfill Material.....	40
Figure 2.1.5A. Systems Theory for Disaster Recovery .....	41
Figure 2.1.5B. Input and Information Feedback Loop, Bam Earthquake, Iran.....	42
Figure 2.2A. Research Causal Loop Diagram.....	43
Figure 2.2B. Research System Models.....	43
Figure 2.3.2A. Windshield Survey Priority Lifelines, San Francisco .....	45
Figure 2.4.3A. Sample Post Earthquake Disaster Waste Classification.....	50
Figure 2.4.4A. Causal Loop Diagram, Imported Materials.....	51
Figure 2.4.4B. Causal Loop Diagram, Recycled Content Products.....	51
Figure 3.1A. Geographic Boundary of Research, City and County of San Francisco.....	57
Figure 3.2A. C&D Waste Characterization, California.....	58
Table 3.3.1A. Building Classification, San Francisco. ....	59
Table 3.3.1B. Construction Classification, San Francisco.....	60
Figure 3.3.2A. San Andreas Fault.....	61
Figure 3.3.2B. Unusable Housing by Neighborhood.....	62
Figure 3.4B. Comparison of Loma Prieta and Northridge Road Clearances.....	64
Figure 3.6A. Causal Loop Diagram, Transfer Stations.....	67
Figure 3.6B. Material Recycling Facilities Studied, San Francisco.....	67
Figure 3.6C. MRF Processing Capacity, San Francisco.....	67
Figure 3.7A. Causal Loop Diagram, Deconstruction and Demolition.....	69
Figure 4A. Causal Loop Diagram of Simulated Systems.....	75
Figure 4B. Base Case Model 1, Housing Unit Driving Model.....	77
Figure 4C. Base Case Model 2, Construction and Demolition Waste Streams Driving Model.....	79
Figure 4.3.1A Housing Stock in Equilibrium Case.....	81
Figure 4.3.1B Landfill & Recovered Material versus Storage and Processing Capacity.....	81
Figure 4.3.2A. Housing Stock with Effects of Earthquake.....	82
Figure 4.3.2B. Construction Rate for Earthquake Base Case with Sensitivity Testing.....	83
Figure 4.3.2C. Landfilled Material and Recovered Material for Earthquake Base Case.....	83
Figure 4.3.2D. Transfer Station Capacity with Sensitivity Tests for Earthquake Base Case.....	84
Figure 5.1.1A. Impact on Landfilled Material by Recovery Mandate Policy.....	91
Figure 5.1.1B. Impact on Recovered Material by Recovery Mandate Policy.....	92
Figure 5.1.2A. Causal Loop Diagram, Deconstruction and Demolition.....	92
Figure 5.1.2B. Sensitivity Analysis on Deconstructed Units Policy.....	93
Figure 5.1.2C. Sensitivity Analysis on Landfilled Material with Deconstructed Units Policy.....	94
Figure 5.1.2D. Red-Tagged Units to be Destructed.....	94
Figure 5.1.2E. Sensitivity Analysis on Landfilled Material with Deconstructed Units Policy.....	95
Figure 5.1.3A. Housing Units, with and without Locked MRF capacity.....	96
Figure 5.1.3B. Transfer Station Capacity Comparison.....	96
Figure 5.1.3C. Comparison of Landfill and Recovered Material.....	97
Figure 5.1.4A. Causal Loop Diagram, Retrofitting Policy.....	98

Figure 5.1.4B. Housing Units Post-Retrofit.....	99
Figure 5.1.4C. Material Recovered, Post-Retrofit Comparison.....	99
Figure 5.1.4D. Landfilled Material, Post-Retrofit Comparison.....	100
Figure 6.1.3A. Economic model of Waste Handling .....	110

## **TABLES**

Table 1.1.1A. Building Damage, San Francisco.....	20
Table 1.4A. Comparison of Debris by Disaster, 1999-2011.....	29
Table 3.4A. Road Closures, adapted from ABAG 2003.....	63
Table 3.5A. Projected Recovery Time for San Francisco.....	65
Table 3.6D. Material Recycling Facilities, Location, Acreage and Capacity.....	68
Table 3.8A. Total and Residential Unit Debris Generated.....	71
Table 6.1.1A. Deconstruction versus Demolition.....	108

## ACKNOWLEDGEMENTS

This work could not have been possible without the support and encouragement of my thesis supervisor, Professor John Fernández. His dedication to this thesis has motivated me to continue pursuing research in the field of disaster mitigation and management.

I am also indebted to Professors James Wescoat and Anjali Sastry, whose guidance has strengthened this work. I would also like to thank those who contributed knowledge, data, and recommendations, especially colleagues in the Building Technology Lab.

Finally, I would like to acknowledge my parents who are my greatest inspiration- Thank you for your enthusiasm in all my endeavors.



## Summary

Investigations have shown that the cause for unprecedented ramifications from recent earthquakes, especially for Japan, is that the city and state did not plan for the consequences of such an earthquake- it far overshadowed their expectations and preparedness.<sup>1</sup> San Francisco has taken many resilient-city initiatives, some more technical and others more community based, as a basis to be able to bounce back efficiently from the next earthquake to shake up the Bay Area. Contemporary case studies of managing recovery from the string of earthquakes to have struck the Pacific Rim of Fire within the last two years have provided our state and other vulnerable cities a guide to necessary preparedness protocols. One of the greatest aspects of resiliency that is currently being tested in the aftermath of the Japanese Earthquake from 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 must be able to reach those in need of assistance within the heart 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 then symbolizes, both literally and in reality, key efforts to jump-start the recovery process.”<sup>2</sup>

This research focuses in 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 as potential to be reintroduced into distressed material supply streams within San Francisco. The simulation bridges 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 units that may not be robust enough to withstand a large-scale disaster. Such housing vulnerabilities along with access impediments must be considered inclusively such that interconnections can be made between variables impacting city-wide hazard mitigation and recovery management.

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 granular 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 and the greater Bay Area.

---

1 Associated Bay Area Governments, *Shaken Awake*, (2011), 1-2.

2 Phillips, Brenda D. *Disaster Recovery*. (Boca Raton, London, New York: CRC Press, 2009), 35-37



## INTRODUCTION

“For major natural disasters, debris removal operations can account for more than 25% of the disaster recovery costs. Although rapid removal of debris is the first priority, concern should be taken for the impact that various kinds of debris will have on the environment and the logistics of handling debris before it reaches a landfill”

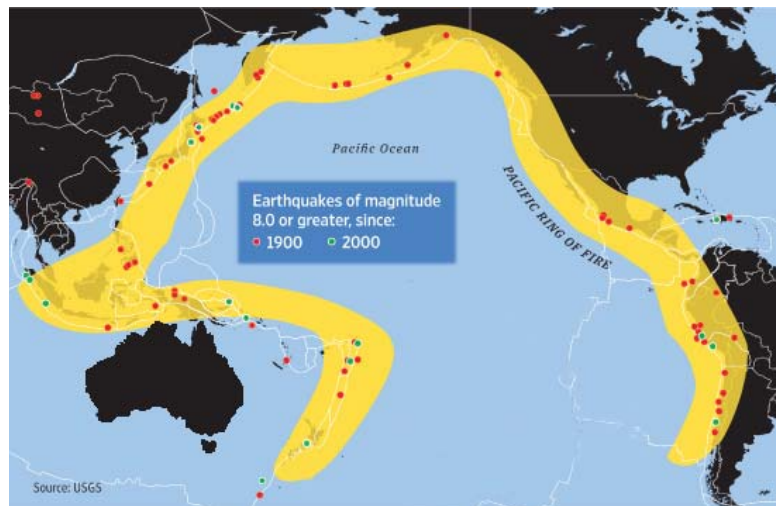
*San Francisco Recovery Annex, 2010*





## 1.0 Background and Problem Statement

San Francisco is vulnerable to earthquakes as a peninsula city lying on the Pacific Rim of Fire. This area bordering the Pacific Ocean is subject to constant tectonic plate motion resulting in many of the world's largest earthquakes, including the recent Japan and New Zealand catastrophes. 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.<sup>1</sup>



**Figure 1A. Pacific Rim of Fire**  
**Source: United States Geological Survey**

Given this vulnerability, the local governments of San Francisco and the Bay Area have invested time and effort in creating preparedness and recovery plans for their respective counties. However, little interconnection has been drawn among debris removal, lifelines, bulk material processing capacity and housing refurbishment, presenting a great weakness in disaster recovery planning. The thesis seeks a meta-analytic approach in combining several important plans, reports and investigations to provide a holistic understanding of post-earthquake repercussions and re-development. A meta-analytical approach synthesizes results of several studies that address related hypotheses in order to understand potential feedback loops in the recovery process for a more sustainable return to pre-disaster conditions in San Francisco.

## 1.1 Motivation

Witnessing the string of recent earthquakes on the Pacific Rim of Fire and learning from case studies has motivated further investigation of San Francisco's preparedness and recovery measures. Often, Japan is used as an analogously vulnerable region, susceptible to earthquakes and tsunamis. Japan's management of the volumes of debris generated by the March 2011 Tōhoku earthquake and

<sup>1</sup> United States Geological Survey, < <http://earthquake.usgs.gov/regional/nca/ucrf/> > (accessed May 10, 2012)

tsunami has made evident the need for greater understanding of San Francisco's disaster debris management protocols. Researchers who have studied disaster waste management have suggested that, "when responding to a disaster, [debris] management has emerged as a significant weakness internationally. This is despite solid waste and disaster debris being identified as the most critical environmental problem faced by countries following the 2004 Indian Ocean Tsunami. Waste management is a considerable challenge for national and local institutions during both the rehabilitation and reconstruction stages. It is important to focus on long-term ecological and economic debris management strategies that are sustainable and therefore increase a community's resilience when facing future hazard events. Thus, it is crucial to maximize sustainable environmental values while also minimizing disaster waste generation.

This research hopes to elucidate some of the key variables related to debris management and housing needs following the next earthquake to affect the Bay Area."<sup>2</sup>



**Figure 1.1A. Debris generated by Tohoku Earthquake, 2011.**  
Source: M. Arias, 2011

Preparedness for a large scale earthquake has involved multiple stakeholders, such as political entities and non-profit organizations, that are attempting to fully engage citizens and inform them of vulnerabilities in the City. Yet preparedness must go beyond traditional emergency kits in a household level. Instead, a broader dialogue prior to the inevitable must be developed and maintained. This will provide San Francisco with a sense of clarity and consensus for reconstruction in a chaotic post-disaster situation. However, dialogue comes with expected complexities and difficult compromises, one of the most profound being the decision to rebuild *faster* versus rebuild *better* when attempting to return to normalcy. History shows that recovery efforts are oftentimes polarized between speed and quantity versus quality of redevelopment. This research has particular interest in comprehending potential reconciliation of recovery quality with recovery speed, using debris management as a primary driver and representative of recovery alternatives. It by no means provides an overarching statement for complete recovery standards, but pushes the notion of the compromises San Francisco will invariably face to inform the City of ways in which it can build-back-better.

---

2 Pilapitiya et al., 2006; Srinivas and Nakagawa, 2007; Baycan and Petersen, 2002; Mensah, 2006; Blakely, 2007 as cited by Karunasena et al., *Sustainable Post-Disaster Waste Management: Construction and Demolition Debris*, (Chichester, West Sussex, UK Ames, Iowa: Wiley-Blackwell, 2011), 259.

San Francisco is no stranger to preparedness and mitigation activity. The City has taken great strides in hazard mitigation activism, and has an impressive number of initiatives for disaster preparedness, nearing 190 safety projects since the Loma Prieta earthquake in 1989. Along with concern for life safety following a potential disaster, San Francisco's vigor for environmental protection and local job creation has helped to achieve the highest recycling rate of any city nationwide – 77% diversion rate as of 2010.<sup>3</sup> Realizing a general lack of research on best practices for disaster debris management in the Bay Area, and in conjunction with San Francisco's spirit of environmental accountability, the need for innovative practices in disaster debris treatment has inspired this research. An objective is for the City of San Francisco and other similarly vulnerable cities is to consider disaster debris as more than an impediment to recovery, and to tenaciously harness its potential in rejuvenating local economies and populations.

Despite the evident benefits of involving multi-partisan dialogue for preparedness and recovery planning, Olshansky et al. have highlighted the importance of “local government in facilitating a lasting recovery”<sup>4</sup> such that democratized conversations can subsequently inform necessary and swift top-down decision making following a disaster. This thesis intends to provide meaningful options for disaster and reconstruction management for any city prone to hazards. The hope is that it will allow San Francisco to plan with sensitivity to the needs of many, but be able to provide the best solution for the majority without further damaging its environmental context. Some of the more pressing issues the City must deal with are discussed in detail in the following sections.

### 1.1.1 Housing

As Mary Comerio affirms, “urban disasters are always housing disasters.”<sup>5</sup> This fact is particularly important for San Francisco as the second most densely populated city in the US, “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.”<sup>6</sup> 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 3 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 prefer not to re-locate away from their neighborhoods, schools and jobs, it becomes increasingly 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

---

3 City and County of San Francisco, “San Francisco Achieves 77% Landfill Diversion Rate, The Highest of Any U.S. City, August 30 2010 (accessed November 1, 2011)

4 Olshansky et al., *Opportunity in Chaos: Rebuilding After the 1994 Northridge and 1995 Kobe, Earthquakes*, Web-Published, 2011, 11-1

5 Comerio, Mary. UCSF, *Learning from Japan: One year later*, March 2012

6 San Francisco Recovery Annex, 2008, 9-12

are expected to suffer significant damage following a 6.7+ magnitude earthquake. For this reason, this research focuses on damages to residential housing due to shaking and ground failure, but not including impacts from fire. Although many earthquake scenarios could be examined, a 7.2 magnitude is used as a control case because 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.<sup>7</sup>

The Community Action Plan for Seismic Safety has suggested the following in regards to housing conditions following a large-scale earthquake in San Francisco:

- 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 usable after the scenario earthquake.
- Thousands of units would necessitate demolition, meaning that many people would be displaced until housing is reconstructed.<sup>8</sup>

Table 1.1.1A explains housing damages after suffering a 7.2M shock.

ESTIMATED DAMAGE TO CITY’S HOUSING FROM 7.2 M SAN ANDREAS SHAKING AND GROUND FAILURE								
Type of Housing	Usable, Light Damage <sup>a</sup>		Usable, Moderate Damage <sup>a,b</sup>		Repairable, Cannot be Occupied <sup>a</sup>		Not Repairable <sup>a,c</sup>	
	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 <sup>d</sup>	60,000	120,000	69,000	130,000	22,000	74,000	3,000	11,000

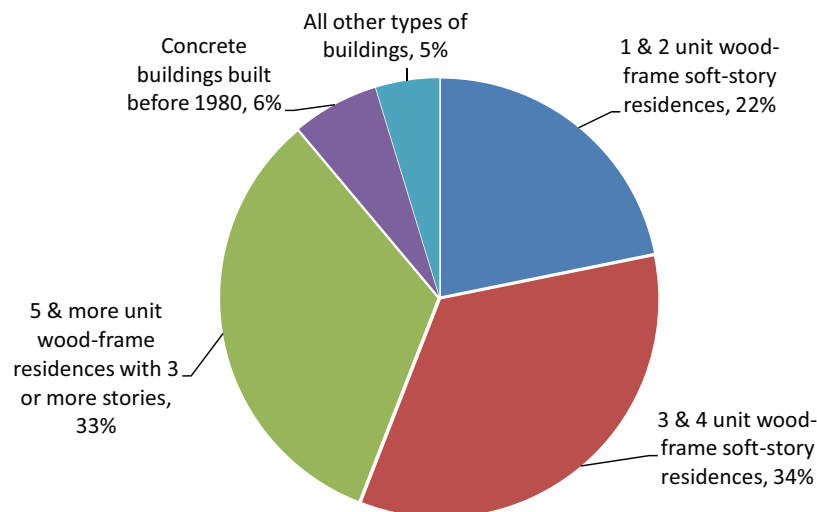
- a. Building functionality categorizations are derived from HAZUS® damage states. For more information, please see the companion technical volume, *Potential Earthquake Impacts: Technical Documentation* (ATC 52-1A Report). Functionality categories are defined in section 3.2.
- b. This level of damage 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 1.1.1A. Building Damage, San Francisco. Cited from CAPSS Report 52-1, Table 15**

<sup>7</sup> Applied Technology Council (ATC), *Here Today- Here Tomorrow: The Road to Earthquake Resilience in San Francisco*, Report 52-1, 2010

<sup>8</sup> *Ibid*, 2010

The type of building determines the characteristic of the debris generated due to structural damage. CAPSS has determined that 26% of the housing units cannot be occupied following the disaster, with nearly 89% of damaged housing being wood frame residential construction resulting in vast quantities of woody debris. This data does not include fires or water damage, and is solely due to shaking and ground failure.



**Figure 1.1.1B. Breakdown of Unoccupiable Dwelling Units by Structural Type**  
Cited from CAPSS Report 52-1, Figure 12

Figure 1.1.1B highlights housing damage by residence type, and illustrates the immense impact on unusable multi-family housing, the largest constituents of the soft-story construction in San Francisco.<sup>9</sup> This provides pressing reason to focus on residential housing resiliency in the City.

Rebuilding housing is not a linear phase of population recovery in a post-disaster context. Olshansky et al. describe some variables regarding post-disaster reconstruction. “These are:

- Property ownership and parcel characteristics
- Sources and types of financing
- Effects of pre-existing plans
- Institutional framework
- Government intervention and regulatory framework”<sup>10</sup>

This abridged list makes evident the multi-factorial and political nature of reconstruction, requiring pre-determined collaboration and consensus-driven activity for recovery. The San Francisco Regional Emergency Coordination Plan proposes logical constraints in such recovery, mainly associated with competition for housing resources, first responders and insurance adjusters. Competition for materials, contractors and other resources will prolong overall reconstruction as multiple jurisdictions will look to the same sources for private contractors.

<sup>9</sup> Soft-story and other vulnerable construction types explained in Chapter 3, Appendix B

<sup>10</sup> Olshansky *et al.*, 11-2

### 1.1.2 Repopulation

The quality and speed of recovery is highly dependent on housing refurbishment, which influences the repopulation of the city after the occurrence of an earthquake. “If most residents can be back in their homes quickly after an earthquake, it would greatly speed all aspects of the city’s recovery. Residents would be able to contribute to helping their neighbors and neighborhoods recover, and would remain close to their jobs, schools, businesses, and services. On the other hand, if many residences cannot be occupied for months or years after an earthquake, neighborhoods would have vacant buildings for extended periods, people may permanently relocate to new areas, perhaps outside the city, and the neighborhood businesses and services that depend on local customers would suffer.”<sup>11</sup> This repopulation issue is still being faced by many neighborhoods in New Orleans since Hurricane Katrina in 2005.

As explained, repopulation is a function of housing renewal, which depends on two factors: the quality of the home pre-disaster and the momentum of recovery. If homes are built to withstand heavy ground shaking, shelter-in-place can reduce relocation of residents. Shelter-in-place is defined 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”<sup>12</sup> to pre-earthquake normalcy. An effective recovery can re-shelter households faster, provided that reconstruction is within a reasonable number of years. A magnitude 7.2 San Andreas fault scenario is expected to damage 25 times as many residences than the Loma Prieta.<sup>13</sup> Due to this, CAPSS estimates recovery in San Francisco to take upwards of 10 years.<sup>14</sup> Case studies suggest that a 10% loss in population can be recaptured in 3 years, while a 50% loss can be regained in 7 years.<sup>15</sup> Therefore, comprehensive disaster planning ensures higher probabilities of repopulation, further stimulating holistic city recovery.

There is strong evidence for acceleration of pre-disaster trends in recovery. Stated differently, rapidly growing cities recover rapidly, whereas stable, stagnant or declining cities recover slowly and may even have their decline accelerated.<sup>16</sup> For example, New Orleans had gradually been losing population and business preceding the 2005 disaster. The post-Katrina recovery was particularly arduous likely due to the city’s pre-disaster circumstances, and recapturing of displaced residents for neighborhood re-planning became especially challenging. Therefore, great initiative and effort has been taken to draw back residents in order to revitalize New Orleans, some neighborhoods being widely successful in this endeavor.

### 1.1.3 Debris

As with any natural disaster, including earthquakes, hurricanes, tsunamis, and tornados, a key

---

11 ATC 52-1, 40

12 San Francisco Planning and Urban Research Association, *Safe Enough to Stay*, 2012, 3

13 Comerio and Blecher, *Estimating Downtime from Data on Residential Buildings after Northridge and Loma Prieta Earthquakes*, 2010

14 ATC 52-1, 40

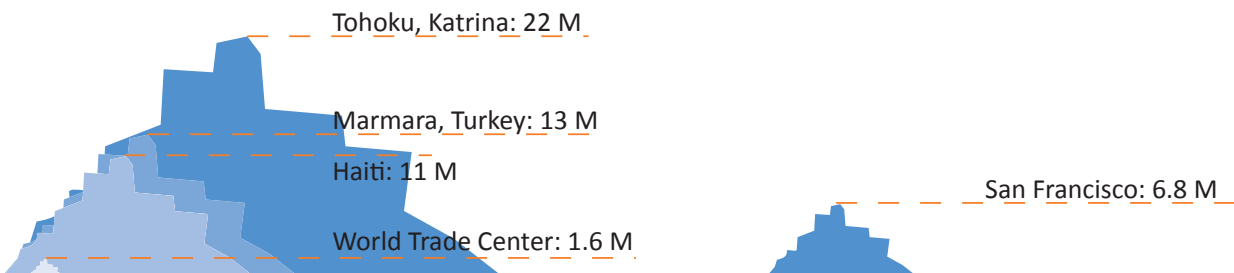
15 Haas and Kates, *Reconstruction Following Disaster*, 1977

16 *Ibid*, pp. 19



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.<sup>17</sup> The California Action Plan for Seismic Safety projects that 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.<sup>18</sup>

A comparison of manmade and natural disasters in Figure 1.1.3A shows the overwhelming amounts of debris generated. Since these are raw values and have not been normalized by the square areas that are affected, a graphic showing the residential housing debris (amounting to nearly 3 million tons) as placed on the Moscone center parcel in downtown San Francisco is shown in Figure 1.1.3B. The debris would reach over 870 feet high, taller than the Transamerica Pyramid, which indicates the severity of debris accumulation in San Francisco, requiring thorough consideration and planning prior to a disaster.



**Figure 1.1.3A. Comparison of Debris by Disaster, 1999-2011**



#### **WASTE CHARACTERIZATION**

Woody Debris	43%
Rock Soils Fines	11%
Concrete	10%
Gypsum	10%
Steel	8%
Asphalt	7%
Brick	5%
Other/Composite	6%

**Figure 1.1.3B. Debris on Moscone Center Parcel, Waste Characterization of Debris.**

**Source: California Integrated Waste Management Board**

<sup>17</sup> Department of Emergency Services, *San Francisco Bay Area Regional Coordination Plan, Recovery Annex*, 2008, 63

<sup>18</sup> ATC 52-1

Disaster debris in this research is considered as inert construction and demolition debris only, although this debris is comprised of other elements as well, such as e-waste and hazardous household wastes.<sup>19</sup> Blakely describes the phases of disaster debris management as commencing “immediately following a disaster and continues during longer term reconstruction. The first phase of debris management is dedicated to immediate disaster relief and is focused on removing debris from access routes and residential and commercial areas. The second phase of debris management is the long-term removal of debris, which assists reconstruction. In the short term, removal of debris is necessary to facilitate recovery of a geographic area, whereas in the long term, it should not pose future threats to health or environment.” Alameda County’s Disaster Waste Management Plan from 1998 highlights “the need to design early stage strategies to manage debris in the most environmentally sound manner, through maximizing source reduction and recycling options while minimizing land disposal.”<sup>20</sup> However, even with instated plans, debris management is often weakened by other issues that take precedence immediately following a disaster event.

In many cases, management of disaster waste is also hindered by lack of preparedness, resulting in clean-up delays, cost escalation, and adverse environmental impacts. Given the magnitude of the cleanup efforts after the Northridge earthquake in 1994 and the fires in Oakland in 1991, a clear necessity for having a methodical debris removal operation exists. According to the California Integrated Waste Management Board, “the key to a successful disaster debris management program is advance planning. In the aftermath of a disaster, the primary focus is restoring and maintaining public health and safety. Consequently, debris diversion programs such as recycling and reuse can quickly become secondary, to be established only if there are time and staff to undertake effort, if at all. Preparedness will assist the State in diverting significant amounts of valuable materials that would otherwise be disposed of. Furthermore, there will be the added benefit of preservation of the State’s landfill capacity.”<sup>21</sup>

Though preserving landfill capacity through material diversion seems to be a logical mode of debris removal, challenges exist for timely material recovery. “Local governments have identified temporary storage sites as the primary obstacle in establishing a debris management program. Without the ability to stockpile or store the disaster debris until such time as a jurisdiction can turn its attention to processing and marketing the materials, the debris is probably destined for the landfill. Securing storage sites is best done before a disaster so that arrangements, such as leases and permits for the land, can be accomplished quickly.”<sup>22</sup> Material recovery is only suitable if markets for recycled content products exist, otherwise time and money spent in reprocessing disaster debris will outweigh its potential benefits. The following diagram illustrates post-disaster activities concerning the recycling and disposal of debris.

Figure 1.1.3C illustrates the processes of post-disaster waste management that are generally applicable to all earthquake contexts.

---

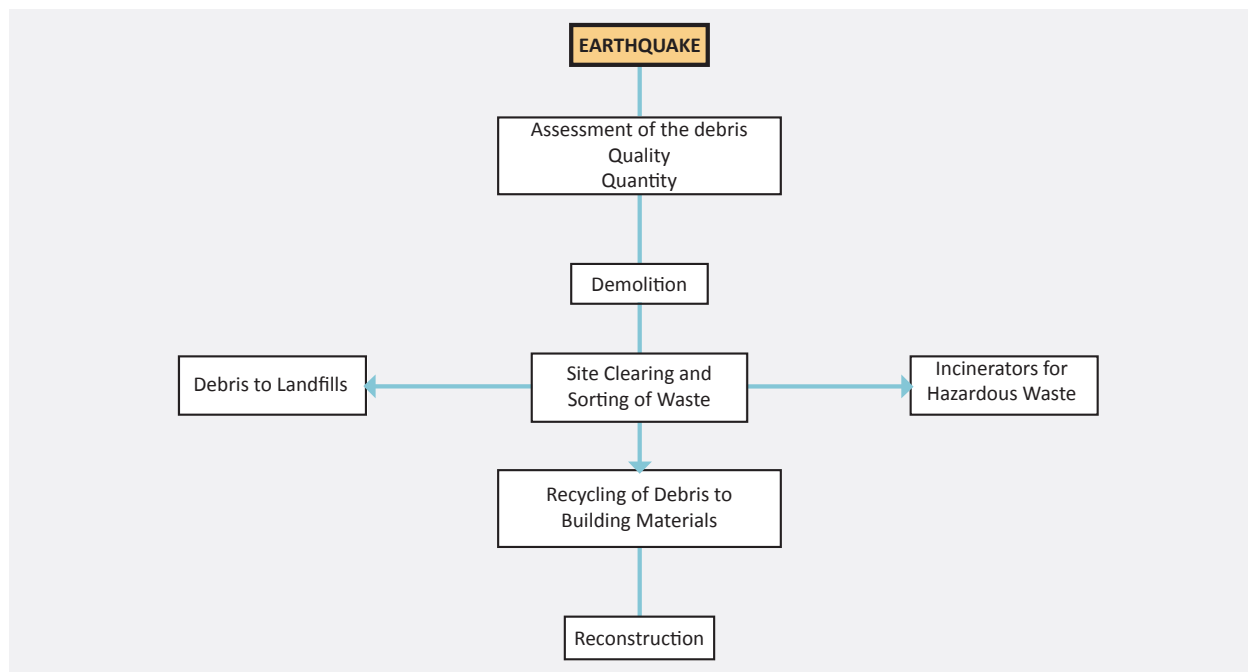
19 More disaster debris waste descriptions in Appendix C

20 Blakely, 2007. As cited by Karunasena *et al.* 2011, 255

21 California Integrated Waste Management Board, *Integrated Waste Management Disaster Plan*, 1997, ES 1

22 *Ibid*, 12





**Figure 1.1.3C. Post Disaster Activities Concerning Recycling and Disposal of Debris**  
 Source: *Disaster Planning, Structural Assessment, Demolition and Recycling*, E.K. Lauritzen, C. de Pauw, 1994

Possibly the most important instrument for sufficient debris diversion rates and material recovery is the environmental regulations set by the respective city. San Francisco is certainly exemplar for its high waste diversion standards, despite the City's generally high waste per capita. In the aftermath of a disaster, the issue of regulation relaxation is a great danger to harnessing the potential of the disaster debris. Attention must be paid to include within a debris plan the pre-disaster standard and accountability for waste diversion, not to be jettisoned in its entirety following the event. Exaggerated easing of the 65% material recovery mandated by the City's Environmental Code will cause severe environmental impacts due to nearsighted and quick emergency phase resolutions.

## 1.2 Sustainable Cities in Recovery

Recognizing that sustainable and vital local economies are essential to healthy recovery, regional industries must be diversified and thus less easily disrupted by disasters. A sustainable economy does not shift its externalities onto another region, nor is it predicated on unlimited population growth, high consumption, or dependence on nonrenewable resources. Especially for a disaster scenario, regional, national and international cooperation and mechanisms will be needed to ensure that costs are determined accurately and distributed fairly,<sup>23</sup> resulting in immense political, cultural and social barriers.

Social processes and decisions lead to unforeseeable vulnerabilities that have increasingly disastrous effects when met with environmental hazards. Mileti states that the "contemporary per-

23 Ardani *et al.*, 2009

spective is that recovery is not just a physical outcome but a social process that encompasses decision making about restoration and reconstruction activities. This perspective highlights how decisions are made, who is involved in making them and what consequences those decisions have on the community. This approach also stresses the nature, components, and activities of related and interacting groups in a systematic process and the fact that different people experience recovery differently. Rather than viewing recovery as a linear with 'value-added' components, this approach views the recovery process as probabilistic and recursive."<sup>24</sup> Therefore, decisions made prior to a disaster are inherently linked with the outcomes following a disaster, leading to a somewhat cyclical evolution of hazard communities.

The social and health implications of recycling disaster debris are significant and should not be diluted. Many communities that have coped with a catastrophe are hesitant to re-circulate disaster debris back into the construction stream due to psychological, physiological or cultural concerns. For this reason, decision making *must* be community based such that singular, top-down decisions do not encumber overall recovery if countered by widespread disapproval.

### 1.3 Hypothesis

Debris clearance becomes a great 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 the building materials 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 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 for this thesis.

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. Various policies and cases are studied for the amount of waste that is landfilled versus recovered, as well as housing refurbishment timelines. To reiterate, the material flow under examination is that of construction and demolition material only, which is analogous to inert disaster debris. Figure 1.3A is a snapshot of the research scope, with the specified inclusions and exclusions of the thesis scope.

---

24 Mileti, *Disasters by Design Disasters by design a reassessment of natural hazards in the United States*. (Washington, D.C: Joseph Henry Press, 1999) 229-230

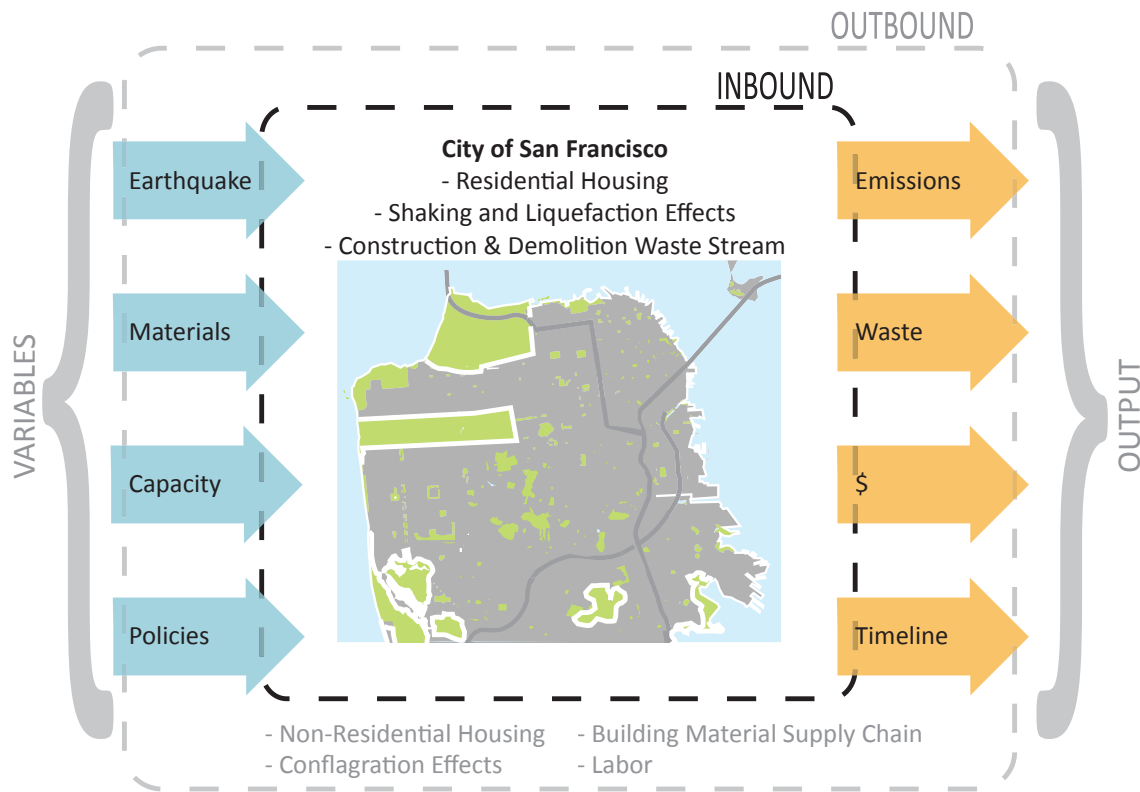


Figure 1.3A. Research Snapshot

## 1.4 Lessons from Previous Disasters

Understanding the impacts of historical earthquakes specifically in the respective of debris management provide useful examples and retrospective for recovery efforts following large scale urban disasters.

### 1.4.1 Northridge Earthquake, California, 1994

The city of Northridge was impacted with a 6.7 magnitude earthquake on January 17, 1994. Los Angeles did not have a pre-disaster debris arrangement plan, and debris was initially directed to three landfills. Within two days of the earthquake, the city contracted waste handlers that were able to recover nearly 80% of disaster material. Following this, and in collaboration with FEMA, supervising officers developed and implemented a recycling program with the capacity to recycle 50% of the earthquake debris collected weekly, which totaled over 1.5 million tons by the end of the removal period. However, it took approximately one month before the disaster debris began being diverted from the landfill to recycling facilities. A year after the earthquake, the city had remarkably established 18 recycling facilities and reduced the total number of landfills from three to one.<sup>25</sup>

25 Ardani, Kristen B., Charles C. Reith, C. Josh Donlan. "Harnessing Catastrophe to Promote Resource Recovery and Eco-industrial Development." *Journal of Industrial Ecology* (2009): 579-591.

#### 1.4.2 Japan, 2011

The earthquake off the Pacific coast of Tōhoku was a 9.0 magnitude earthquake followed by a tsunami with waves that reached up to 40.5 meters. As of summer 2011, no comprehensive plan to dispose of the overwhelming amount of debris existed. At first, the Self Defense Forces assisted with the debris removal because the immediate need was search and rescue of possible survivors. Now local municipalities are left to figure out the best way to deal with the piles. Most local governments hope to use contractors, funded by the national government, to perform the remainder of the debris removal and sorting.

Iwate Prefecture plans to complete the cleaning, sorting, and disposal of its disaster debris in the next three years. Private land is currently being utilized as temporary sorting sites for debris; however, space is limited, so some of the rubble from this prefecture is being taken by barge to temporary sorting sites in a northern prefecture.<sup>26</sup>

Local officials in Japan claim that the disaster debris will be recycled as much as possible. However, in Fukushima, the debris contaminated by radioactivity has proven to be problematic for debris staging and recycling. Many prefectures are unwilling to stage or process this debris, and radioactivity will require complex screening prior to any thought of recycling.

#### 1.4.3 Haiti, 2010

The 7.2 magnitude earthquake that struck Haiti in January 2010 accumulated nearly 10 million metric tons of debris mainly due to non-engineered structures. With a land area of just less than 11,000 square miles, roughly the size of Maryland, and a population of 10 million, the population density in Haiti is high. As a result, studies believe that landfilling this volume of debris is nearly impossible. This debris has created a logjam in reconstruction, since land cannot be cleared, and streets are obstructed. Research at Georgia Tech University recommends that the Government of Haiti consider the benefit of recycling rubble debris as aggregate for concrete structures, ensuring systematic recovery of material and the “building-back-better” of Port-au-Prince.<sup>27</sup>

#### 1.4.4 New Orleans

Hurricane Katrina’s damage to New Orleans resulted in a significant increase in the amount of waste flowing into New Orleans East, resulting in nearly 22 million tons of debris. Due to the intensity of the flooding and the severity of housing damage, material recovery could not be expedited as in an earthquake scenario since search and rescue operations lasted weeks. Combined with the lack of a comprehensive disaster debris management plan, mountains of debris had lined the streets of New Orleans. Quick decision making opened two new landfills in eastern New Orleans, which subsequently received 38 million cubic yards of debris, enough to fill the Superdome three times. In addition, environmental

26 Earthquake Engineering Research Institute, *The March 11, 2011, Great East Japan (Tōhoku) Earthquake and Tsunami: Societal Dimensions*, August 2011

27 American Ceramic Society, Vol. 90, No. 1, *Breaking the Reconstruction Logjam*, March 2011

regulations limiting and restricting landfilling of hazardous materials were relaxed in the days and weeks after the Hurricane, incentivizing contractors to dump as much material as possible.

Table 1.4A summarizes the housing loss and damages incurred in these and other disaster struck cities.

HOUSING LOSS AND DAMAGE ESTIMATES

	Hurricane Katrina (2005)	China (2008)	Haiti (2010)	Chile (2010)	New Zealand (2010-11)	Japan (2011)
Damage Value	\$80B to \$150B	\$150B	\$12B	\$30B	\$40B	\$300B
Housing Units Lost	400,000	5 million	300,000	200,000	10,000	190,000 plus radiation area evacuation

**Table 1.4A. Comparison of Debris by Disaster, 1999-2011, Adapted from Comerio, PEER Research Center, *The Great East Japan Earthquake and Disasters: One Year Later*, UCSF, March 19 2012**

In hindsight, the low recovery of material can be attributed to poor staging of disaster debris. “The New Orleans long-term rebuilding effort was likely impeded by the failure to sort staged materials throughout the immediate disaster relief phase of the debris management program. Immediate debris management efforts included 343 large staging sites around the metropolitan area. However, those sites failed to separate recyclable materials suitable for use in reconstruction efforts,”<sup>28</sup> leading to high rates of landfill dumping.

This case provides an interesting insight on debris management that provides a short-term, and oftentimes, the ostensibly best practice solution- landfill dumping. Ardani et al. argue that New Orleans missed an opportunity to capitalize on a resource recovery program and to establish *eco-industrial* relationships, both of which could have resulted in new jobs and environmental improvement. Eco-industrial planning is the “matchmaking of adjacent industries around shared or exchanged resources, which results in job creation and fosters a more diversified web of enterprises to facilitate rapid and efficient recovery from future disasters.”<sup>29 30</sup>

Disasters often present opportunities to increase a region’s recycling activity and advance eco-industrial development by creating secondary materials. Although opportunities for debris diversion and recycling are typically limited throughout the immediate aftermath of a disaster, later phases of disaster recovery present enhanced prospects for material reuse. With adequate pre-planning and community based dialogue, San Francisco can set up eco-industrial partnerships with local foundries, lumber manufacturers and waste contractors to ensure appropriate salvaging and recovery of inert debris material

28 March and Wiley, 2007, as cited by Ardani *et al.*, 2009

29 Ardani, Kristen B., Charles C. Reith, C. Josh Donlan. “*Harnessing Catastrophe to Promote Resource Recovery and Eco-industrial Development.*” *Journal of Industrial Ecology* (2009): 579-591.

30 Deutz and Gibbs, 2004, as cited by Ardani *et al.*, 2009

such that landfilling becomes the last option and not a primary, rapid-action solution.

The cases described can provide promising lessons for other cities and communities facing similar hazards from natural events. The difficulty is in applying a tactic or methodology of mitigation, emergency management, or recovery planning from one locale to the next. One of the major setbacks in comparing vulnerable cities is that the contexts of each disaster is contingent on enough factors that it cannot provide a one to one example for another context. Local government structures, economic states, social and housing conditions as well as execution of recovery can vary dramatically, sometimes within the same country. In this way, it is useful to recognize the isolated issues communities face when exposed to a disaster, but great caution must be taken in implementing or avoiding the strategies of one municipality to another. Previous cases can enable comparability to current situations with integrated analyses through methods of non-linear understandings of certain cause and effects through application of an industrial ecological perspective.

## 1.5 Industrial Ecology

Housing refurbishment and debris recovery operations as a material flow analyses can be described as a study of industrial ecology, which is defined as a “concept in which an industrial system is viewed not in isolation from its surrounding systems but in concert with them. Industrial ecology seeks to optimize the total materials cycled from virgin material to finished material, to component, to product, to waste product, and to ultimate disposal.”<sup>31</sup> The approach strives to understand the lifecycle of products or materials as in a natural ecosystem in order to develop methods to restructure economies into a sustainable system.<sup>32</sup> This report takes approaches of industrial ecology in dissecting a question of urban sustainability following a significant disaster that derails its normal functioning. Therefore, principles of industrial ecology push for the use of a material flow analysis in the following ways:

- Controlling pathways for materials use and industrial processes
- Creating loop-closing industrial practices
- Dematerializing industrial output
- Systematizing patterns of energy use
- Balancing industrial input and output to natural ecosystem capacity

The results of a material flow analysis reveal the most important processes during the life cycle of a material in its economy and environment for interconnections between variables or factors. Such analyses is able to show losses to the environment as final sinks with mapping of recycling loops. Material flow analysis in the context of an urban metabolism describes the transfer, storage, and transformation of materials within the system and the exchange of materials with its environment. Metabolism can be applied to anthropogenic systems to investigate and evaluate material balances of complex urban

---

31 Jelinski *et al. Industrial Ecology: Concepts and Approaches*, (AT&T Bell Laboratories, Murray Hill, NJ), 1994

32 Brunner, P and H. Rechberger, *A Practical Handbook of Material Flow Analysis*, (Boca Raton, FL: CRC/Lewis, 2004)

conditions.<sup>33</sup>

After numerous disasters in the Pacific Coast, resulting in great volumes of debris, emergency management must consider the need for a systems approach to debris handling. Fields that address urban sustainability have generally understudied the particular environmental and resource consequences of disasters, an area in which tools of material flow and Life Cycle Analyses could be applied more directly to the issues that arise as a result of disasters. Therefore, a systematized approach emphasizes the interdependency and connectivity of all aspects of debris management, and the circularity of seemingly disparate variables. A system based material flow analysis within an urban context can unpack complexities and reveal behaviors of influential factors leading up to and following a disaster. This approach has motivated the methodology of this study, and is explained in the following chapter.

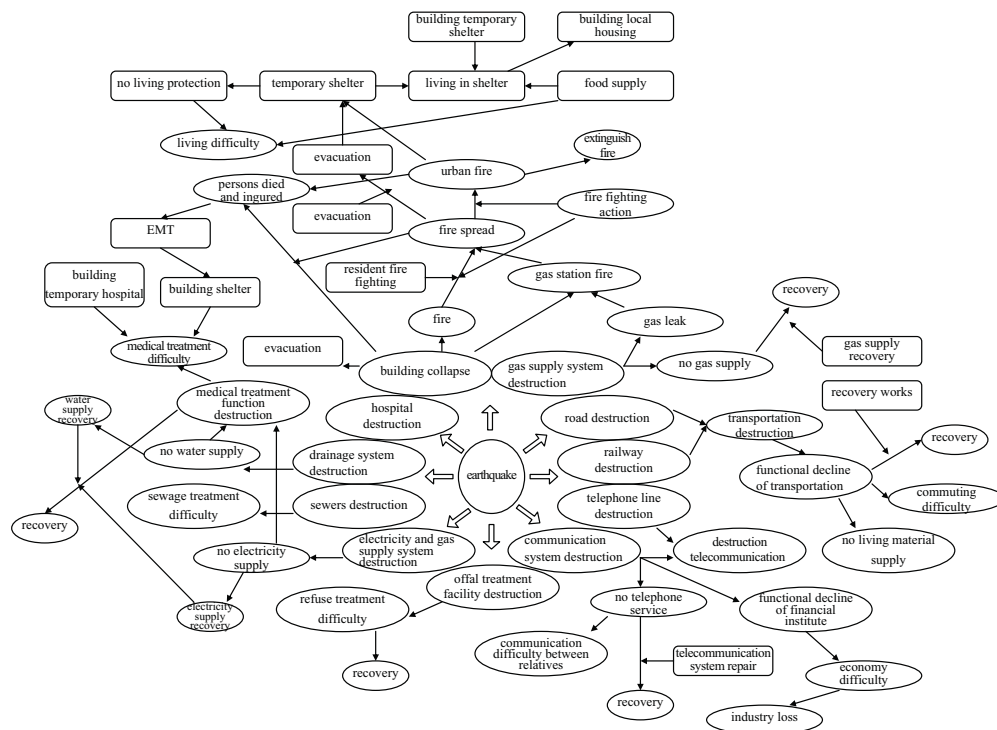
---

33 *Ibid*





# SYSTEM DYNAMICS FOR POST-DISASTER MATERIAL FLOW ANALYSIS



*Impacts of an Earthquake, Chiang and Jin, 1994*



## 2.0 Research Methodology

This chapter overviews the application of System Dynamics methodology. The first section introduces key concepts in systems theory and the following subsections illustrate the topic with examples of debris management as part of a broader disaster debris recycling model.

### 2.1 System Dynamics

System dynamics is a methodological approach to policy analysis and design, applicable to complex social, managerial, economic or ecological systems. It is most effectively applied to multi-variable scenarios characterized by interdependence, mutual interaction, information feedback, and circular causality.<sup>1</sup> System dynamics can assist in strategy assessment and provides insights into possible changes in the system during policy implementation.<sup>2</sup> This theory is best applied to a question about the behavior of a system rather than an effort to model the entire system; therefore, delineating a defined boundary of the question in concern is essential.

The methods of systems thinking provides tools for better understanding of complicated problems or situations, and requires looking away from isolated events and their causes to examine the scenario as a system made of interacting parts.<sup>3</sup> Given the various components influencing post-disaster recovery, a systems analysis is an apposite means of investigating potential outcomes in a defined time frame.

The system dynamics approach involves:

- “Defining problems dynamically, in terms of graphs over time.
- Striving for an endogenous [internal], behavioral view of the significant dynamics of a system, a focus inward on the characteristics of a system that themselves generate or exacerbate the perceived problem.
- Identifying independent stocks or accumulations (levels) in the system and their inflows and outflows (rates).
- Deriving understandings and applicable policy insights from the resulting model.
- Implementing changes resulting from model-based understandings and insights.”<sup>4</sup>

#### 2.1.1 Feedback Loops and Causal Loop Diagrams

Each system is made of elements that make up the whole. These elements form relationships that go beyond linear cause-and-effect chains, instead within a system involving circular chains of cause-and-effect. When an element of a system indirectly influences itself, the portion of the system

1 “Overview” <[www.systemdynamics.org](http://www.systemdynamics.org)> (accessed November 8, 2011)

2 Sterman, John. *Business dynamics : systems thinking and modeling for a complex world*. Boston: Irwin/McGraw-Hill, 2000.

3 Kirkwood, Craig W. “System Dynamics Methods: A Quick Introduction.” (College of Business, Arizona State University, 2010), 1-5

4 [Systemdynamics.org](http://Systemdynamics.org)

involved is called a feedback loop or a causal loop. Feedback is defined as the transmission and return of information,<sup>5</sup> and a feedback loop is a closed sequence of causes and effects, that is, a closed path of action and information.<sup>6</sup> Feedback structures often explain causes of system behavior, and are key in understanding circularity within the system.

To map feedback systems, a *causal loop diagram* (CLD) is a starting point for analyzing what may cause a particular pattern of behavior. This diagram includes elements and arrows, called causal links, which connects the elements together using a sign (+ or -) on each link.

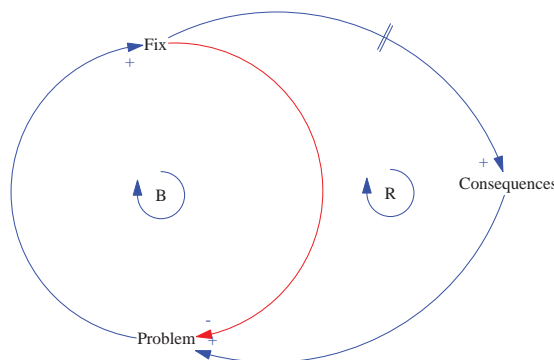
These signs have the following meanings:

- +** : A causal link from one element A to another element B is positive. If either (a) A adds to B or (b) a change in A produces a change in B in the same direction.
- : A causal link from one element A to another element B is negative if either (a) A subtracts from B or (b) a change in A produces a change in B in the opposite direction.

In addition to the signs on each link, a complete loop is also given a sign. The sign for a particular loop is determined by counting the number of minus signs on all the links that make up the loop. Specifically,

- A feedback loop is positive, or reinforcing, if it contains an even number of negative causal links
- A feedback loop is called negative, or balancing, if it contains an odd number of negative causal links

A positive, or reinforcing, feedback loop reinforces change with even more change, and can lead to rapid exponential growth. As growth speeds up, it may become difficult to solve the problem this growth is creating. Some examples that fall under this category include pollution and population growth. Positive feedback loops are called vicious or virtuous cycles, depending on the nature of the change that is occurring.



**Figure 2.1.1A. Causal Loop Diagram Example, Balancing and Reinforcing Loops**

5 Richardson, George and Alexander Pugh. *Introduction to system dynamics modeling*. (Waltham, MA: Pegasus Communications, 1981)

6 *Ibid*

A negative, or balancing, feedback loop seeks a goal. If the current level of the variable of interest is above the goal, then the loop structure pushes its value down, while if the current level is below the goal, the loop structure pushes it up. Typically, outcomes of balancing loops show oscillating behavior, by overshooting then recovering to goal levels.<sup>7</sup>

Figure 2.1.1A<sup>8</sup> is an example of a causal loop diagram with both a reinforcing and balancing loop. This example shows a basic understanding of problem solving. Fixing a problem ideally reduces or removes the problem, creating a goal seeking balancing loop, “B1.” In attempts to solve a problem, unforeseen consequences may actually reinforce the problem, after some delay in time, shown by “R2” in the model. In this example, the reinforcing feedback loop of unforeseen consequences creates a vicious cycle that may lead to more problems initially, but with some time steps, a shift of polarity may cause the balancing loop to take effect and lead the goal in mitigating problems. This combination produces an s-shaped pattern of behavior in the system.<sup>9</sup>

### 2.1.2 Endogenous and Exogenous Variables

The concept of endogenous (internal) change is fundamental to the system dynamics approach, and dictates how the model is formulated. Exogenous (external) disturbances to the system are seen as triggers of system behavior, like the displacement a pendulum. The causes that are contained within the structure of the system itself (such as the interaction of a pendulum’s position and momentum that produces oscillations).

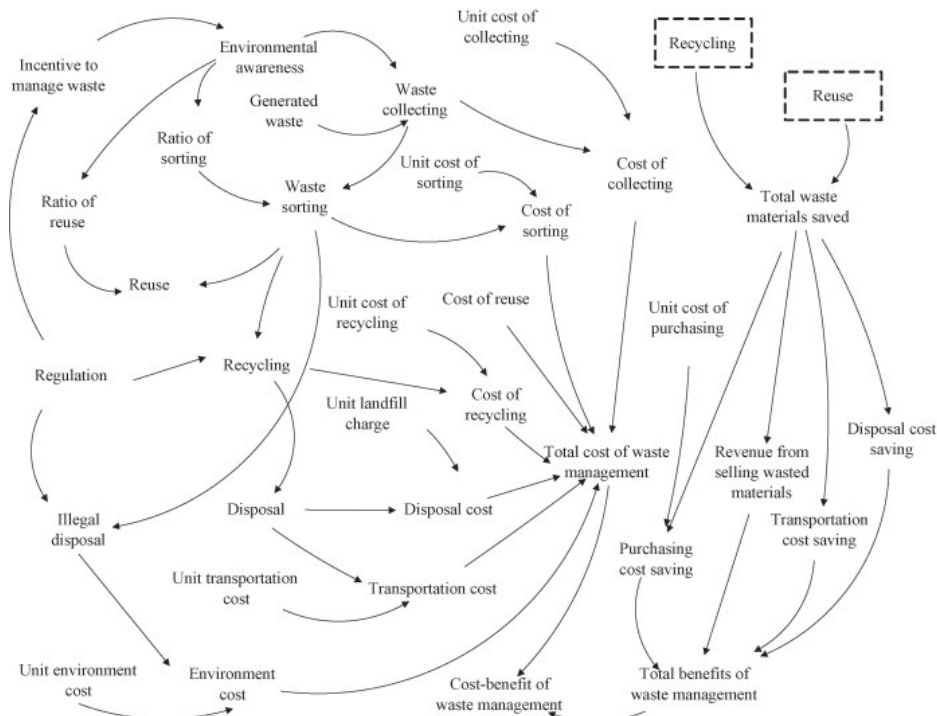


Figure 2.1.2A. Endogenous System

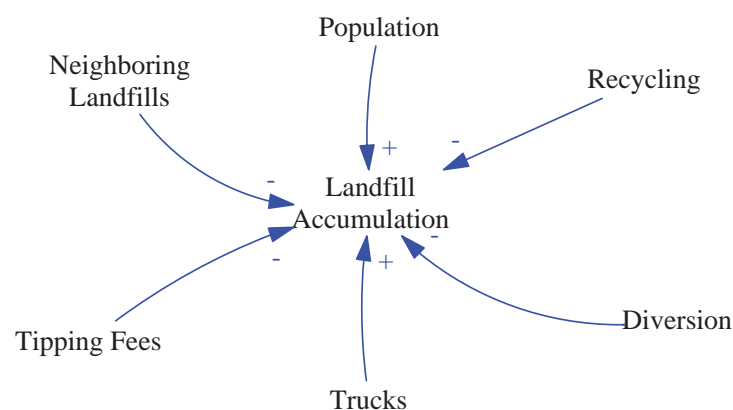
7 Kirkwood, 1-5

8 Adapted from Wikimedia Commons, Author Svarnyp

9 See Appendix A

Those aspects that arise from relationships within the system itself uncover patterns of behavior when provoked by an external, exogenous force. Therefore, policy levers significantly affect endogenous perspectives. Figure 2.1.2A<sup>10</sup> is an example of an endogenous system, whereby nearly all factors are influencing each other and creating a complex web of interdependencies.

Figure 2.1.2B shows an exogenous system, where outside forces are influencing landfill accumulation. It is important to note that exogenous variables are relative to the investigator's definition of system boundary. A figurative line must be drawn between the landfill accumulation and tipping fees such that the fees are not circularly affected by the landfill. In reality, this may not be the case; it may be possible that as landfill space is nearing its limits, tipping fees may subsequently increase. However, the model builder decided that this is a one way effect, naming tipping fees, trucks and population as exogenous variables.



**Figure 2.1.2B. Exogenous System**

An endogenous model affected by an earthquake can have numerous repercussions, oftentimes leading to arduous modes of recovery. A conceptual causal loop model by Chiang and Jin in Figure 2.1.2C<sup>11</sup> shows the web-like nature of post-disaster scenarios, with multiple variables aiming to correct to a predetermined recovery goal state.

### 2.1.3 Stock and Flow Structures

Stocks are considered levels and the flows, or rate per unit time, that affect them are essential components of systems structure. A map of causal influences and feedback loops is not enough to determine the dynamic behavior of a system. A constant inflow yields a linearly rising stock and a linearly rising stock creates a system behaving parabolically. Stocks are accumulations and provide snapshots of the state of the system at any given time period being examined. Figure 2.1.3A shows a simplified example of a stock and flow structure relevant to this research.

<sup>10</sup> "A Model for Cost-Benefit Analysis of Construction and Demolition Waste Management Throughout the Waste Chain", Resources, Conservation and Recycling Volume 55, Issue 6, April 2011, pp. 604-612

<sup>11</sup> Ho, Yufeng, Chienhao Lu and Hsiao-Lin Wang. *Dynamic model for earthquake disaster prevention system: a case study of Taichung City, Taiwan*. Thesis. Taichung, (Taiwan: Graduate School of Architecture and Urban Design, 2006), 1-23



case would be a transfer rate of material based on the total accumulation affecting outflow. An exogenous variable in this case would be an external effect, such as an earthquake, influencing total inflow rates. The clouds represent an infinite source or sink of values and material.

#### 2.1.4 Delays

A material delay is a delay in physical flow, while an information delay is a delay in perception. Material delays are pertinent to understanding material flow following a disaster, and have large implications on recovery times. A first order delay is one that involves a single stock affecting a flow which is dually influenced by a delay time. For example, in the diagram below (Figure 2.1.4A) “Landfill” stock accumulation is affected by *outflow*, which is postponed by a first-order delay of “Debris Accumulation.” The outflow is calculated by dividing “Debris Accumulation” by the Delay time.

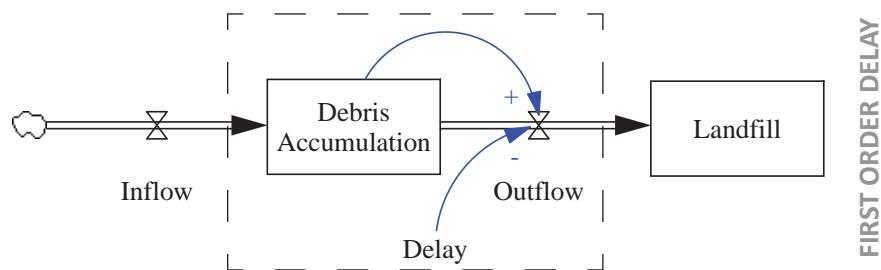


Figure 2.1.4A. First Order Delay, Stock and Flow

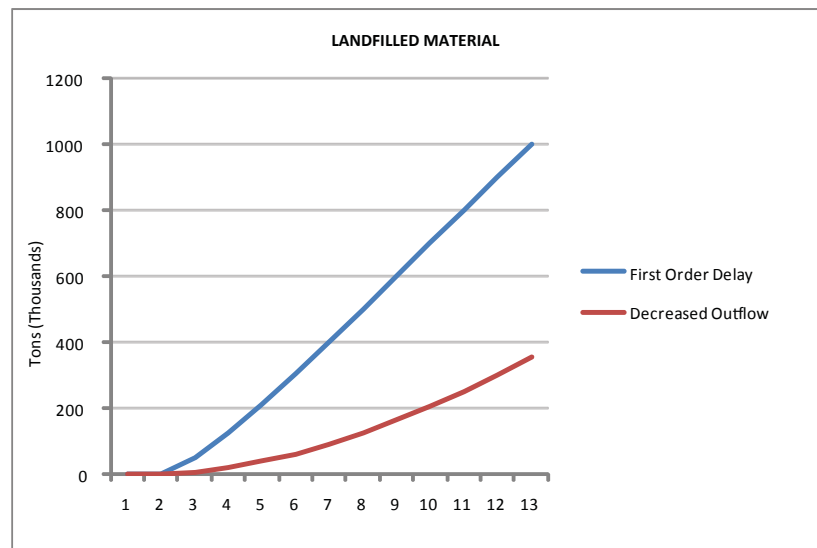


Figure 2.1.4B. Exponential Growth Model Behavior, Landfill Material

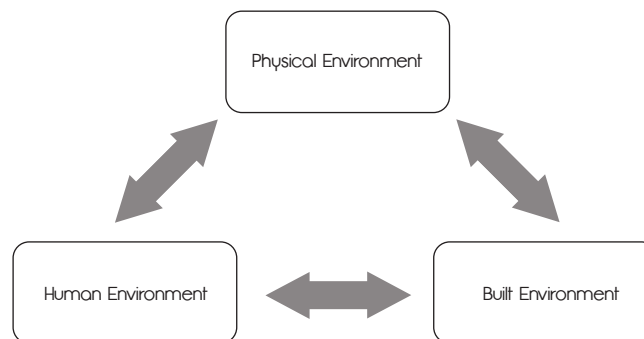
The graphical behavior shows a slow exponential growth of landfilled material since there is no outflow from this stock. If for any reason the delay time is increased, or the “Debris Accumulated” is decreased, the overall outflow leading to “Landfill” will *reduce* in rate. This is shown in Figure 2.1.4B; the decreased outflow with greater delay (red) causes a slower landfill accumulation than a higher outflow rate (blue).



### 2.1.5 System Dynamics for Recovery Analysis

Few studies have used system dynamics to evaluate post-disaster environmental and social systems for recovering communities, either in the emergency phase or in long-term development. However, systems models are becoming increasingly valuable for understanding complicated post-disaster contexts and behavior of factors. Every system modeler must create a specified boundary because the effort is meant to model a question, or scenario, rather than modeling the full system. The scope should focus on several feasible aspects rather than attempting to model the entirety of the situation.

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.” Figure 2.1.5A illustrates this phenomenon.

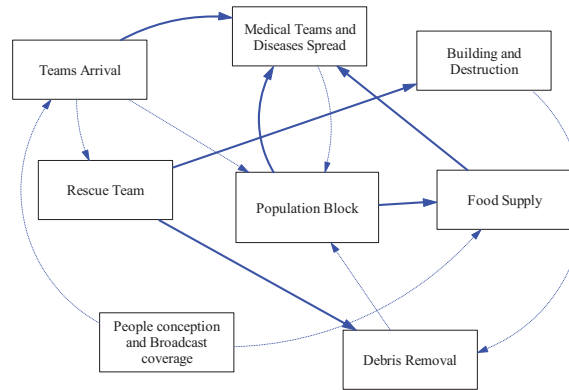


**Figure 2.1.5A. Systems Theory for Disaster Recovery**  
**Source: Phillips, Adapted from Figure 21**

Past researchers that have pursued dynamic modeling of post-disaster scenarios have been able 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<sup>12</sup> 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.<sup>13</sup> The research considered eight block cases, each with its own dynamic model, and all interrelated in the post-earthquake scenario. Figure 2.1.5B diagrams the feedback structure between the eight cases in question. Importantly, this work focuses heavily on post-disaster emergency relief and humanitarian logistics, and posits useful management goals by comparing original-case and a best-case scenario.

12 Ramezankhani, Atefe and Najafiyazdi, Mostafa. “A System Dynamics Approach on Post-Disaster Management: A Case Study of Bam Earthquake.” (International Conference of the System Dynamics Society. Athens, Greece, 2008), 1-34

13 *Ibid* 2



**Figure 2.1.5B. Input and Information Feedback Loop, Bam Earthquake, Iran**

Another related research is that on the Taichung City earthquake in Taiwan conducted by Ho, Lu and Wang, a 7.3M 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.<sup>14</sup> The authors are interested in understanding effects of debris from damaged buildings as a constituent of pollution to the water resources in Taichung City, and map the refuse and water streams simultaneously to test outcomes.

Post-disaster reconstruction is complex to understand 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.<sup>15</sup> 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 in providing similar analyses to San Francisco.

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 it occurring within the next three decades. The benefit is the application of results to anticipatory planning by lending itself to disaster managers for improved preparedness.

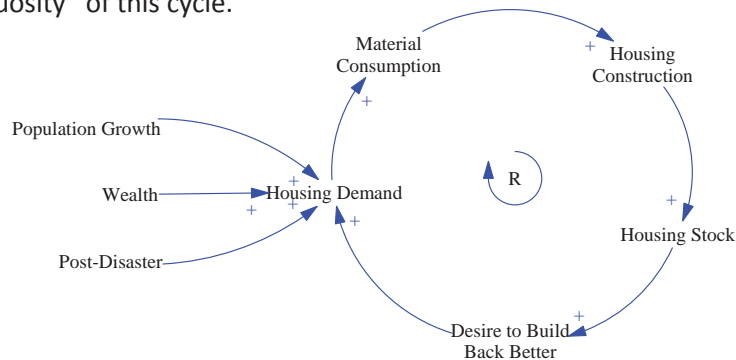
## 2.2 Modeling an Earthquake in San Francisco

Every system dynamics model begins with a causal loop diagram (CLD) with a defined boundary. The driving CLD for this research (Figure 2.2A) illustrates factors that influence housing demand, which effectually circle around to increase demand for housing. For example, an external force of a disaster

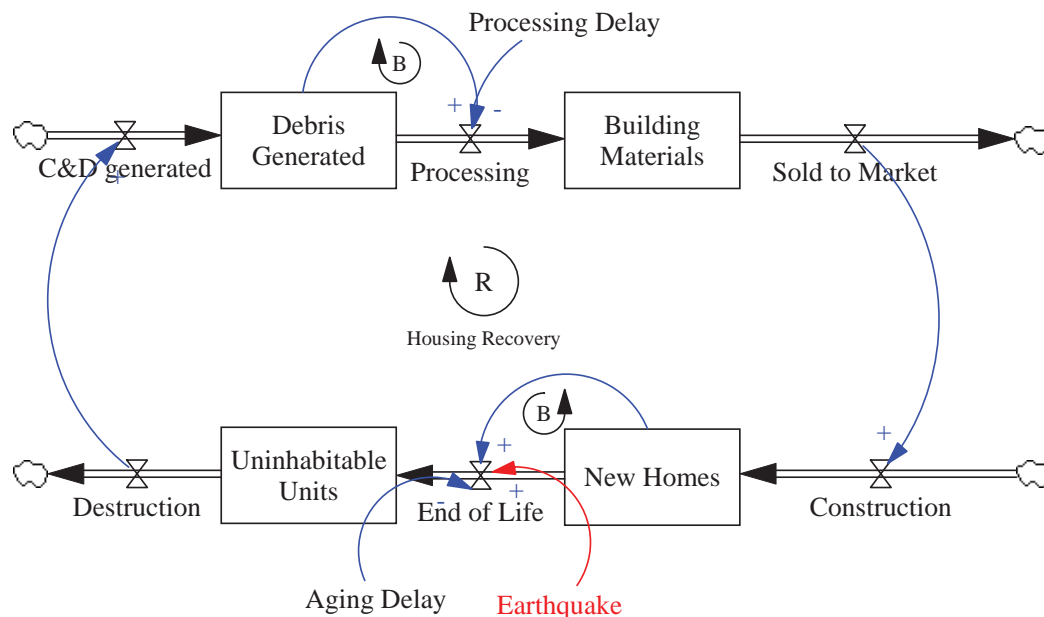
<sup>14</sup> Ho, Lu and Wang, 2006

<sup>15</sup> Quinn, David. *Modeling the Resource Consumption of Housing in New Orleans using System Dynamics*. (Cambridge: Massachusetts Institute of Technology, 2008)

will presumably hurt housing stock, increasing demand for new housing. Subsequently, a push towards reconstruction will require more material, increasing material needs as housing is reconstructed, a desire to build back communities and housing in an improved manner will again relate back to housing demand. This reinforcing loop would be considered virtuous in the way it has been described, but could also work in the opposite direction, decreasing housing demand if no exogenous factors are inciting the system. Each variable within has its own effective variables, causing greater complexity in the model. For example, “Housing Stock” in Figure 2.2A will have components of construction rate and delays that impinge on the “virtuosity” of this cycle.



**Figure 2.2A. Research Causal Loop Diagram**



**Figure 2.2B. Research System Models**

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 2.2B. *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 this housing recovery reinforcing loop.

A comprehensive model will be explained in Chapter 4, including all influencing variables and more detailed descriptions of important stock and flow structures.

## 2.3 Debris Management

The Rio Declaration of 1992 described the environmental challenges for the 21<sup>st</sup> century, implying that disaster waste be managed according to principles of best available technologies and not incur excessive costs. Related to this, Lauritzen comments on debris handling by stating that, “it is very important to remember that emergency action and short term activities based on rapid reactions might not comply with long term consideration and environmental policies. In particular, uncontrolled handling and mixing of wastes can be very difficult to sort out later”<sup>16</sup> Therefore, pre-disaster planning for post-disaster debris management becomes a fundamental condition of overall recovery and environmental protection. Many classes of issues exist in disaster planning, making it a convoluted and oftentimes unpredictable aspect of disaster planning. Debris management is greatly predicated on the type of disaster and the urban fabric of the susceptible city, along with other factors further complicating matters. The Community Action Plan for Seismic Safety estimates 14 years of routine solid waste management to clear the debris generated from one 7.2 magnitude earthquake.<sup>17</sup> The following subsections describe components that influence disaster debris management and recyclability.

### 2.3.1 Emergency Demolition

“In the emergency phase immediately after an earthquake, all efforts are concentrated on rescuing lives, knowing that persons may survive up to 7 days and nights trapped in ruins. It becomes necessary to choose the demolition methods that are rapid to effectively rescue people. On the other hand, care should be taken that no future uncontrolled collapse is provoked, thus increasing risk to trapped people. It is recommended that local authorities make long-term strategies for the disposal of all wastes, including wastes from the emergency demolitions. If waste streams are not planned and controlled initially, a number of problems will arise later in reconstruction and much effort will be expended on moving waste from one location to the next.”<sup>18 19</sup>

### 2.3.2 Transportation

The movement of emergency vehicles, equipment for debris removal, and collected debris is a

---

16 Lauritzen, E.K. “Emergency Construction Waste Management.” (*Safety Science*, 1998: 45-53., 1998), 52

17 ATC 52-1, 2010

18 *Ibid*, 50-52

19 Appendix C for more information on waste management

pressing issue proceeding a disaster. According to the Associated Bay Area Governments, traffic in San Francisco was paralyzed for three months following the Loma Prieta earthquake. Personal travel will certainly be affected following a disaster, but the movement of freight will be a major issue for an efficient and timely recovery operation. Identifying the type of debris generated may aid in prioritizing this transport. While inert C&D debris are the direct result of an earthquake, the indirect wastes such as spoilage of foodstuffs and generation of waste at the response sites may become a high priority to ensure public



**Figure 2.3.2A. Windshield Survey Priority Lifelines, San Francisco**  
**Source: Disaster Debris Management Plan, San Francisco, 2010**

health. Variables that must be evaluated in assessing transport options include the amount of debris generated, damaged infrastructure, region, land use and the type of debris generated. In understanding these variables and the resources required to remove debris, landfill and recycling facility capacities as well as hauling times should be determined.<sup>20</sup>

“The greatest transportation issue will be mobility in terms of road outages and bottlenecks which will encumber debris removal. In most cases, timely debris removal is accomplished by transporting the collected material to a temporary storage site where separation operations may or may not take place and then to a recycling or disposal site. While this may be the most efficient for quick removal of debris, it is not as cost effective as direct transport from the point of collection to the recycling or dis-

posal site.”<sup>21</sup> A thorough explanation of debris processing is described in Section 2.5.

The Debris Management Plan for San Francisco has delineated the following lifelines map (Figure 2.3.2A) for primary, secondary and tertiary roads required for accessing critical points in the city. These indicate the priority of road clearance.<sup>22</sup>

### 2.3.3 Case Studies of Disaster Debris Recycling

Reports on debris removal following Hurricane Andrew in South Florida which struck in 1992 have shed light on problems of waste hauling and dumping logistics.<sup>23</sup> Area landfills reached permitted capacities and the operation of eighty burn sites was chosen over opening more landfills. This was implemented in attempts to avoid the landfill crisis created in North Carolina by Hurricane Hugo where 14 years worth of waste was landfilled during the cleanup efforts.<sup>24</sup>

Los Angeles is another case where proactive recycling operations were conducted by Hayden Brother Engineering following the Northridge earthquake in 1994. Coke describes the bold efforts in recovering material through quick and effective decision making after the disaster, and incentivizing contracts for debris recovery:

“The contract required that 80% of the debris processed be recycled. It stipulated a base rate of \$25/ton of earthquake debris with provisions to pay \$27/ton for achieving a 90% recovery rate. The contract further specified recovery of specific items, including dirt, yard waste, metals, concrete block and wood. The Los Angeles Sanitation District utilized the dirt, crushed concrete, and yard waste at the landfill while the contractor must market the remaining materials. During the startup phase, the operation was able to process 500 tons per day and eventually reached a 1500 tons per day processing rate with consistent recovery rates of over 90%. During the first six months of operation, an average recovery rate of 93% was recorded with the diversion of 554 tons of metal, 1911 tons of wood, 47,437 tons of dirt, 41,873 tons of concrete, 1,532 tons of green waste and 31 tons of cardboard.”<sup>25</sup>

These case studies provide important lessons on waste management for San Francisco, including economic incentives, environmental concerns, and supply-driven contracting. The following section further examines disaster debris recycling and potential values from material recovery in the aftermath of a disaster.

## 2.4 Disaster Debris Recycling

Though disaster debris recycling is the environmentally responsible approach in managing building debris following an earthquake, its viability depends on several factors:

21 Reinhart, 27

22 City and County of San Francisco, Public Works and Engineering Annex. *Appendix B: Disaster Debris Management Plan*. (San Francisco: City and County of San Francisco, 2010)

23 Donovan 1992 as cited by Reinhart, 11

24 Reinhart, 11

25 Coke, 1995 as cited by Reinhart, 15



- “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.”<sup>26</sup>

Processing prior to recycling of debris includes de-nailing and chipping for wood, removal of mortar for bricks, crushing for concrete, and grinding for gypsum. More in-depth descriptions of debris processing can be found in the Appendix C. 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 debris since they cannot be easily recycled, and must be treated in other ways when attempting disposal.

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.<sup>27</sup>

#### 2.4.1 Landfills

“The most common practice for disposing of disaster waste is using landfill. Although landfilling might be warranted immediately following a disaster, continued use of landfills throughout the reconstruction period exacerbates environmental hazards such as methane generation and ground water contamination. Landfills can often hinder sustainable development and cause significant economic and environmental damage. Despite these warnings, most construction and demolition waste goes to landfills, thereby increasing the burden on landfill loading and operations.”<sup>28</sup>

“Although landfill capacity is available nationwide, specific areas report problems with the lifespans of their landfills. The total number of landfills appears to have declined in recent years. Disasters can claim that life span overnight. Thus, careful use of permanent landfills has to be ensured so that disaster prone cities do not shortchange the routine solid waste disposal. Generation of municipal solid waste increases annually, and evidence suggests that the per-person amount of waste generation has risen over the past

---

26 Solis *et al.* as cited by Reinhart

27 Appedix C

28 Baycan and Petersen, 2002; Peng *et al.*, 1997; Ajayi *et al.*, 2008 as cited by Karunasena, 2011, 257

several decades.”<sup>29</sup>

San Francisco is contracted with Altamont Landfill in Livermore, California, nearly 60 miles east of the City.

#### 2.4.2 *Transfer Stations*

A Transfer Station is a short-term material staging site, typically a midpoint between the origin of waste and the landfill site for dumping. It is the only means to salvage materials after it has been collected by waste trucks. As mentioned above, transfer stations and reprocessing facilities play a central role on the fate and quality of disaster debris. Staging sites (empty sites such as parking lots) in the urban context become overflow for transfer and processing centers, but must be created and maintained with extreme caution. These sites fall under danger of environmental implications if the debris remains staged for long periods of time with no chance for removal. In these cases, it becomes critical that disaster debris recycling plans consider transferability and processing of material following its staging.

“Regarding the recycling of debris, the assessment and classification of the damage to buildings can give an idea of the amount and quality of the building waste and what is to be expected. This information is necessary for planning and dimensioning the recycling plants, providing optimal equipment and choosing the best location to implement the plants.”<sup>30</sup> A FEMA directed methodology for examining potential or past disaster effects, along with the Community Action Plan for Seismic Safety, has provided significant information on building vulnerabilities, probable destruction and debris generated. This information has been used as raw data for this research.

The quality of debris is also important in that it affects the quality of the recycled products, and thereby the possibilities for reuse. Although the type of buildings indicate the quality of the debris, it is also determined by demolition work and site clearance. Traditionally, disaster debris is collected quickly without sorting so reconstruction can start immediately; however, this causes the building debris to become mixed with other debris, and thereby impedes debris recyclability.<sup>31</sup> Although sorting on site is largely difficult when debris must be cleared with immediacy, the utility of transfer stations and staging sites become an essential first step in material recovery. If bypassed, opportunities for recycling are lost; in other words, planning and managing of transfer stations should not be understated if landfill diversion is desired.

#### 2.4.3 *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 recycled product life.<sup>32</sup> Information

29 Environmental Protection Agency, 2006 as cited by Phillips 2009, 124

30 Lauritzen, E.K. and C. de Pauw. *Disaster Planning, Structural Assessment, Demolition and Recycling* (Rilem Report, 9). (London: Spon Press; 1st edition, 1994).

31 *Ibid*

32 Tukker and Gielen, 1994, as cited by Woolley, G.R., Goumans, J.J.J.M and P.J. Wainwright; *Waste materials in construction WASCON 2000*.



from the San Francisco Debris Management Plan<sup>33</sup> has revealed that woody debris will be the predominant material generated from destroyed housing. 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 in the following.<sup>34 35</sup>

#### 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
- Reuse for making formwork and shuttering in 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 a 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 as a driving assumption of this case.

33 Appendix C

34 Addis, William. *Building with Reclaimed Components and Materials: A Design Handbook for Reuse and Recycling*. (9London Sterling, VA: Earthscan, 2006).

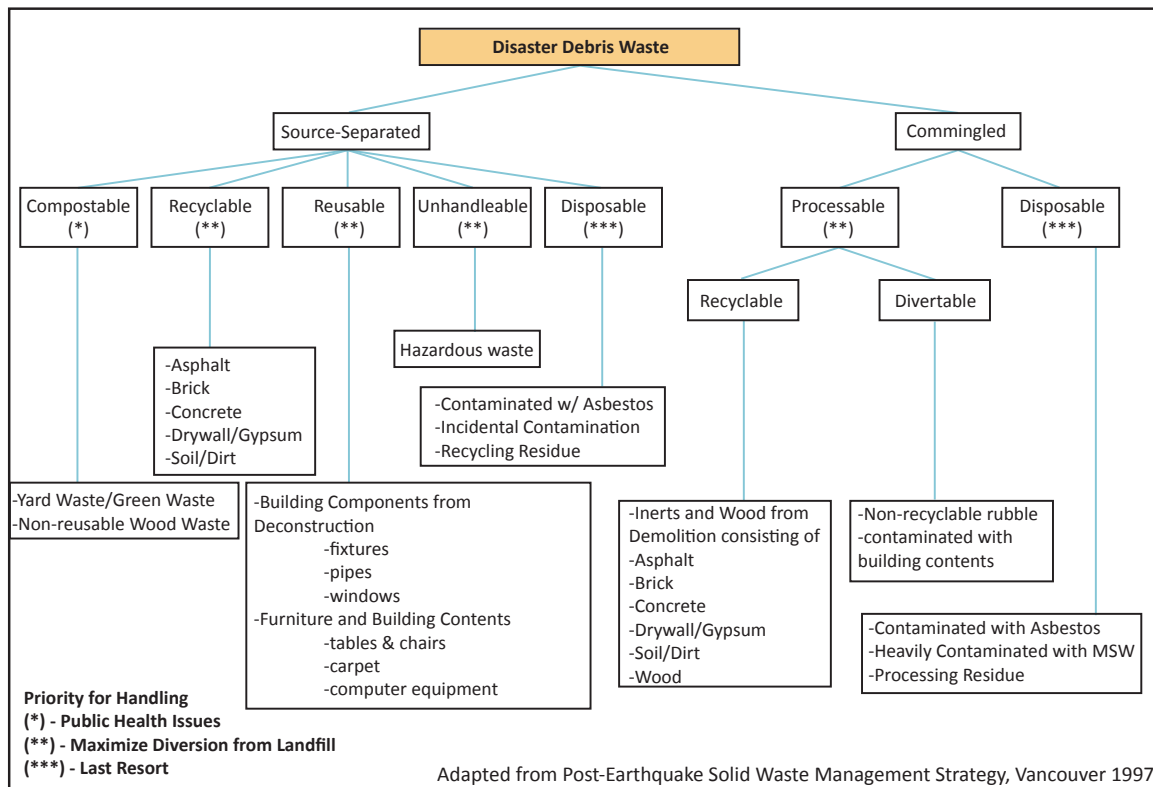
35 Appendix D for more information on material recyclability

## 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 percent of the gravel aggregate, such as for concrete slabs for the 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.<sup>36</sup>

## 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 dependent 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 needed components made from new steel.

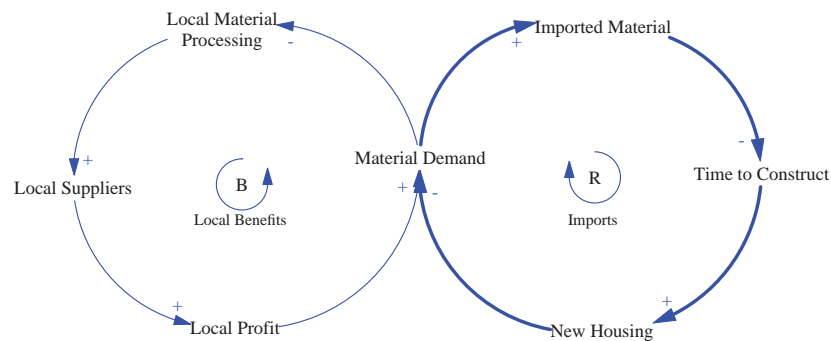


**Figure 2.4.3A. Sample Post Earthquake Disaster Waste Classification**

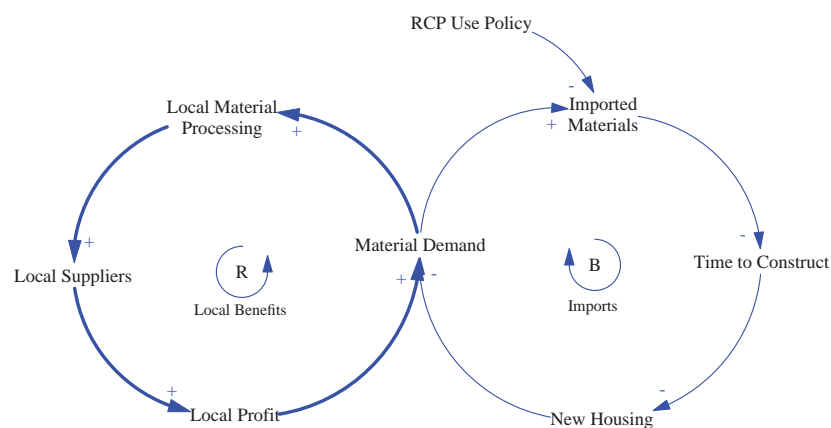
Figure 2.4.3A explains several management techniques for disaster debris handling. This sample classification scheme for post-earthquake disaster debris is based on the waste source, degree of separation and potential disposal options. It is general description of how disaster debris is typically managed by municipal authorities.

## 2.5.4 Recycled Content Products and Imported Building Materials

A leading concern in understanding 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.



**Figure 2.4.4A. Causal Loop Diagram, Imported Materials**



**Figure 2.4.4B. Causal Loop Diagram, Recycled Content Products**

The visuals in Figures 2.4.4A and 2.4.4B show the reinforcing cycle of using imported material goods as decreasing the time to construct, since this is a familiar method of acquiring building products, to increasing new housing and decreasing 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. More details on such policy notions are explained in Chapters 4 and 5.

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%<sup>37</sup>. It is important to highlight that this value is aggregate; different materials have significantly different recycling rates, but the collective recyclability percentage is nearly 72.5%. 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 this simplified study, this option for waste management is defined to be beyond the scope of this research, but can certainly be applicable in post-disaster cases.

#### 2.4.5 Problems with Disaster Debris Recycling

Though the benefits of recycling debris seem obvious, problems do exist in actualizing recovery of 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 many 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.”<sup>38</sup>

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 to note is that a proposed 7.2 M earthquake will not be isolated to 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<sup>39</sup>, an occupation that has high correlations with 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 is infeasible.

37 Appendix D

38 De Pauw and E.K. Lauritzen, 114-116

39 CAPSS 52-1, 45

Yet 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 a community-driven and integrated approach to recovery. The following chapters define these aspects, and investigate the effects of policy levers on the behavior of the post-disaster system.



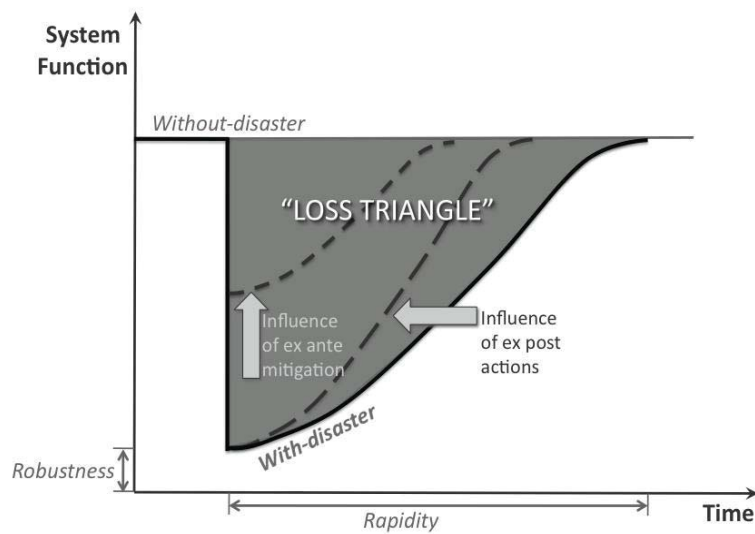
## DEFINITIONS AND METHODOLOGY OF DATA GATHERING

**re·cov·er·y** [ri-kuhv-uh-ree]

noun

1. The regaining of or possibility of regaining something lost or taken away.
2. Restoration or return to any former and better state or condition.

*Random House Dictionary*



adapted from Bruneau, et al,  
2003





### 3.0 Definitions and Methodology for Data Gathering

Contents of this chapter will cover essential variables used as part of the systems methodology that has been employed to model a post-disaster San Francisco. Descriptions of these factors will verify the complexities of not only creating such a model, but also of the challenges the City will face in the aftermath of an earthquake.

#### 3.1 Area of Focus

This research investigates the repercussions of the next large-scale earthquake in the City and County of San Francisco and speculates on waste handling and housing reconstruction. Since rigorous studies have been completed in the past on the earthquake effects in SF, a large quantity of empirical data is available for public peruse. Therefore, this work leveraged accessible information through various research and non-profit entities, to be able to conduct a specified analysis. In the future, this thesis could be expanded to the larger Bay Area, given that localized data on housing and debris generation is made available.



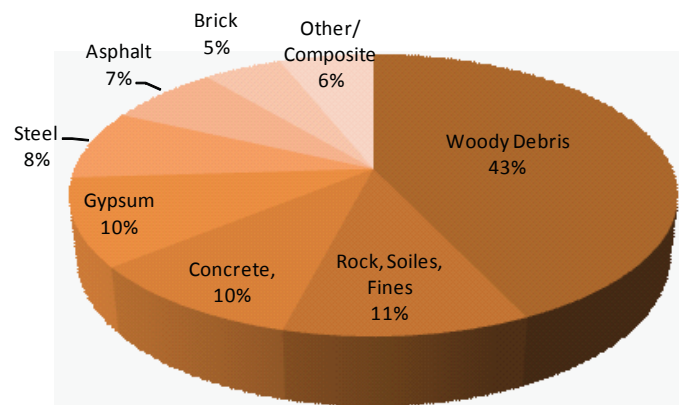
**Figure 3.1A. Geographic Boundary of Research, City and County of San Francisco**

Impact analysis and debris generation studies have been conducted by FEMA's HAZUS methodology to estimate the amount and types of damage that could occur in an earthquake scenario. HAZUS software is a risk assessment methodology for analyzing potential losses from floods, hurricane, and earthquakes. In HAZUS, current scientific and engineering knowledge is coupled with graphic informa-

tion systems (GIS) to produce estimates of hazard-related damage before or after a disaster occurs.<sup>1</sup> The analysis using HAZUS has been greatly customized to represent the unique buildings and conditions in San Francisco.<sup>2</sup> The Community Action Plan for Seismic Safety has conducted an in-depth overview of the report as it relates to damages in San Francisco following four specific scenario earthquakes.<sup>3</sup> The analysis of magnitude 7.2 San Andreas case provides the baseline data for the breadth of this research.

### 3.2 Challenges

A few challenges arose in searching for required data in conducting the simulation analyses; namely, that of debris classification and tonnage of construction material per housing unit. Though HAZUS has provided overall estimations of light-weight and heavy-weight debris,<sup>4</sup> categorization of the debris make-up has not been defined. However, since building debris is similar in composition to inert construction and demolition (C&D) debris, information from the California Integrated Waste Management Board<sup>5</sup>, along with C&D analysis of other counties and states<sup>6</sup> has been extrapolated to better inform the total make up of debris tonnage. Research shows that most C&D debris is woody waste (up to 43%) with concrete and gypsum also making a large proportion of the generated debris.<sup>7</sup>



**Figure 3.2A. C&D Waste Characterization, California**

Acquiring material tons per housing unit proved to be a difficult set of data to obtain from public sources. This information is critical in understanding how recycled content product (RCP) materials can be put back into use as construction material for devastated housing stocks, which influences the hypothetical recovery state. The author calculated tons per unit data with help from the Applied Technical Council reports and interpolation of single-family and multi-family unit construction makeup, with application of RS Means cost and construction data. The applied value for average ton per housing unit is

- 
- 1 Federal Emergency Management Agency, <[www.fema.gov](http://www.fema.gov)> (accessed November 3, 2011)
  - 2 ATC 52-1
  - 3 ATC 52-1A
  - 4 Appendix C
  - 5 CalRecycle, 1997
  - 6 DSM Environmental Services, Inc. *2007 Massachusetts Construction and Demolition Debris Industry Study*. Massachusetts Dept. of Environmental Protection, 2008.
  - 7 Appendix D

34.5 tons<sup>8</sup>, using an average of standard single-family and multi-family units.<sup>9</sup>

### 3.3 Description of Housing

Assessment of building use and vulnerability is described in the following subsections.

#### 3.3.1 San Francisco Residential Units

“San Francisco is comprised of approximately 160,000 buildings ranging from small homes built over a century ago to newly-constructed high-rises. Densities of buildings and their purpose is varied throughout the city, where many of the districts – including the Sunset, Twin Peaks, Ingleside, and the Excelsior are primarily residential. About 95% of all buildings in the city are residential, accounting for 70% of all building value.”<sup>10</sup>

Table 3.3.1A classifies the various types of buildings and the estimated cost of replacement for each. As can be noted, single-family and multi-family housing make up the largest percentage of building stock in San Francisco, which, when combined with inherent structural vulnerability, become extremely problematic in a disaster event.

**ESTIMATED NUMBER AND VALUE OF BUILDINGS USED FOR  
VARIOUS PURPOSES IN THE CITY**

Building Use	Estimated Number of Buildings <sup>a</sup>	Estimated Replacement Value of Buildings <sup>b</sup> (\$ Billions)
Single-family Houses	112,000	\$53
Two unit Residences	19,000	\$22
Three or more unit Residences	23,000	\$45
Other Residences <sup>c</sup>	800	\$13
Commercial Buildings	5,000	\$48
Industrial Buildings	2,100	\$7.7
Other <sup>d</sup>	700	\$2.6
Total <sup>e</sup>	160,000	\$190

a. These numbers are estimates for 2009.

b. These figures represent an estimate of the cost to replace or reconstruct a building in 2009. They do not include the value of the land the building sits on or a building's contents. Replacement values are significantly different than real estate prices or assessed valuation. Building value is based on square footage from San Francisco Assessor's Tax Roll, not the estimated number of buildings.

c. Other Residences includes hotels, motels, nursing homes, and temporary lodging.

d. Other includes religious and educational buildings listed in the Assessor's Tax Roll.

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

Sources: This study, San Francisco Assessor's Tax Roll, Census data, San Francisco Planning Department, and San Francisco Department of Building Inspection.

**Table 3.3.1A. Building Classification, San Francisco. Cited from CAPSS Report 52-1, Table 2**

8 Assumed a 675 square foot average unit size of SF and MF unit, Appendix B

9 Appendix B for floorplan of typical unit

10 ATC 52-1, 1-15

For this research, wood frame edifices are concerning as they are the most vulnerable type of construction, and constitute the largest proportion of building stock in San Francisco City (see section 3.3.2). Table 3.3.1B indicates construction type and estimated replacement value which estimates that the replacement value for all buildings accumulates to a staggering \$190 billion. This table is also used to approximate the percent of buildings that have a minimum standard of life-saving construction through retrofitting, totaling a dismal 10% of the entire building stock.

**ESTIMATED NUMBER AND VALUE OF BUILDINGS OF VARIOUS STRUCTURAL TYPES IN THE CITY**

Structural Type	Estimated Number of Buildings <sup>a</sup>	Estimated Replacement Value of Buildings <sup>b</sup> (\$ Billions)
Wood-frame single-family soft-story	60,000	\$29
Wood-frame two unit residential soft-story	10,000	\$12
Wood-frame three or more unit residential soft-story <sup>c</sup>	13,000	\$26
Wood-frame single-family not soft-story	52,000	\$24
Wood-frame two unit residential not soft-story	9,000	\$10
Wood-frame three or more unit residential not soft-story <sup>c</sup>	6,000	\$12
Concrete built before 1980 <sup>d</sup>	3,000	\$19
Tilt up concrete	200	\$0.8
Modern concrete <sup>e</sup>	600	\$4
Steel moment and braced frame	1,500	\$21
Unreinforced masonry, retrofitted <sup>f</sup>	1,500	\$5
Unreinforced masonry, unretrofitted <sup>g</sup>	400	\$1
Other <sup>h</sup>	4,200	\$27
Total <sup>i</sup>	160,000	\$190

- The numbers of buildings are estimates for 2009 based on available studies and engineering estimates.
  - These figures represent an estimate of the cost to replace or reconstruct a building in 2009. They do not include the value of the land the building sits on or a building's contents. Replacement values are significantly different than real estate prices or assessed valuation. Building value is based on square footage from San Francisco Assessor's Tax Roll, not the estimated number of buildings.
  - The City is currently discussing a program to require evaluation and possible retrofit of residential wood-frame buildings with 3 or more stories and 5 or more residential units. Some but not all of these buildings have a soft-story. There are an estimated 4,400 of these buildings with an estimated replacement value of \$14 billion.
  - Concrete built before 1980 includes concrete shear wall buildings and concrete frames with masonry infill walls. The 1980 date was chosen to be consistent with the survey work of the Concrete Coalition (see footnote, next page, for a description of the Concrete Coalition).
  - Modern concrete buildings include concrete moment frame and shear wall buildings built after 1980.
  - This includes buildings retrofitted under the City's program.
  - This includes buildings in the City's retrofit program that have not yet received their certificate of completion, and buildings not included in the City's retrofit program, such as buildings with fewer than five residential units.
  - Other includes steel frame with cast in place concrete walls or masonry infill walls, reinforced masonry buildings, and non-residential wood-frame buildings.
  - Numbers in table have been rounded, which can make totals differ from sum of columns or rows.
- Sources: This study, Concrete Coalition, and San Francisco Department of Building Inspection.

**Table 3.3.1B. Construction Classification, San Francisco. Cited from CAPSS Report 52-1, Table 4**

### 3.3.2 Structural Vulnerability

Buildings represented in Table 3.3.1A respond to earthquake shaking depending on the materials they are constructed from, size and shape of units, engineered design, quality of construction, maintenance and age. Some building types are known to have specific weaknesses in earthquakes and are prone to concentrated damage after a quake. Since the San Andreas fault runs through the peninsula, a sizeable magnitude earthquake will likely have deleterious affects for soft-story buildings, concrete

buildings built before 1980, unreinforced masonry bearing wall buildings, welded steel moment frame buildings, concrete tilt-up buildings, older steel buildings with masonry infill walls, and hillside buildings. Given that the focus is on residential housing, which are typically of soft-story construction, vulnerability for such structures are described in detail.



**Figure 3.3.2A. San Andreas Fault, USGS**

### Soft-Story Buildings

The first floor in many San Francisco homes are significantly weaker and more flexible than the stories above. The weakness at the ground level usually comes from large openings in perimeter walls, due to garage doors or store windows, and/or few interior partition walls. During strong earthquake shaking, the ground level walls are unable to support the stiff and heavy mass of the above floors. The walls may shift sideways until the building collapses, crushing the ground floor.

This type of weakness, called a soft-story, is common in single-family homes, where the dwelling space sits over a garage, and multi-family buildings, which may have parking or large and open commercial space at the ground level.”<sup>11 12</sup>

These soft story account for an estimated 25% of buildings that are unusable after a disaster, meaning that damage is so heavy that residents must be relocated until the unit is repaired or reconstructed. San Francisco Urban and Planning Association has anticipated how housing will be impacted in various districts in the city.<sup>13</sup> Figure 3.3.2B shows the unusable housing by district.

To fully understand repercussions on the construction and demolition waste stream proceeding an earthquake, aggregate information on the degree of unit damage is employed within the scenario simulation. CAPSS report 52-3 has compiled a survey of 2,800 residential units in San Francisco to project safety tagging for a subset of housing following a 7.2 earthquake. “In California, inspectors

11 ATC 52-1, 9-10

12 See Appendix B for more information on seismically vulnerable buildings

13 San Francisco Planning and Urban Research, *Safe Enough to Stay*, 2012, Table 3, 14



## EFFECTS ON HOUSING BY DISTRICT

Different neighborhoods have different housing stock and soil conditions, which means the degree of earthquake damage will vary across the city. After a Magnitude 7.2 earthquake on the San Andreas Fault, we expect the percentages of housing in red to be unusable, meaning not safe enough for residents to shelter in place.

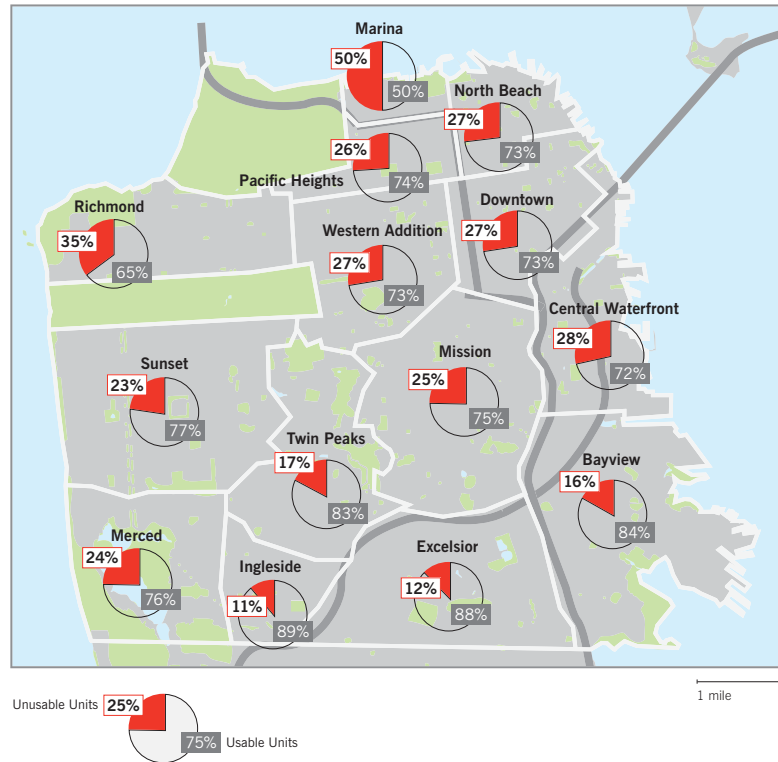


Figure 3.3.2B. Unusable Housing by Neighborhood, cited from SPUR 2012

use a system of red, yellow and green tags to evaluate the safety of structures after earthquakes. This system provides information to owners or renters as to an initial assessment of the structural integrity of the building, as it provides local and state officials with a preliminary understanding of the extent of the damage.” However, Comerio notes that “tag color is not completely representative of the degree of damage.”<sup>14</sup>

The various tagging-schemes are described by the Applied Technical Council 20-1 as follows<sup>15</sup>:

- Green Tag (Inspected): No apparent hazard is found although repairs might be required. Residents should be able to continue to occupy these structures.
- Yellow Tag (Restricted use): A hazardous condition exists or is believed to exist that requires restrictions on the occupancy or use of the structure. Residents might be able to continue to occupy some, but not all, of these structures, with restrictions.
- Red Tag (Unsafe): Extreme structural or other hazard is present. There might be imminent risk of further damage or collapse from creep or aftershocks. Occupants cannot use any of these buildings. Some are collapsed. Some would need to be demolished, but others can be repaired.

Red-tagged units are of particular relevance since these indicate that housing is damaged be-

14 Comerio, Mary. *Disaster Hits Home: New Policy for Urban Housing Recovery*. Berkeley: University of California Press, 1998.

15 ATC 52-3, 15-16

yond repair or completely collapsed. *An assumption for this research is that red-tagged units are either completely collapsed, or must go through the deconstruction and demolition waste stream.* Delays in housing repair may be shorter than rebuilding delays, but are much more ambiguous since levels of required restoration per building are uncertain. For this reason, repair times have been addressed in research but are left exclusive to the investigative model. See Chapter 4 for additional details on housing unit life-cycle.

Within the system model, it is calculated that 36% of the red-tagged units will be immediately collapsed buildings due to the violent shake, and 64% will be tagged for severe damage and will require complete rebuilding.<sup>16</sup>

### 3.4 Road Closures and Transfer Delays

Debris becomes increasingly problematic when lifelines are blocked due to building collapse. The Associated Bay Area Governments (ABAG) have mapped out potential road blockages in the San Francisco Bay Area. ABAG estimates a total of 335 road blockages will occur in a 7.2M incident, out of a total 866 road closures in the entire Bay Area. Seventy-three percent of the closures in San Francisco are expected to be generated by building damage, due mainly to the degree of urbanization within the City.<sup>17</sup> Using ABAG hazard maps and GIS extrapolation, an estimated 25% of 1,220 road miles will be blocked immediately after the earthquake. ABAG also mapped the timeline of street and freeway closures after the Loma Prieta and Northridge Earthquakes, shown in Figure 3.4A and 3.4B.

ROAD CLOSURES  
SAN ANDREAS 7.2M

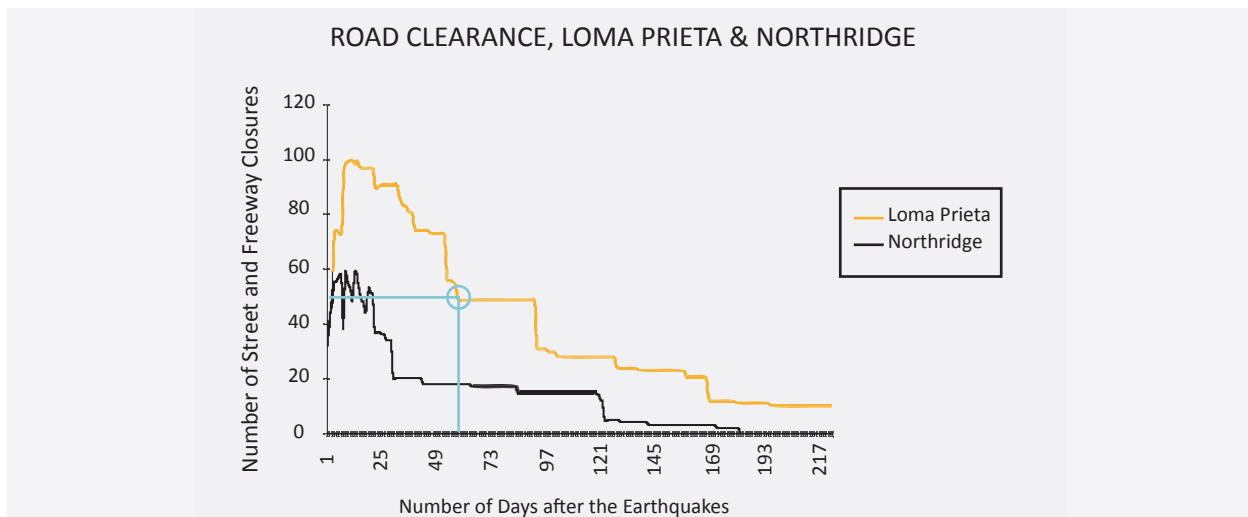
County	San Francisco	Bay Area
Ground Shaking	10	90
Faulting	0	163
Liquefaction	7	40
Water Pipelines	5	38
Gas Pipelines	1	8
Landslides	7	66
Building Damage	246	278
Hazmat Incident	1	6
Structural Damage	5	41
Miscellaneous	52	135
Total	335	866

Table 3.4A. Road Closures, adapted from ABAG 2003

16 Appendix B

17 ABAG, *Road Closures*, 2003 < <http://www.abag.ca.gov/bayarea/eqmaps/eqtrans/pastex.html>>

According to ABAG, “the pattern of closures over time during the first month increases, as public officials barricade areas deemed to be unsafe. At the same time that these officials reopen streets that have been repaired or the hazard has been removed, they close streets to enable more complete repairs or as additional hazards are discovered.”<sup>18</sup> Both cities followed this procedure of road clearing, however, during the first month after the Northridge earthquake, sets of streets that had been closed were opened at the same time that new sets of streets were closed, such that total streets closed never exceeded 60 at one time. Comparing average number of closure days for both event, the Loma Prieta had a 134 day



**Figure 3.4B. Comparison of Loma Prieta and Northridge Road Clearances; ABAG 2003**

average while Northridge cleared roads at an average of 22 days. The former value has been used as basis for an appropriate delay time after a future 7.2 magnitude earthquake.

Another factor influencing debris clearance and material transfer is truck capacity. Open flat-bed solid waste trucks have a maximum capacity of around 15 tons. For the simulation model, it is suggested that 20,000 tons are transferable in two months. This is contingent on the number of trucks available in San Francisco, estimated to have a ceiling of about 20 trucks.<sup>19</sup> Transfer tonnage per month is consequently variegated as per the after-effects of the earthquake event. For example, in a traditional post-disaster scenario, the Army Corps of Engineers provides debris removal assistance, increasing the total amount of tonnage removed per day. This is captured in a table function within system dynamics model via specified output modes based on the time scale. The output graph also illustrates the decline of external support of debris removal and transference through slow reduction of material transfer rates to the city standard of 10k tons / month.

While both the road clearance and truck capacity are inherently linked and contribute to overall reconstruction, another aspect not mentioned in this section is the processing capacity of debris at Material Recovery Facilities (MRF). These are certainly a viable means of ensuring not only debris removal, but material reprocessing, and a crucial component of this investigation. MRF's as they relate to the

18 ABAG, <http://www.abag.ca.gov/bayarea/eqmaps/eqtrans/pastex.html>, 2003

19 Richard Valle, CEO Tri-Ced Recycling, 2011



system model are discussed comprehensively in section 3.6.

### 3.5 Reoccupation of Housing

The Community Action Plan for Seismic Safety approximates that San Francisco’s recovery from a large earthquake could take up to 10 years.<sup>20</sup> Recovery in this analysis refers to the time it takes to refurbish lost residential housing stock, which is determined mainly by degree of damage. Comerio and Blecher have estimated San Francisco’s average rebuilding time using the Loma Prieta and the Northridge earthquakes as case studies. Table 3.5A indicates the relative number of months it will take to tear-down and rebuild housing for occupation. These values are also included as recovery delays in the dynamic model.

Many factors influence the refurbishing of housing units and include some of the following:

- *“Amount of Building Damage.* The amount of damage influences the length of time required for buildings to recover. If there is a lot of damage in the city, all construction work will presumably take longer because many of the construction resources in the Bay Area would be overwhelmed. There may not be enough skilled design and construction professionals to do required work without substantial delay. Additionally, construction materials and equipment may be limited.

AVERAGE TIME REQUIRED TO REPAIR AND REBUILD HOUSING AFTER  
1989 LOMA PRIETA AND 1994 NORTHRIDGE EARTHQUAKES

Building Damage Level <sup>a</sup>	Loma Prieta Average Time to Reoccupy <sup>b</sup> (Months)	Northridge Average Time to Reoccupy <sup>c</sup> (Months)	San Francisco Average Time to Reoccupy After Loma Prieta <sup>d</sup> (Months)
Needed repair	11	25	7
Needed rebuilding	34	36	46

a. Only includes analysis of buildings with enough damage to be deemed unsafe to occupy.

b. Analyzed data from San Francisco, Hollister, and Watsonville.

c. Analyzed data from Los Angeles, unincorporated Los Angeles County, and Santa Monica.

d. San Francisco Loma Prieta results are based on a small dataset, and detailed timing information was not available for all damaged buildings.

Source: Comerio and Blecher ( 2010).

**Table 3.5A. Projected Recovery Time for San Francisco, CAPSS Table 16**

- *Economy at Time of Earthquake.* If the disaster strikes during a period of strong economy, rebuilding would happen at a faster pace than if it strikes during a weak economy.
- *Insurance.* Payments from insurance companies can help finance repair and rebuilding, but they can also lead to delays. Currently, only 6 to 7 percent of San Francisco residents carry earthquake insurance.<sup>21</sup> This means that insurance payments would play a small roll

20 ATC 52-1, 40

21 Marshall, 2010 as cited by ATC 52-1, 42

in financing San Francisco's reconstruction. However, it is common for insurance payouts to take many months, and disputes increase the general delay in reconstruction.

- *Building Use.* Multi-family housing, particularly rental housing, is repaired and replaced significantly slower than single-family housing. Owners have little incentive to rebuild if construction costs cannot be recovered through rents. For units serving lower-income households, access to construction financing becomes especially challenging.
- *Availability of Construction Professionals.* A shortage of skilled workers can cause delays and make construction more expensive, which could lead to additional delays for some owners.
- *Construction Logistics.* Given the density of the urban city, many residences have little excess space to stage construction materials. Streets and sidewalks have tendencies to serve this function, but because they are typically narrow and steep, construction takes longer than it would in a sprawled city. Construction equipment may also be in shortage, causing additive delays."

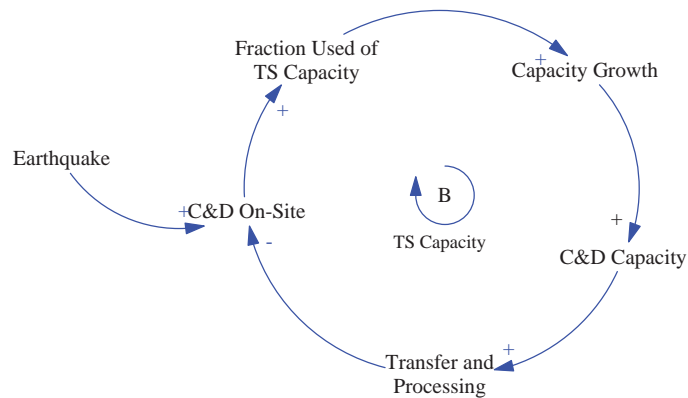
More rehousing delays may exist, however, these mentioned are encapsulated by the 7 months for rebuilding and the average of 46 months for reconstruction, which may include deconstruction and demolition delays as well.

### **3.6 Material Recycling Facility (MRF) and Landfill Site**

As materials are diverted from landfill, these recyclable materials are prepared for shipment to markets in a facility called a materials recovery facility. An MRF is a special type of transfer station that separates, processes, and consolidates recyclable materials for shipment to one or more recovery facilities rather than a landfill or other disposal sites. A transfer station can be described as a processing site for temporary deposition of waste, and is often used as a place where local waste is deposited prior to loading into larger vehicles. It is at transfer stations and MRFs that material recovery is possible. *Transfer Stations and MRFs are used interchangeably throughout this research. It is assumed that reprocessing of certain materials (such as crushing concrete for aggregate) occurs at the MRF, while other materials (such as wood waste or metal) is processed at local eco-industrial sites.*

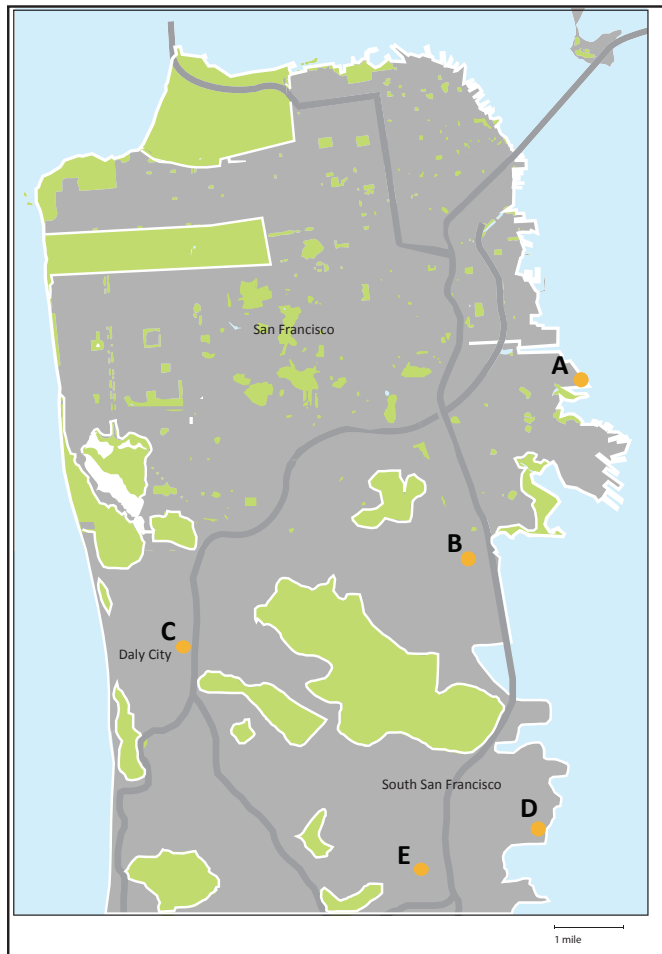
Transfer stations are a vital element in modeling this system in that they provide the required processing of disaster debris for new construction materials. Thus, understanding attributes of transfer stations as they apply to this research are important, especially those of capacity and location.

The causal loop diagram for material recycling facilities (Figure 3.6A) shows a balancing loop of effects following an earthquake. As the amount of debris on site is increased, the processing ability of the material is decreased requiring MRF capacity growth. Growth in this sense is in the additional square footage of space for processing, and includes a proxy for labor and machinery. Once the MRF has more processing power, greater material handling and transference capabilities will allow for removal of the debris on site. This balancing causal loop diagram is translated in a stock flow structure of the driving model described in Chapter 4.



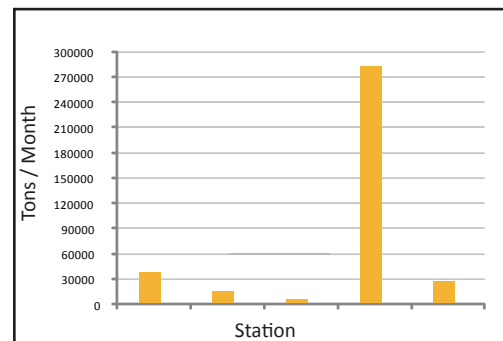
**Figure 3.6A. Causal Loop Diagram, Transfer Stations**

Five transfer stations near the city of San Francisco have been analyzed for throughput volumes of disaster debris processing. All transfer stations in study are within a five mile radius of San Francisco, within San Francisco City, South San Francisco and Daly City. Figure 3.6B shows the location of transfer



**Figure 3.6B. Material Recycling Facilities Studied, SF**

stations, and Tables 3.6B, C and D have information on capacity per MRF. The San Francisco Debris Management Plan from 2010 has described the various transfer station and landfill locations in and around the Bay Area, which amount to about 20 facilities in a one hundred mile radius. The motivation for choosing those MRFs within a close proximity to San Francisco is to explore the city's ability to localize the debris processing, and promote self-efficacious redevelopment following a disaster within the context of the hypothetical scenario. It should also be stated that a 7.2 magnitude earthquake will not only have disastrous effects for San



**Figure 3.6C. MRF Processing Capacity, SF**

Francisco, but the many Bay Area counties. Therefore, the MRFs will be more burdened with material than this research model has suggested. For sake of simplification, however, the five MRFs will provide information on general capacity requirements for C&D material processing, affecting system-wide recovery times.

TRANSFER STATION CAPACITY

	Transfer Station	County	Processing (Tons/Month)	Acres
A	West Coast Recycling Company	San Francisco	27000	4.247
B	San Francisco Solid Waste and Recycling	San Francisco	282000	47
C	Mussel Rock	San Mateo	15000	5
D	Blue Line	San Mateo	37500	10
E	San Bruno	San Mateo	6000	1
Total			367500	67.347

Table 3.6D. Material Recycling Facilities, Location, Acreage and Capacity

Contrary but relevant to transfer stations are landfill sites, which are the bottom tier of the waste stream. From landfill, material recovery is impossible, therefore efforts to avoid dumping material with potential benefit is widely desired. The Altamont Landfill in Livermore, CA is the contracted waste facility for the City of San Francisco. It is nearly 60 miles due east of the city, and has been accumulating San Francisco waste for many years.

Landfill agencies typically have contracts with cities for a certain amount of years. Capacity is determined by throughput per unit time, and therefore, allows total landfill capacity to be described in landfill-years.

Recology is a private waste-collection agency that collects waste from the city. It estimates roughly 1,100 tons of non-recyclable garbage are being produced each day, over 400,000 tons per year from SF City alone. When contract with the Altamont landfill expires in 2015, a new agreement currently under discussion will allow for use of landfill disposal 130 miles north east of the city, with a throughput of 500,000 tons per year.<sup>22</sup> This value is determined to be equivalent to one landfill year, and is used for calculations of cost and capacity in this research.

### 3.7 Demolition and Deconstruction

Two methods for building tear-down are traditional demolition and hand-demolition, also known as deconstruction. Demolition is described as “any wrecking activity directed to the disassembling, dismantling, dismembering of any structure.”<sup>23</sup> Deconstruction as defined by the EPA is the “disassembly of buildings to safely and efficiently maximize the reuse and recycling of their materials.”

22 Higa, Lori. *Neighborhood News*. February 2011 <[http://neighborhoodnewswire.net/index.php?option=com\\_content&view=article&id=116:garbage-companies-talk-trash-over-city-landfill-contract&catid=40:recycling&Itemid=62](http://neighborhoodnewswire.net/index.php?option=com_content&view=article&id=116:garbage-companies-talk-trash-over-city-landfill-contract&catid=40:recycling&Itemid=62)> (accessed January 3, 2012)

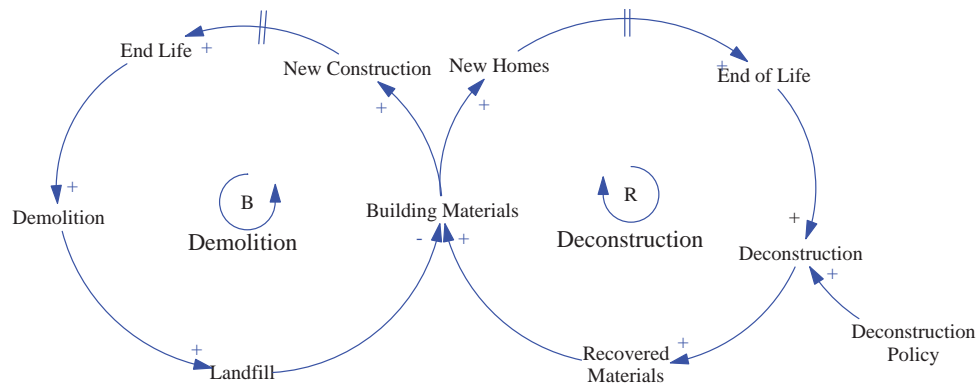
23 Dept. of Energy, CN <<http://www.ct.gov/dep/cwp/view.asp?a=2714&q=469620>> (accessed Jan. 3, 2012)

In deconstruction, materials are source separated from each other during dismantling of the building, as opposed to co-mingling the materials that may end up in landfill.

Deconstruction can be separated into two categories: non-structural and structural.

- Non-structural deconstruction is also known as soft-stripping and hand-demo, which consists of reclaiming non-structural components including appliances, doors, windows, and finish or trim materials.
- Structural deconstruction involves dismantling the structural components of a building and removing the entire building down to its foundation.

Many in the industry find structural deconstruction to be a comprehensive approach to whole building disassembly, allowing the majority of materials to be salvaged for reuse.<sup>24</sup> For this research, deconstruction will be defined as structural, since damage to buildings will require partial or total dismantling.



**Figure 3.7A. Causal Loop Diagram, Deconstruction and Demolition**

Figure 3.7A indicates the salvagability of materials via demolition and deconstruction. Demolition of material will have direct cost implications given that in the short-term, it seems to be less expensive than whole house deconstruction. One of the critiques of deconstruction is its relative cost per ton compared to demolition; however these are slowly being countered with arguments for increasing demand for recovered materials. Reinhart states that, “stimulating demand for the materials that are generated and reducing the costs associated with their recovery could increase the diversion of demolition debris. Techniques that could be used to increase the demand for recovered debris materials include:

- Inventorying the entire building prior to demolition and noting material condition.
- Developing estimates of the volume and tonnage of material that cannot be reused or recycled.
- Advertising the reclaimable material inventory to potential consumers.
- Specifying the use of recovered materials in new construction wherever possible.

- Providing subsidies and tax-incentives for the reclamation and re-use of materials.”<sup>25</sup>

Factors of storage and processing space, labor, liability and machinery can increase both deconstruction and demolition costs. “Identifying areas where recycling will increase and decrease costs is imperative when attempting to increase the rate of debris recovery. Systemized deconstruction will increase material quality and revenue from materials. It will also decrease costs associated with separation activities. However, systemized deconstruction requires more planning, management, and supervision than a traditional demolition operation.”<sup>26</sup>

For any debris management plan, deconstruction statutes should be addressed and recognized as a viable means for reduction of landfill accumulation. High tipping fees become a large disincentive for landfilling materials in San Francisco, mainly because of the various tolls and distances required for dumping. When applying requisites for recovering materials, direct tipping costs as well as indirect emission costs from landfilling must be compared with reprocessing costs of disaster debris material. Even if the costs for dumping are relaxed, the environmental implications are large, and harnessing second-life for many usable materials is lost. In assessing the “deconstruction policy” as shown in the causal loop diagram, results show that although fees may be compromised for depositing in a MRF, the holistic benefits of deconstruction make it a viable option for dismantling housing, even in extreme conditions. The results in Chapter 4 describe these benefits and provide some economic basis in comparing deconstruction and demolition.

The assumptions for modeling housing deconstruction and demolition streams are:

- 64% of all housing following an earthquake must enter the demolition/deconstruction stream
- A surveying process of damage level causes delays in overall demolition/ deconstruction
- All housing units are either demolished or deconstructed
- Demolition provides a 50% material recovery rate; deconstruction an 81% rate
- Deconstruction takes twice as long to accomplish
- Post-earthquake effects on deconstruction and demolition will greatly slow all processes for the first month, then accelerate with additional external help and finally return to typical rates after three more months.

### 3.8 Debris Generated

Based on HAZUS calculations, an estimated 6.8 million tons of debris will be generated from damaged buildings.<sup>27</sup> As this research focuses only on residential units, the amount of debris produced must be appropriately reduced to reflect generation from housing alone. Using data from the San Francisco Debris Management Plan, and interpolating results based on debris maps, an approximate 3 million tons of debris would be created by residential housing.<sup>28</sup> This can further be classified as 600,000 tons of

25 Reinhart, 8

26 *Ibid*

27 ATC 52-1, 59

28 SF Debris Management Plan, 2010

brick and wood debris, and 2.3 million tons of concrete and steel debris.<sup>29</sup> The proceeding table accurately presents the results. The total residential housing debris is calculated by multiplying the tons per unit by number of units (34.5 tons / unit x 85,000 units) equaling about 3 million tons of debris. This total is moderated in the systems model by the percentage of housing that will collapse on impact, nearly 36%, as per CAPSS estimates.<sup>30</sup> This provides an accurate understanding of total debris generated by housing collapse, versus that from deconstruction and demolition material output. Table 3.8A simplifies the classification of debris and provides totals and percentages of the nearly 3 million tons of residential building debris.

**TOTAL AND RESIDENTIAL UNIT DEBRIS**

Debris Class	7.2M Earthquake Generating 6.8M	Percentage of Total (%)	Residential Housing Debris
Brick/Wood/Other Debris tons	2867613	20.4	598230
Concrete & Steel Debris tons	3931448	79.6	2334270
Total	6,800,000	100	2,932,500

**Table 3.8A. Total and Residential Unit Debris Generated**

The following chapter includes these defined factors as they are applied within the system dynamics model to understand behaviors of San Francisco's material streams following a future scenario earthquake.

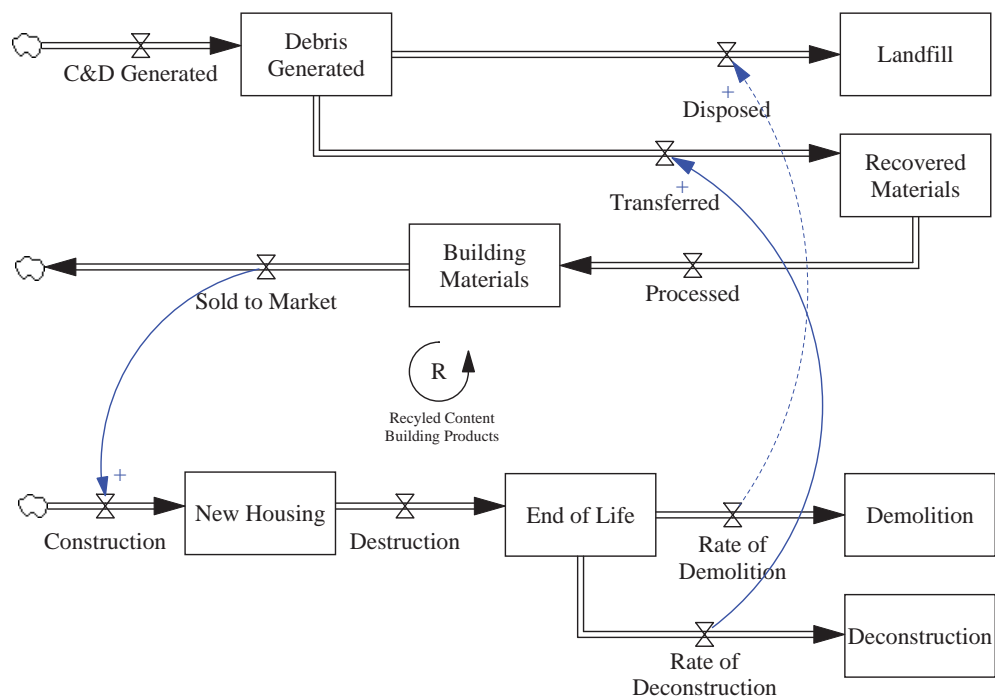
---

29 Appendix C  
30 Appendix B





## SYSTEM DYNAMICS ANALYSIS OF SAN FRANCISCO





## 4.0 System Dynamics Analysis of San Francisco

System dynamics models begin with a question or problem, for which data must be mined and subsequently applied within a stock and flow structure such that results and model behaviors can be drawn. This section explains the final step of the modeling process, and presents results in the form of accumulation and delays from the material waste stream and the housing construction stream.

### 4.1 System Causal Loop Diagram

A conceptual understanding of the simulated model begins with a system causal loop diagram (CLD), which links end-of-life housing units to debris to new housing in a virtuous or reinforcing loop. Adding the exogenous factor of the 7.2M earthquake can accelerate these trends increasing new housing, contingent on several other factors further detailed in the driving system dynamics models. This 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.

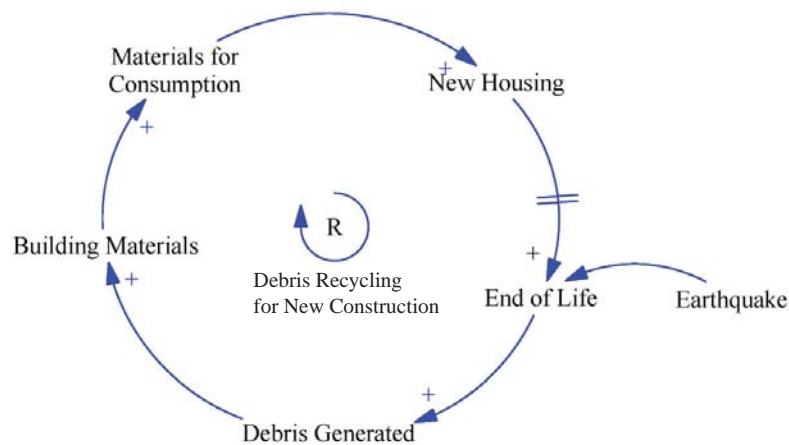


Figure 4A. Causal Loop Diagram of Simulated Systems

### 4.2 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 impulsed by an earthquake disruption and further tested by subsequent sensitivity analyses and policy implications (explained

in chapter 5). In order that results are comparable, control variables are set with values and explanations illustrated here for the base case models. Results are detailed in section 4.4.

#### *Housing Units Base Case Model Description (Figure 4B)*

- 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. See following for more information on “Local RCP Use Policy.”
- 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” in the construction flow represents 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 such that other variables can be tested and compared, an RCP policy measure of 25% is maintained, meaning 25% of the construction material is imported material 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 indicating compacted and careful tear-downs of buildings.<sup>1</sup> These tend to resemble deconstruction techniques more than traditional, demolition-ball destruction methods.

#### *Construction and Demolition Waste Stream Base Model Description (Figure 4C)*

- 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

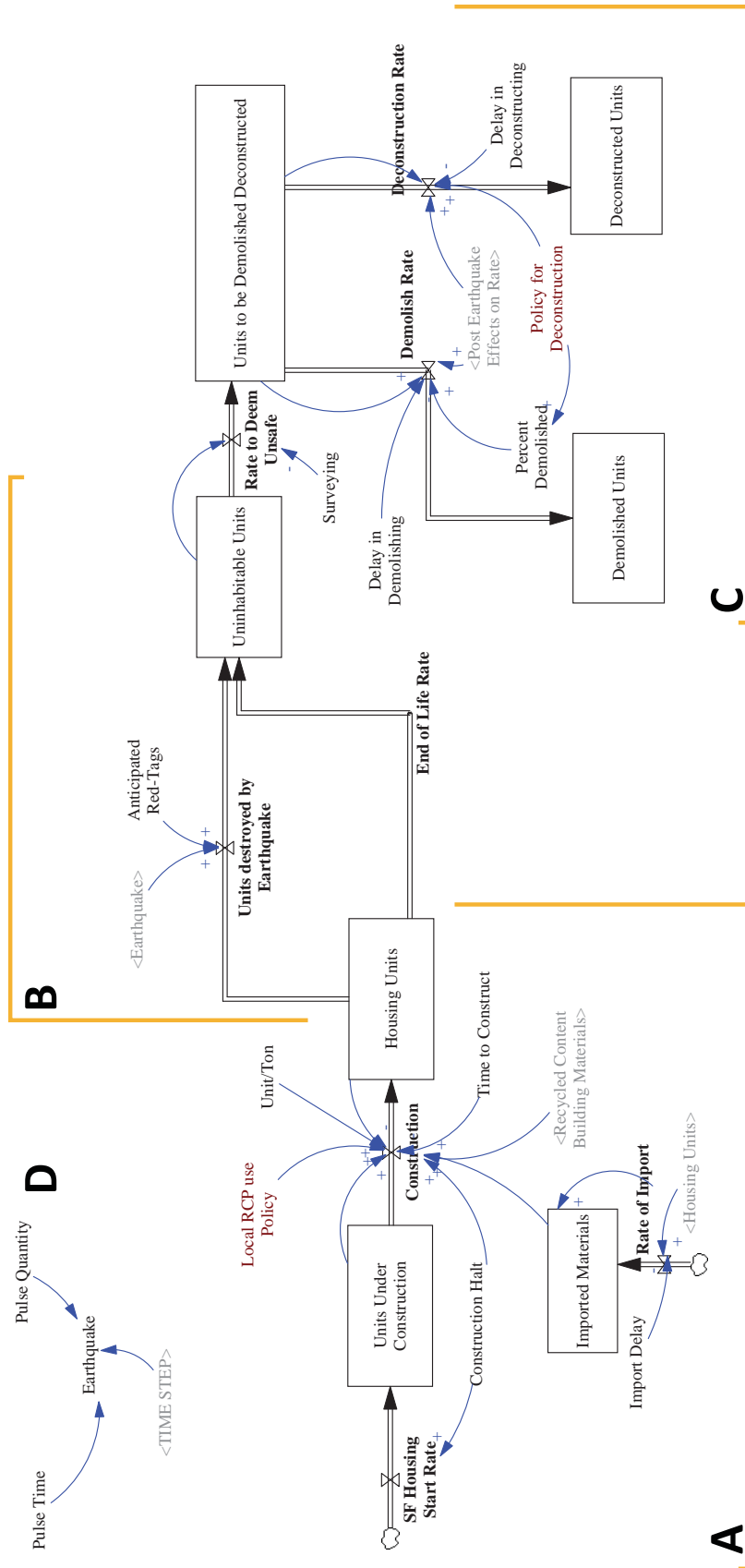


Figure 4B. Base Case Model 1, Housing Unit Driving Model

demolition from source is estimated to be 5,760 tons per month<sup>1</sup>, 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 of recovery time, but by 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 ABAG data, the total road mileage that is affected due to the earthquake nears 25%.<sup>2</sup> From the Loma Prieta earthquake, it is noted that on average, it took 134 days to clear the roads. However, since the 7.2M San Andreas earthquake is expected to generate far more debris than the Loma Prieta, this value has been increased to about 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 2 months to transfer 20,000 tons of material.<sup>3</sup>

Also detailed in this segment is the fact that all recovered materials are not inherently recyclable. Calculations show that about 72.5%<sup>4</sup> 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 high material diverting.

- 1 1600 tons per day, 12% of which is C&D Debris, CalRecycle, 1997
- 2 Appendix E
- 3 Conversation with Richard Valle, CEO Tri-Ced Recycling, Union City, CA
- 4 Appendix D

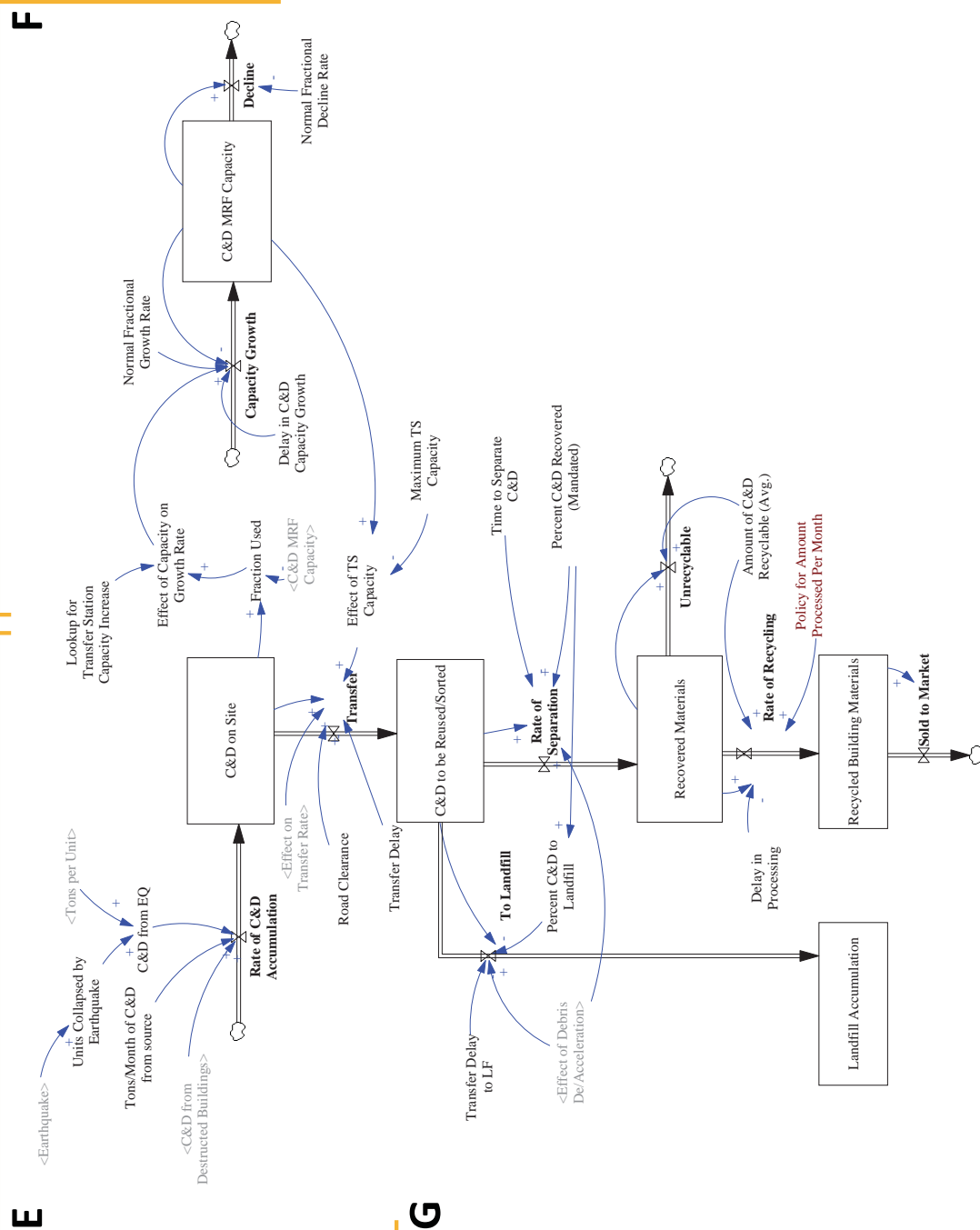


Figure 4C. Base Case Model 2, Construction and Demolition Waste Streams Driving Model

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<sup>5</sup>. 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 relaxing of various ordinances, policies, and norms in a post-disaster setting, which greatly influences how recovery is managed and the city is rebuilt, and is discussed further in section 4.4.

The time frame for simulating both models is 120 months, with the pulse occurring at month 12. Not included in the models above 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 on 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<sup>6</sup>.

### 4.3 Results and Recovery Forecast

Performing numerous simulations of the base model with the policy alternatives described in chapter 3, 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 serve as building material following processing. The overall results indicate *6.8 years of recovery following a 7.2M 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 and upwards of 1.6 million tons of potentially usable debris from being disposed.

The following are graphical results explaining the above mentioned conclusions, including effects of sensitivity analyses. Situational alternatives are detailed in the next chapter.

#### 4.3.1 Base Case Model Experiencing No Earthquake

Under normal conditions, San Francisco would experience a normal growth rate of housing and a near stable transfer station/MRF capacity. A growth of about 0.89% in housing units occurs over the

---

5 San Francisco Environmental Code Ch 14.

6 Appendix



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 materials 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.

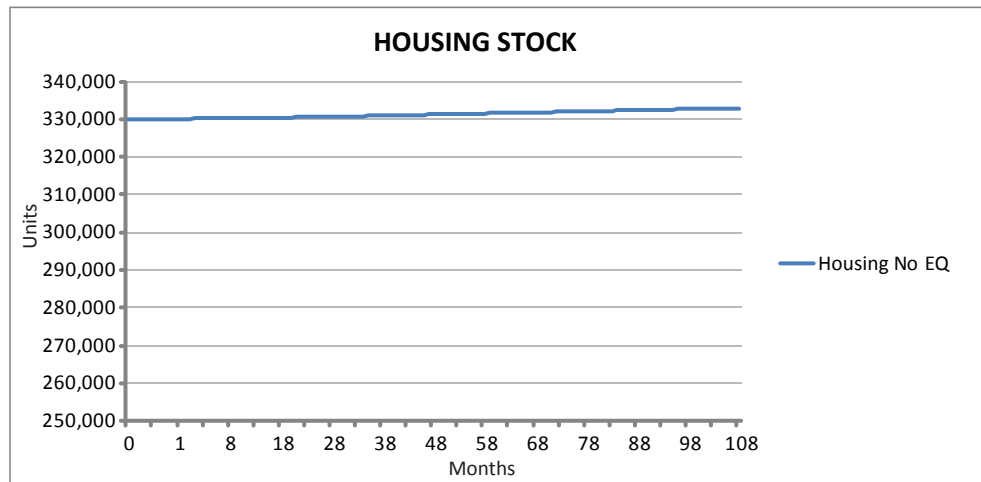


Figure 4.3.1A Housing Stock in Equilibrium Case

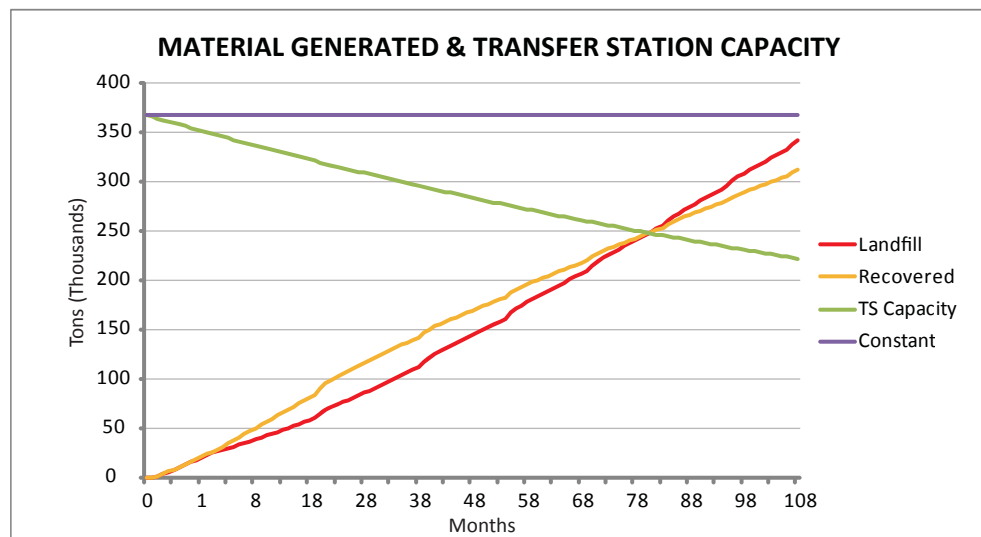


Figure 4.3.1B Landfill & Recovered Material versus Storage and Processing Capacity

#### 4.3.2 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 the Figure 4.3.2A. 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 mate-

rial is limited in and near San Francisco, and a phase of learning and implementation by local producers following the earthquake will slow the RCP supply chain, further escalating the recovery period. Figure 4.3.2B 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.

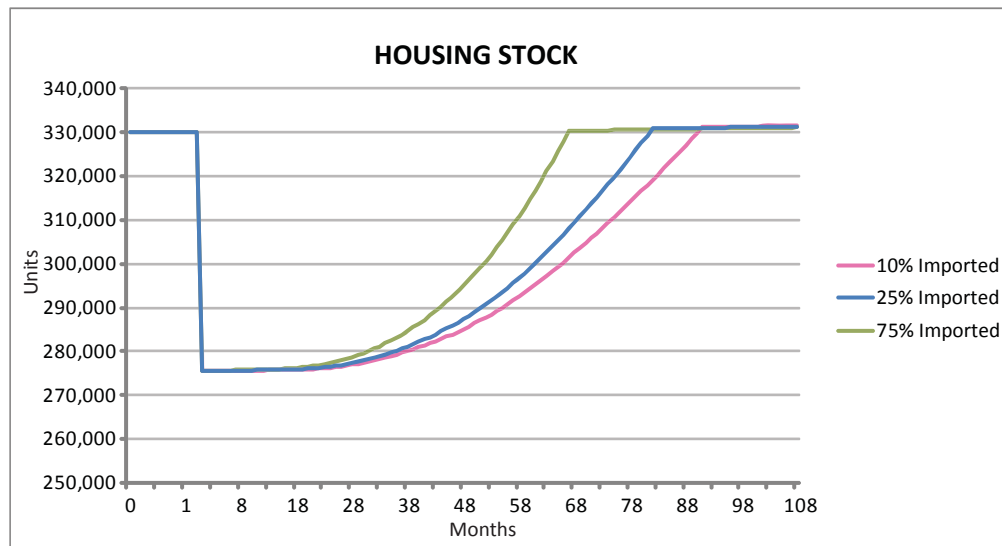
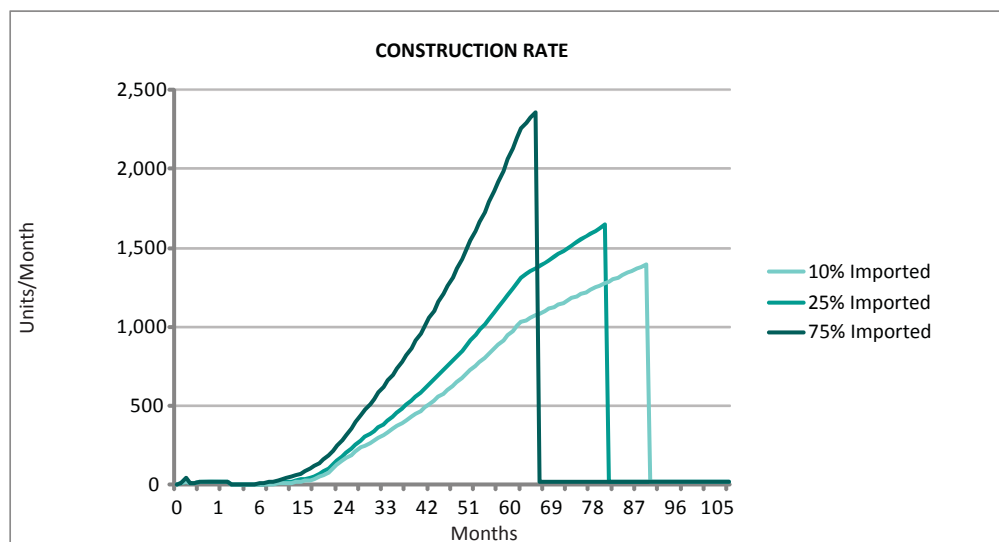


Figure 4.3.2A. Housing Stock with Effects of Earthquake

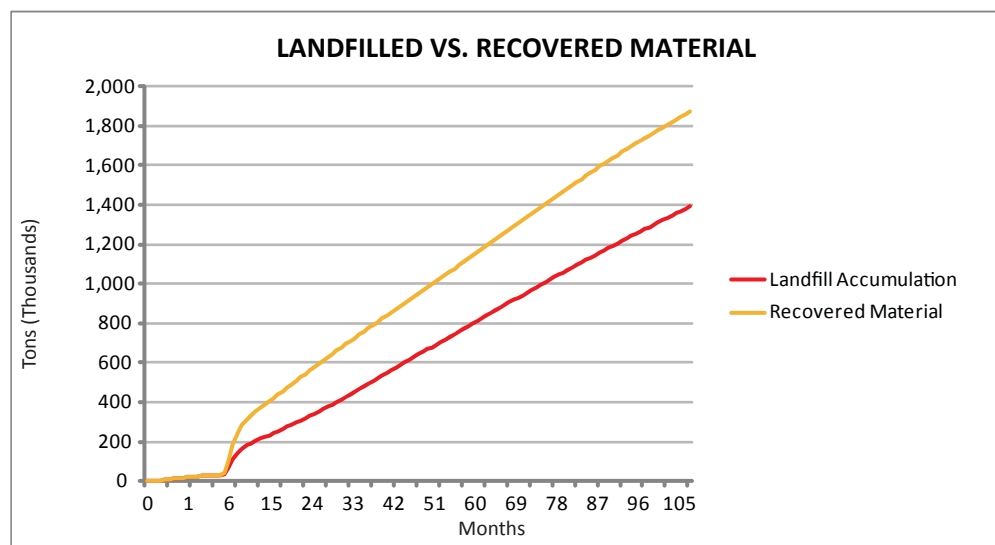
Effects on the internal balancing loop for transfer station capacity outputs an increase of 70,000 tons/month of transfer station capacity required to achieve the subsequent results. Therefore at the point of recovery, the throughput capacity reaches a value of 445,500 tons per month of processing function 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 4.3.2D) 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. Results from these additional cases are described in Chapter 5.

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 4.3.2C. 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 trade off for a greater recovery period comes with the benefit of nearly 3 years of landfill space that

is conserved with RCP application<sup>7</sup>, saving nearly \$6.6 million dollars in landfill contracting.<sup>8,9</sup> 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 4.3.2A. To ensure environmental protection in the recovery phase alongside the rebuilding of quality housing stock, a trade-off in recovery time must occur to allow necessary time for preparation and planning of reconstruction.



**Figure 4.3.2B. Construction Rate for Earthquake Base Case with Sensitivity Testing**



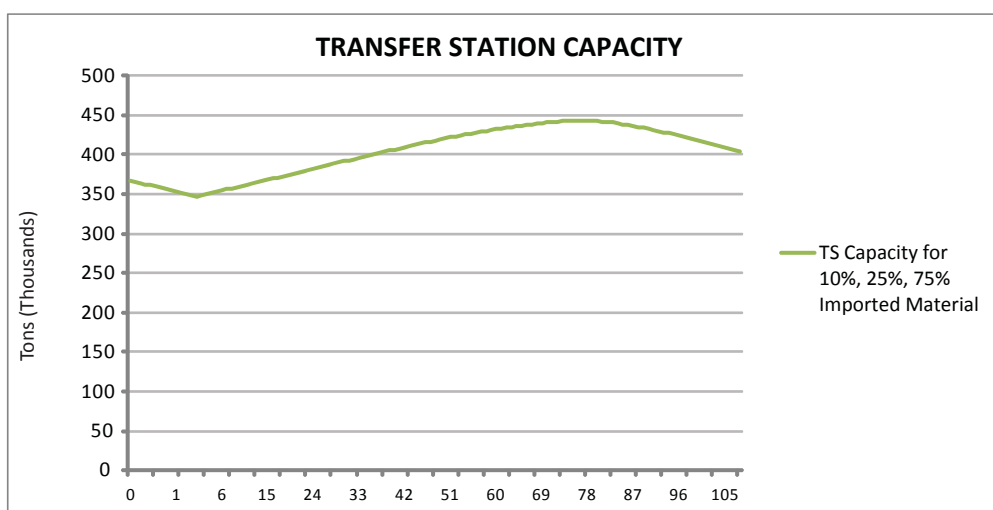
**Figure 4.3.2C. Landfilled Material and Recovered Material for Earthquake Base Case**

7 Compared to 5 years of landfill space used if no recovery is instated.

8 San Francisco Chronicle, <<http://www.sfgate.com/cgi-bin/article.cgi?f=/c/a/2010/08/06/MNLN1ELPE1.DTL>> (accessed January 4, 2012)

9 Assuming 500,000 tons per year landfill capacity

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 use are witnessed.



**Figure 4.3.2D. Transfer Station Capacity with Sensitivity Tests for Earthquake Base Case**

#### 4.4 Conclusions

Results from the control case described in this section show clear incentive for harnessing the potential of debris as material for new construction. Comparing the extreme cases of a 75% import rate to a 10% import rate shows an increase in recovery of nearly 2 years (5.6 years versus 7.6 years, respectively). In spite of this, the compromising housing recovery delay is befitting 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.

Finally, it is 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<sup>10</sup>, economic impacts from a 7.2M disaster will result in direct costs of nearly \$14 billion dollars in housing, property and material damage and loss. Secondary economic hardships would also ensue, re-

10 ATC 52-1, vi

sulting 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 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/months 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 years of landfill space.<sup>11</sup>

Another important measure of landfilling is the amount of CO<sub>2</sub> 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 truck loads would be necessitated to move all debris to landfill if recovery is implemented, about 100,000 truck loads 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<sub>2</sub> emitted by a near 63,000 ton reduction in noxious truck fumes, which is 23 times more emissions than a recovery scenario.<sup>12</sup> 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.

#### **4.5 Insights**

The results and situational alternatives (detailed in the following chapter) 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 is critical for material that is to be recovered, and that which is deemed harmful and must be disposed of in other ways.

Additionally, the fact that a relatively large delay (9 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 slow and steady transfer station capacity growth, a great amount of material can be processed

---

11 MRF cost comparison based on construction costs only; variable costs have not been included

12 Appendix B

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.

The retrofit policy analysis (explained in Chapter 5) also attests to the large benefits from retrofitting housing prior to a hazard event. Retrofitting has been a foregoing and prominent means of community resiliency, but is faced with financial and societal complexities which hinder its widespread application. Testing the feasibility of retrofitting within the system bounds again prove its viability and necessity in a community prone to adverse environmental threats. Retrofitting is shown to cut overall recovery time by nearly 2 years, which allows possibilities for greater life safety prior to a disaster event, as well as maintenance of citizens following an earthquake, both indicative of a resilient city.

#### **4.6 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 design 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 exists, 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 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 saw 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 simplified 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.

Trade off 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 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 stimulate. 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.

The following chapter provides situational alternatives and policy recommendations to further test the systems model and investigate different outcomes of the post-disaster context.





## POLICY ALTERNATIVES AND SCENARIOS

“After disasters, critical policy choices emerge, forcing unwelcome decisions on local government about whether to rebuild quickly or safely. Post-disaster recovery and reconstruction planning and management commonly reflect an effort to balance certain ideal objectives with reality. Recovery is characterized by wanting to (1) rapidly return to normal (2) increase safety and (3) improve the community.”

*Mileti, Dennis S., Disasters by Design, 1999*



## 5.0 Policy Analysis

System Dynamic modeling allows for simulation of a complex question or hypothesis given a defined boundary. These simulations provide projections and behaviors of certain stocks and flows which inform decision making for a likely future event, or even a past event that may have had a different outcome at present. One of the advantages of system dynamics is the ability to apply certain factors representing decisions or policies to test the repercussions on the system as a whole. As such, several policy alternatives are suggested to understand impacts on recovery periods and material salvage rates. The policies suggested below are few of many, but have greatest influence on debris management.

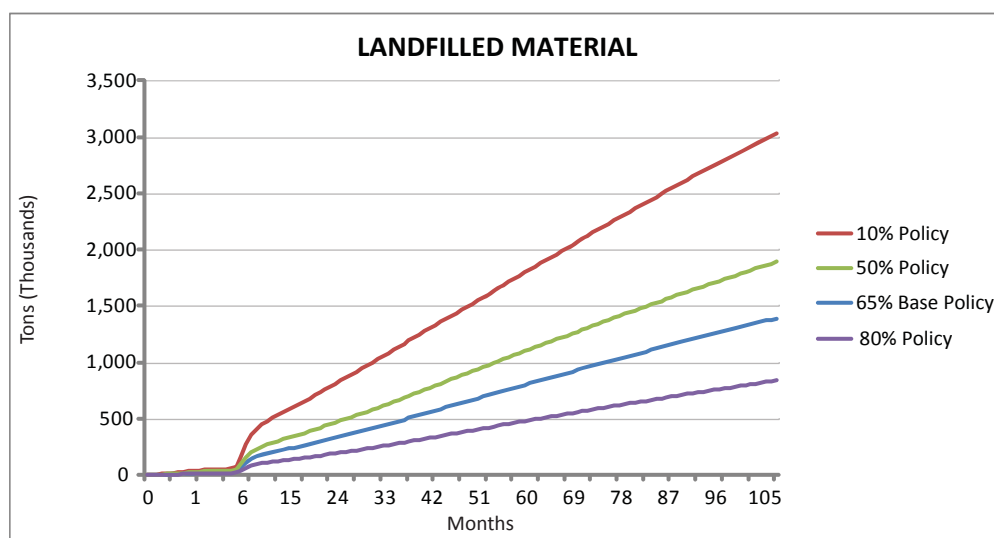
### 5.1 Sensitivity Tests and Situational Alternatives

The following subsections describe exogenous and endogenous variables that were varied to understand the systems model, with intentions to provide recommendations of improvement to the post-disaster case.

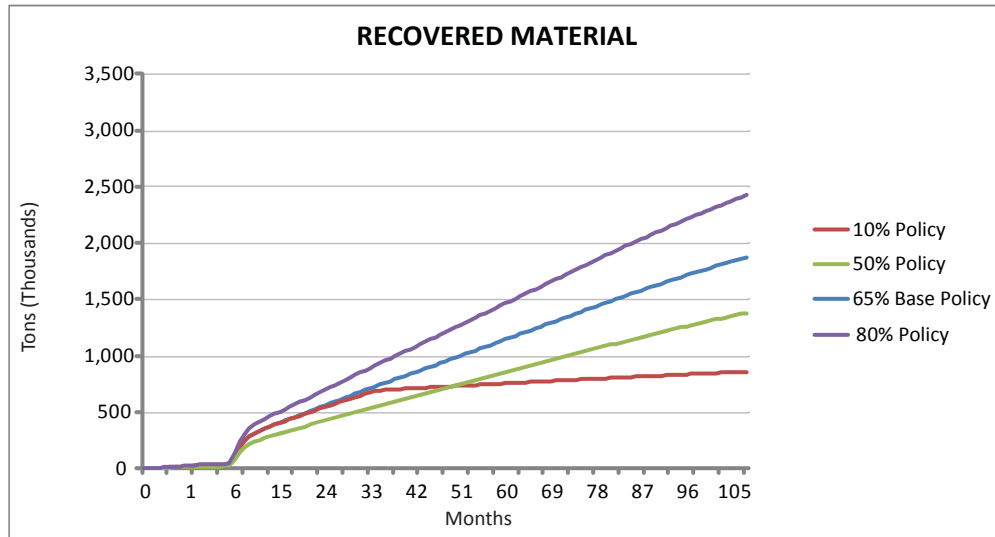
#### 5.1.1 Mandated Recovery Rates

As is mentioned in the earlier chapter, in order that this research question argues for validity, a mandated ordinance of recyclability must be maintained or increased in San Francisco such that not all material is landfilled in disaster debris management. San Francisco's Environmental Ordinance 27-06 enforces a 65% material diversion rate for all construction and demolition contractors. Examining the notion of recyclability rates and landfill diversion with sensitivity tests presents the following results:

The percent policy refers to the percent of material that must be recovered from C&D sites. The differences in recovered and landfilled material vary proportionally as the policy increases or decreases. The graphs indicate that a higher policy (or one that is enforced at 65%) will result in more RCPs



**Figure 5.1.1A. Impact on Landfilled Material by Recovery Mandate Policy**

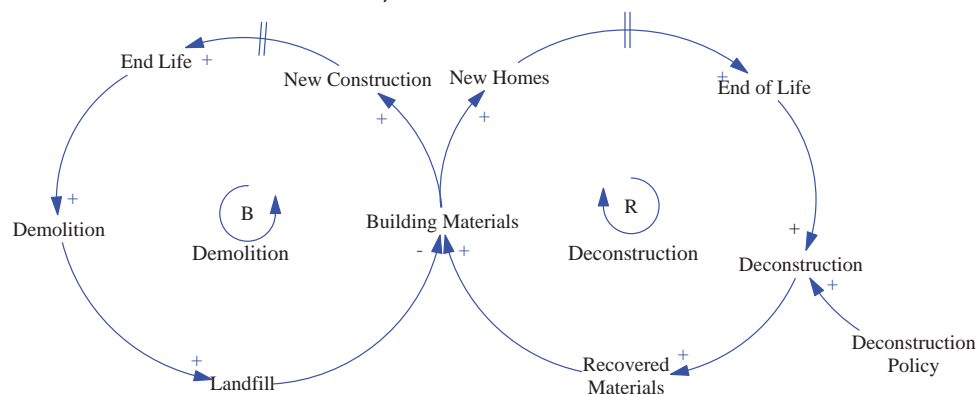


**Figure 5.1.1B. Impact on Recovered Material by Recovery Mandate Policy**

to be used in housing construction. However, between the highest and lowest tested policy [10%, 100%] only a four month increase in housing recovery is attained due to the imported materials that take place of RCP deficits. Nevertheless, the amount of localized construction material that is generated is greatly influenced by a more rigid policy concerning material recovery rates.

### 5.1.2 Deconstruction and Demolition Policy

In order that landfilled and recovered materials are comprehensively analyzed, the base case model is slightly modified to include all non-recovered materials into the appropriate landfill stock. The simpler base model contains only the three million tons of debris generated immediately by the quake, mainly from residential wood frame housing<sup>1</sup>. It does not incorporate additional material generated via deconstruction and demolition processes, or residual unrecyclable material through other processes suggested within the model bounds. Therefore, the outcomes of the simulations in this section show graphs

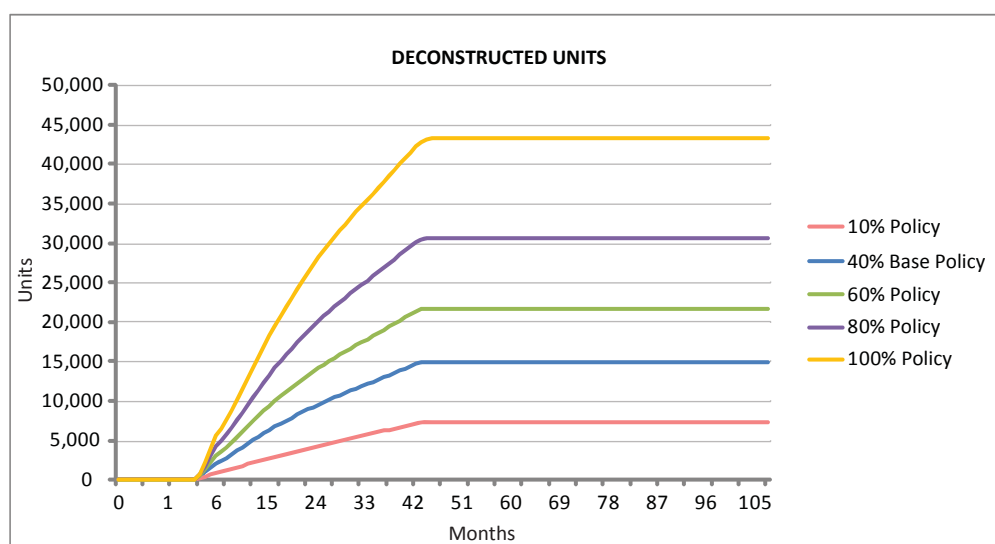


**Figure 5.1.2A. Causal Loop Diagram, Deconstruction and Demolition**

that look slightly different than the original landfilled versus recovered material comparisons, which con-

sist of only the direct disaster debris management processes.

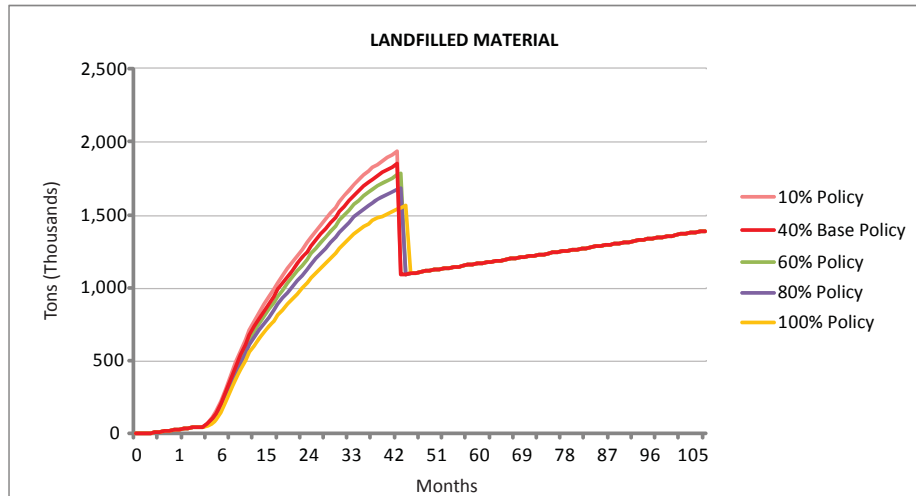
Building deconstruction and demolition as explained in chapter 3 and contrasted in chapter 4 are two means of building destruction, which are represented in the “Housing Units” driving model. This research leans favorably towards deconstruction since this mode of building tear-down provides greater material recovery than does tradition demolition (81% versus 50% recovery, respectively). Therefore, modifying deconstruction policy correlates with the number of units that are deconstructed, which therefore translates to the amount of material landfilled through destruction. As the policy value is amplified, more material recovery is possible, reducing overall material that is sent to waste (see Figure 5.1.2B and 5.1.2C). The percent policy referred to in the graph are the percent of red-tagged or uninhabitable housing units that are deconstructed, the rest being demolished, via an estimated control value of 40% deconstruction.



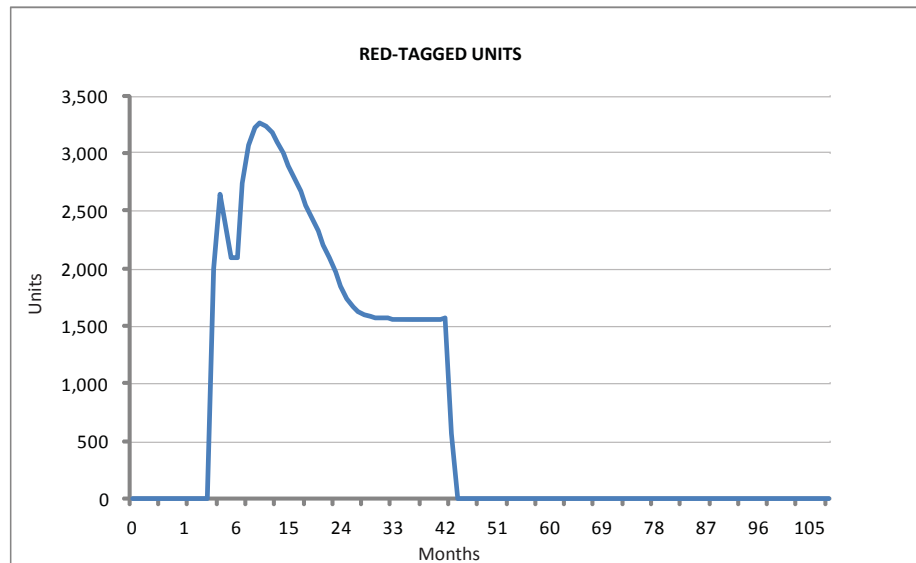
**Figure 5.1.2B. Sensitivity Analysis on Deconstructed Units Policy**

A precipitous decline post month 42 can be attributed to the destruction of all red-tagged units deemed unsafe to live in and requiring complete rebuilding (see Figure 5.1.2D). After this point, the graphs in the landfilled sensitivity analysis converge, since the rest of the material traveling to landfill or being recovered is now contingent upon the disaster debris management downstream in the “C&D Waste Stream” model. The amplitude after the inflection point in the graph can then be controlled by the transfer station processing capacity, as well as the recovery mandates by the City. This means that once the units to be deconstructed or demolished are cleared, the landfill and recovered material streams are directly affected by the processing capacity of materials as well as the mandated recovery rate.

The base case value of 40% deconstruction (60% demolition) is an assumption based on San Francisco density, labor costs, and time constraints that may convince contractors to pursue demolition rather than deconstruction, regardless of environmental consequences. Using the control case, a com-



**Figure 5.1.2C. Sensitivity Analysis on Landfilled Material with Deconstructed Units Policy**



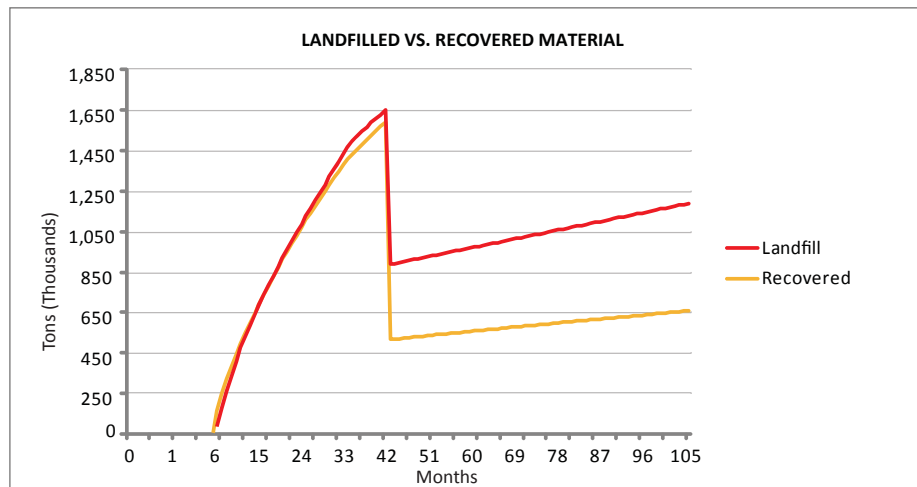
**Figure 5.1.2D. Red-Tagged Units to be Destroyed**

parison is made between landfill and recovered material, shown in Figure 5.1.2E. The simulation shows that landfilled material far overshadows recovered material after month 42. This is accredited to two factors: unit destruction method and mandated material recovery rates. The contribution of landfilled material from demolition and deconstruction is sizeable, when considering that half of the material from demolition is deposited in landfill. Therefore, a 60% unit demolition rate causes a significant increase in landfilled material. The second factor is that of the mandated recycling rate. Though 65% is relatively high compared to other cities, it does influence the total amount of material being recovered, and effectively that which is being dumped as nonreusable waste.

Given the gravity of these two rates on total landfill accumulation, it is important to verify overall outcomes through sensitivity analyses. Mandated recyclability has been experimented with in Section

5.1.1, while “Policy for Deconstruction” has been tested and graphed in Figure 5.1.2B. For intentions of reducing total landfilled material, a higher recyclability rate must be established, provided more units are deconstructed rather than demolished along with an enhanced capacity at Material Recovery Facilities in and near the San Francisco Bay Area.

It is important to note the choice of exclusivity of the above mentioned results in the overall driving model and baseline results (chapter 4). The more scrupulous definitions of landfilled materials versus recovered materials in this section are a means to understand total impact of factors that are beyond pure disaster debris management. While it is important to run these simulations, they are considered outside of the scope of the central hypothesis, and prove to have greater uncertainty at this point of completion, which affects the overall validity of the research. Future work will provide a more in-depth understanding of deconstruction and demolition waste streams throughout the recovery period, while simultaneously honing landfill and recovered material stream models.



**Figure 5.1.2E. Sensitivity Analysis on Landfilled Material with Deconstructed Units Policy**

### 5.1.3 Transfer Station / Materials Recycling Facility Simulation

Transfer stations as embedded in this model are simulated as expandable or contractible tons of processing capacity, dependent on debris collected on site. When debris on site is increased beyond capacity, the feedback structure in the simulation increases processing bandwidth at the MRF, with appropriate delays. Realistically, this capacity would be based on a variety of aspects, including but not limited to facility square footage, labor, funding and available land. For purposes of this research, transfer station capacity has been simplified to be correlated with square footage alone.<sup>2</sup>

If, for any reason, capacity and square footage are not expendable and total C&D processing capacity cannot be increased, repercussions on the global system may take place. For this reason, a simulation has been conducted which caps the total capacity of the MRFs to 375,000 tons/month. The effects

2 See Chapter 3; 1 acre provides staging/processing capacity for 200 tons per day

of this simulation are shown in Figures 5.1.3A and 5.1.3B.

Results from this simulation reveal an interesting system-based phenomenon. That is, transfer station capacity does not significantly slow the overall recovery of housing. This is shown with the slight skewing of the housing recovery by a month after transfer station capacity has been locked. What is affected in this scenario is the amount of total recovered material at the end of the recovery period. As can be seen in Figure 5.1.3C, at the mid-point of the suggested recovery time frame (month 40), recovered material in the case with flexible capacity is far greater than that with the locked capacity case. Therefore, in a situation with fixed capacity, less processing of disaster debris is likely for recovered material, attenuating total recovered material. Additionally, landfilled material is also somewhat lower due to

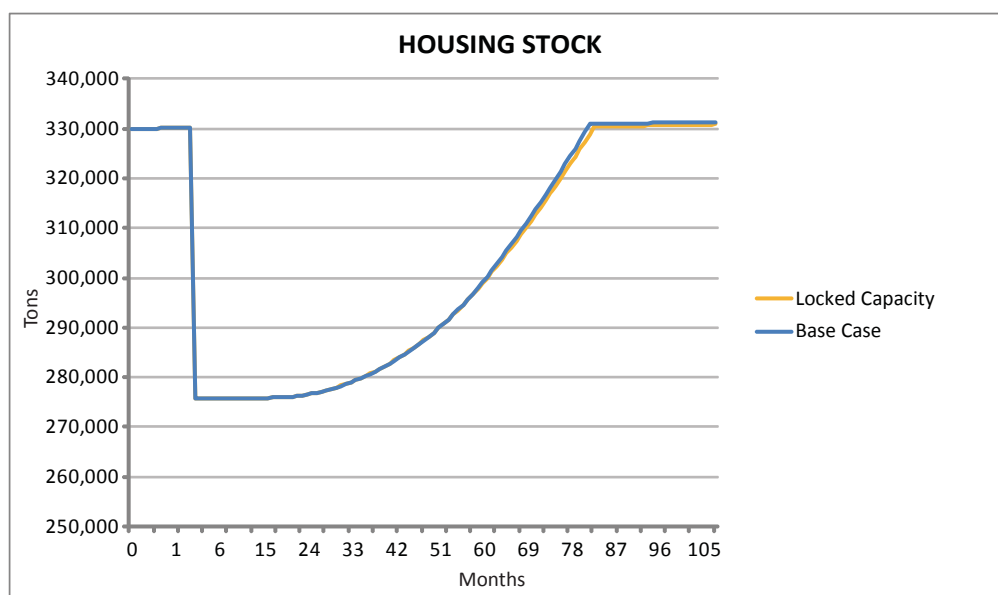


Figure 5.1.3A. Housing Units, with and without locked MRF capacity

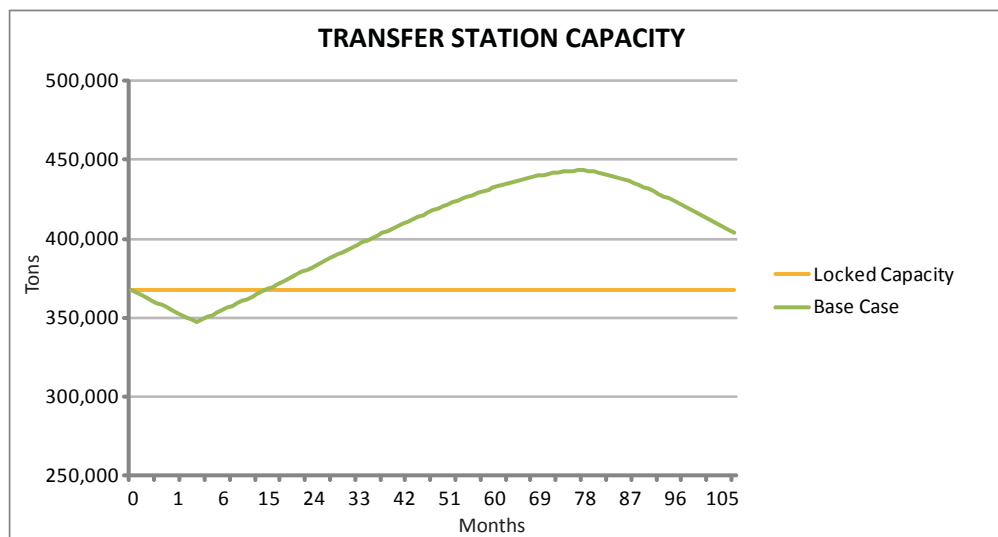
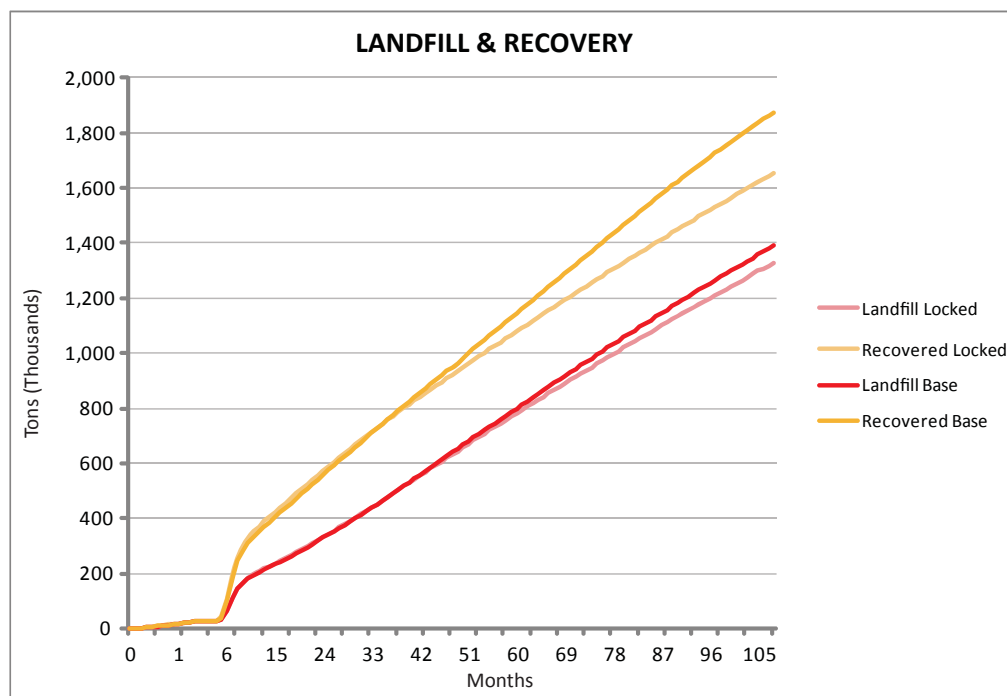


Figure 5.1.3B. Transfer Station Capacity Comparison



greater general impedance of roads by debris. Therefore, the system faces a holistic delay with capped MRF processing power, but that which does not impinge on housing recovery critically.



**Figure 5.1.3C. Comparison of Landfill and Recovered Material with Locked and Flexible MRF Capacity**

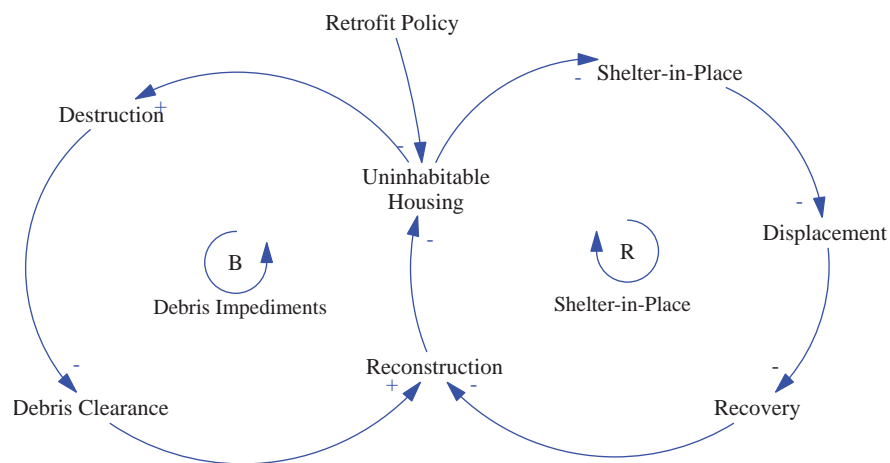
#### 5.1.4 Retrofit Policy

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 5.1.4A demonstrates how retrofitting homes becomes dually beneficial if enough homes are retrofitted to at least a minimum standard.<sup>3</sup> This retrofit scheme is a minimal retrofit 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 after an earthquake.<sup>4</sup> This is determined as the least costly method of retrofit, at an average of \$6.60/ sq. ft., adding to around \$11,000<sup>5</sup> per housing unit.<sup>6</sup> 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

3 Appendix B  
 4 ATC 52-3, 24-25  
 5 *Ibid*  
 6 ATC 52-3, 28

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).<sup>7</sup> The San Francisco Planning and Urban Research Association estimates that only 75% of the city's current housing stock will provide adequate shelter for residents after a large earthquake, slowing city recovery. SPUR's goal for resilience is that the housing stock reaches a 95% shelter-in-place standard.<sup>8</sup> This goal is augmented by substantial retrofitting, which helps to retain the San Franciscan population 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 the diagram.



**Figure 5.1.4A. Causal Loop Diagram, Retrofitting Policy**

An added loop of influence is the amount of disaster debris that would be mitigated as more housing is retrofitted, and is demonstrated by the left-side of the causal loop diagram. That is, a pre-disaster retrofitting policy can decrease the number of uninhabitable units after an earthquake, reducing overall destruction and thereby speeding debris clearance off of lifeline routes, consequently accelerating housing and city-wide reconstruction.

Simulating the retrofitted scenario yields a much faster recovery time, as expected with a 57% reduction in damaged housing units. Retrofitting all units would allow housing recovery in about 51 months, or 4.25 years (Figure 5.1.4B), as well as a substantial drop in uninhabitable units<sup>9</sup>. This recovery time is *more than 2 years faster* than the base case of 6.8 years for recovery. In addition, impacts on recovered and landfilled material are apparent as less debris is generated, indicated by the balancing loop in the causal loop diagram (Figure 5.1.4C and 5.1.4D).

7 SPUR, Safe Enough to Stay, 5

8 *Ibid*, 2

9 Appendix A

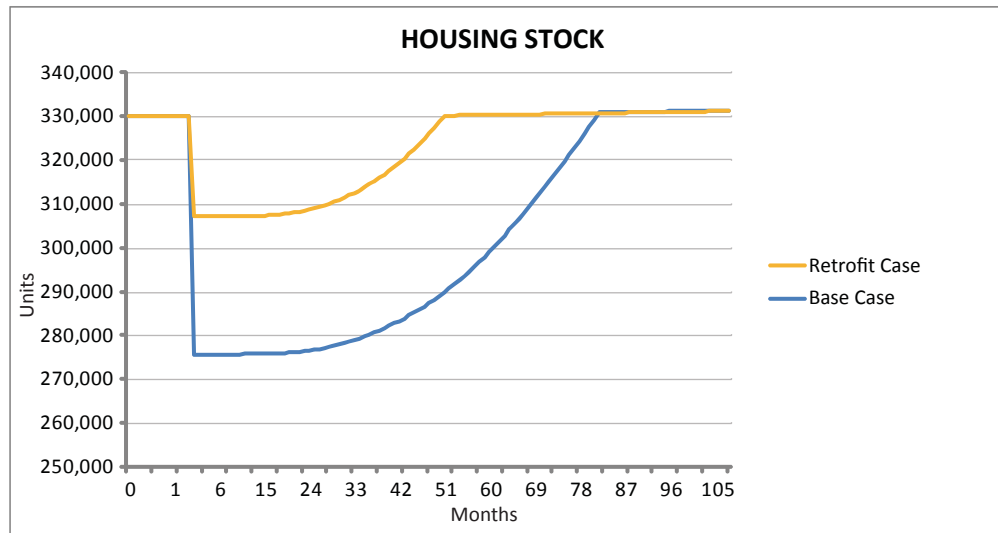


Figure 5.1.4B. Housing Units Post-Retrofit

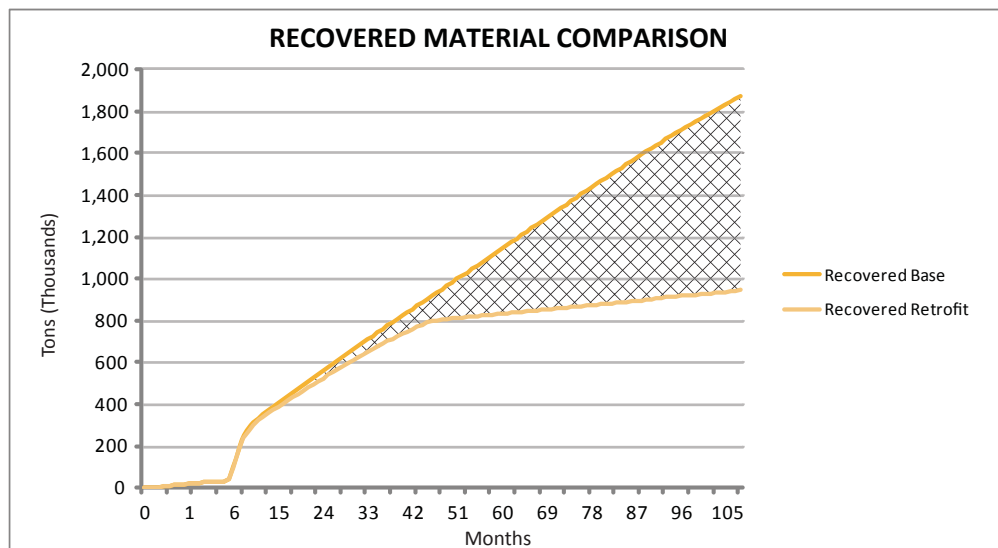
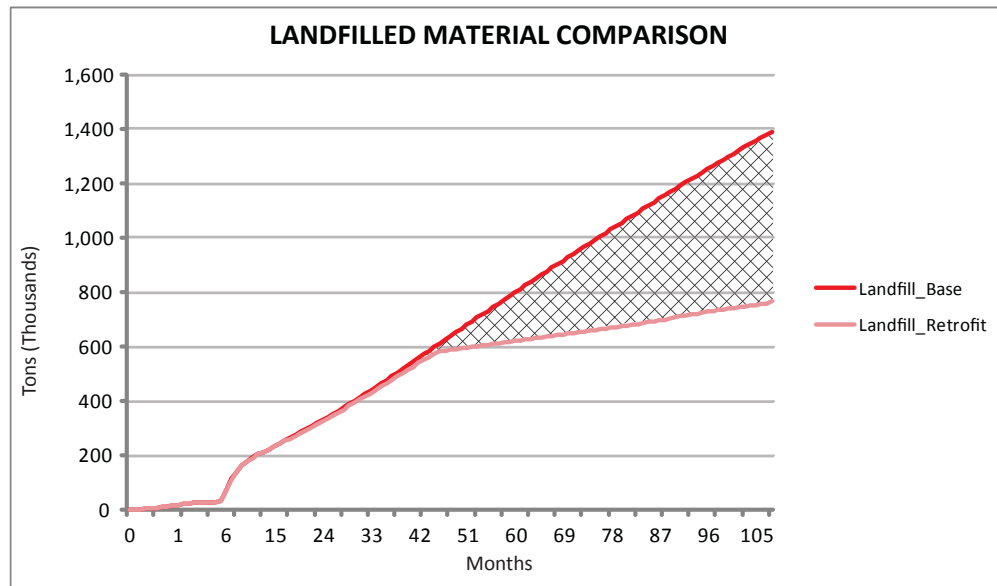


Figure 5.1.4C. Material Recovered, Post-Retrofit Comparison

Realistically, retrofitting all housing units even to the most basic standard becomes unlikely given the general lack of incentive to retrofit in many counties within the Bay Area. Many homeowners underestimate the severity of the next big quake, and its potential consequences on their homes. Cost of retrofit also outweighs near future risk for many residents, limiting the actual number of completed retrofits and countering goals for a resilient SF. Studies within the Bay Area have shown that two-thirds of retrofits are not being done properly and prove little to no benefits<sup>10</sup> Lack of housing retrofit is not only burdened by home owners, but also by the State of California. The recently passed standard for single-family homes (IBC, Chapter A3) only applies to very specific housing types and excludes adopted standard for multi-family buildings. This lack of standard means that permits are issued for voluntary

10 Shaken Awake, ABAG, 2010



**Figure 5.1.4D. Landfilled Material, Post-Retrofit Comparison**

seismic retrofits and may not be adequate.<sup>11</sup>

Following the Sendai earthquake of 2011, homeowner requests for retrofit work increased significantly as people became fearful that their home would be damaged by an earthquake. Although a hopeful first step to resiliency, there are many more ways to motivate mitigation other than earthquakes. The Associated Bay Area Governments have suggested the following to local governments in providing more incentive for earthquake preparedness through housing damage mitigation<sup>12</sup>:

- Disclosing building vulnerabilities to tenants and homeowners
- Waiving permit fees
- Providing low cost loans for retrofitting with long repayment periods
- Reduction of business taxes
- Servicing free consultation to walk owners through retrofitting process

The discussion for making San Francisco more resilient through retrofitting vulnerable housing, especially soft-story multi-family housing with more than 5 units, is an ongoing dialogue between various parties within a city; these include officials, not-for-profit groups as platforms for mitigation activism, and homeowners who by and large are uncertain of the durability of their home in the wake of a large earthquake.

For the purposes of this research, however, retrofitting seems to be the most proactive means of a sustainable and forceful recovery as compared to other policies suggested here which are generally reactive to a potential disaster. The simulation in this section exemplifies an extreme case of retrofitting, that of all wood-frame housing units in San Francisco, which may be improbable but sig-

<sup>11</sup> *Ibid*, 2

<sup>12</sup> ABAG, *Shaken Awake*, 2-10

nificant in understanding the effectiveness of retrofitting in safeguarding lives and promoting a more expedited recovery phase.

The following chapter synthesizes the results and situational alternatives to provide conclusions and recommendations for application of this thesis to San Francisco and the greater Bay Area.



## DISCUSSION

“When a community begins to rebuild after a natural disaster, demand for recycled materials in all areas spike up.”

*Fickes, Michael, “Calculating Recycling Markets,” World Wastes, 1997*





## 6.0 Discussion

The relevance of this research resides in a nuanced vantage of post-disaster, city-wide recovery through disaster debris management. Typically, discussions of disaster management prioritize housing, infrastructure, and lifeline recovery which are critical in a reconstruction context. However, debris must be understood as having value if its benefits are to be actualized. This research intends to bring debris to the forefront and projects its potential uses for aspects of housing reconstruction. Its strength is in the processes of mapping material flow through the city, with linkages to variables which may have ostensibly unrelated implications, but prove to be influential to the system results. One of the assets of a systems model of this sort is its useful temporal projections of variables related to recovery following a disaster. This provides empirical information to encourage policy makers to rethink disaster debris as a catalyst for growth, rather than an impediment to recovery. It allows stakeholders to make sophisticated decisions across domains, and to further flesh out aspects of recovery. Additional iterations of this work will include additional factors of vulnerability or risk, and can help strengthen the simulated results. The following sections provide research conclusions, including obstacles for recycling disaster debris, useful recommendations, and future work utilizing similar methodologies.

### 6.1 Conclusions

Value of material reuse and recycling is inherently evident- it has positive social, economic, and environmental implications. San Francisco has pushed for high recyclability over the years, which has allowed it to become an archetype of an environmentally conscious city. This provides more reason to promote and continue waste recyclability following a disastrous scenario. Sustainable waste management is a product of rigorous pre-disaster planning and policy making, which is then tested for robustness following a large earthquake. "Sustainable waste management encourages the generation of less waste, and the reuse, recycling and recovery of waste. By focusing on long-term debris planning and setting measures for ecological and economic sustainability, it is possible to improve a regions' resilience to future disasters. Furthermore, the expansion of recycling capabilities and eco-industrial planning results in more job creation and promotes partnerships."<sup>1</sup>

Not to be underestimated is the notion of pre-disaster communication and dialogue. In attempting to promote sustainable waste management, key logjams must be resolved prior to a disaster event. Phillips suggests that "normal operations represent the optimal time period to conduct planning [for debris management]. Local planners should look for and encourage a variety of partners to join the planning process, as more perspectives bring a wider view of options, encourage partnerships, provide more realistic assessments of what can be done, and encourage pre-event communications. In short, face-to-face interaction among all key partners makes for a more effective post-event recovery. Identification of temporary storage and permanent disposal sites should occur during normal operations, as well as designing appropriate types of contracts and procedures to monitor contracts. Further, this time period

---

1 Yahya and Boussabaine, 2006; Blakely, 2007; Duetz and Gibbs, 2004 As cited by Karunasena, 251-255

can serve as an opportunity to spur local recycling, reduction, and reuse efforts.”<sup>2</sup> Further description of means for enhanced landfill divertability following a disaster are described in the following sections.

### 6.1.1 Obstacles

While the benefits of sustainable waste management following a disaster have many implications for recovery, it does not come without challenges to the City when managing large volumes of waste. “Enabling property owners to return to an area following a disaster and assist with cleaning up, separating and managing hazardous and non-hazardous waste”<sup>3</sup> prove to be problematic when conflict of interest arises in quality and quantity of recovery. “In addition, deconstruction, establishment of permanent recycling infrastructure and enhancement of eco-industrial networks through strategic planning have been identified as some of the key barriers in C&D debris management that need to be addressed.”<sup>4</sup>

For San Francisco specifically, capacity for material staging and processing is the largest obstacle in promoting debris recycling. Transfer stations used will not be able to manage all the debris that will be generated in San Francisco, since the earthquake will not be isolated to the City and the produced debris will include more than C&D materials. These and other regional facilities will be inundated with debris from all over the Bay Area, which must be accounted for when drafting a debris management plan. Possibilities of temporary staging sites may also prove difficult in a post-disaster context, since space is severely limited in San Francisco.

Researchers have suggested other obstacles municipalities may face when assessing disaster debris management. Some of these are listed in the following:

- The cost associated with separation of recyclable material adds to the total project cost
- Politically necessary expedience of recovery reduces priority given to recycling
- Recycling requires the support of local debris management contractors
- Possibilities of large quantities of recycled products may overwhelm local market<sup>5</sup>
- Potential for lack of funds to acquire required technology and equipment
- Inadequacies in resources to deconstruct
- Lack of knowledge in a relatively new practice (disaster debris reprocessing)
- Limitations of recycling markets and limited market awareness<sup>6</sup>

The overarching obstacle is that of political and social will. In a time of chaos, the best solutions are eclipsed by nearsighted decisions because fast action is required. Therefore, a community must decide on what is important and necessary to them, and realize that compromises must be made if positive

---

2 Swan, 2000. As cited by Phillips, 112

3 Luther, 2008 as cited by Karunasena, 251-255

4 Baycan and Petersen, 2002; Zeilinga and Sanders, 2004; Ardani et al., 2009. As cited by Karunsena, 260

5 Reinhart, Planning Tools for Disaster Debris Management.

6 Ardani et al., 2009; UNEP, 2005; Srinivas and Nakagawa, 2007; Arslana and Cosgunb, 2008; Raufdeen, 2009 as cited by Karunasena, 260-263

outcomes are desired. Issues of disaster management tend to be undervalued, removing potential for creative ideologies in handling massive amounts of disaster debris. This can be overcome with intentions by the City and its citizens to weigh their costs and benefits, and to abide by these decisions. As with any major recovery decision, pushback from various stakeholders and groups should be expected, since long-term benefits may not be unanimously foreseeable in the immediate aftermath of the disaster.

### 6.1.2 Recommendations

Numerous case studies beyond California and the United States have made clear the necessity of discipline within a community following a disaster. Discipline in this sense means the strict regard for policy mandates, housing statutes, and obstinate “building-back-better” which should not be relaxed in a post-disaster scenario. This entails decision making through community dialogue with policy makers who can subsequently acknowledge pressing issues *prior to a disaster*. In this research, a factor requiring resolute decision is that of a mandated policy for material recovery from all construction and demolition sites. Implementation of this strategy following a disaster needs city-wide participation, from disaster managers to stake holders to community members, who must understand the necessary trade-offs required for a sustainable recovery. Without such discipline, great value is lost not only in recyclable materials, but that of the City’s tried and true recycling operations prior to a disaster. Out of such discipline can come resilience, which in this case means the vigor of pre-disaster systems, methods and functions that remain staunch in a disaster scenario. Encouragingly, San Francisco has garnered success in methods of material diversion, which can hopefully remain true given that policy mandates are not relaxed proceeding an earthquake.

Research and results from the simulation model provide insight on suggestions for disaster debris recycling as new material for refurbishing lost housing. These include:

- *Stabilizing or increasing mandated material recovery rate from C&D sites.* Relaxing of stringent ordinances provide short-term panacea, but prove to have grave repercussions in the long-run, as mentioned previously.
- *Establishing relationships with local Material Recycling Facilities, foundries, contractors and waste managers to be key drivers in recovery of disaster debris material.* This includes eco-industrial partnerships necessary for staging and processing material. Eco-industrial planning is the “matchmaking of adjacent industries around shared or exchanged resources which can result in job creation, foster a more diversified web of entrepreneurship and facilitate rapid and efficient recovery from future disasters.”<sup>7</sup> In other words, local industries that would typically be unrelated to disaster management can assist in progressing material diversion and reprocessing by adjusting their respective business plans following a disaster event. For example, a large scale foundry can provide services to reprocess rebar metal found in concrete buildings that have been dismantled by the earthquake. This new material can be input into the construction material stream for restoration of housing units. In this way, local

---

7 Duetz and Gibbs, 2004

eco-industrial collaborations can promote sustainable recovery. Eco-industrial partnerships also foster local supplies of material, and curb off-shoring of material processing for reuse. These partnerships require pre-disaster communication and dialogue such that post-disaster processes are streamlined and expedited.

- *Encouraging deconstruction over demolition with building contractors prior to the earthquake.* A result of this would be red-tagged units being hand-demolished rather than conventionally demolished to provide more recovered material for processing, further diverting from landfills. Although deconstruction requires twice the labor and time, it provides returns that are economically and environmentally beneficial. Table 6.1.1A describes the differences between deconstruction and demolition.

DECONSTRUCTION VS. DEMOLITION

	Deconstruction	Demolition
Cost	\$3.64/sq. ft.	\$1.74/ sq. ft.
Labor	12 people	5 people
Time	5 days	3 days
Man-Hours	480 hours	120 hours

**Table 6.1.1A. Deconstruction versus Demolition**

**Source: Deconstruction Institute, GreenHalo Systems. Note: For a typical 2000 square foot home**

- *Advocating for city- and region- wide prescience for housing retrofit and homeowner incentive for mitigative activities.* Research and results from this thesis attest to the advantages of retrofitting housing in San Francisco. Currently, only 10% of the housing stock is retrofitted, under which only a small percent have been retrofitted sufficiently. This means that many single- and multi- family units are extremely vulnerable to shaking impacts during an earthquake event. Retrofitting is primarily for life-safety purposes, but mandates can impel building code requirements for some level of building-life safety as well. Since every \$1 of mitigation activity equals \$4 of recovery activity, retrofitting is an appropriate means of safeguarding vulnerable populations in and around San Francisco. Additionally, if a home is retrofitted suitably, it is likely to be useful as shelter-in-place. This means that populace can reside in their homes following a disaster, since the housing has suffered little damage, deeming it shelter-in-place. Retaining citizens following a disaster is imperative for recovery, especially if San Francisco wants to reach pre-disaster operation levels and economies following a large-scale event.
- *Initiating preemptive and regional conversations that must take place in order that various cities can manage debris staging and processing corroboratively, since disasters cross jurisdictional boundaries.* Such conversations should reach populations as well, if eco-industrial partnerships are to be formed and linkages to be drawn. Citizens must be aware of their role and responsibility in material recovery and overall restructuring of their city for comprehensive recovery.
- *Campaigning for public education.* “By educating the public about disaster debris, we can

reduce materials placed into landfills and raise cash to offset costs. Involving the public requires a pre-planned educational program that starts, ideally, even before the disaster strikes. Citizens should know where to find information about debris management. The media can prepare public information messages, send reports to cover debris sites, and encourage residents to participate.”<sup>8</sup>

Researchers have also posed viable recommendations regarding disaster debris recycling. These include:

- Recycling as part of the community disaster debris management plan. Historically, planning for recycling “after-the-fact” has not been wholly successful
- Planning that ensures that recycling is cost-effective and the approach is streamlined to avoid delaying cleanup
- Planners who must work with recycling coalitions to identify available recycling infrastructure
- The political and regulatory environment must also support creation of the infrastructure necessary to recycle disaster debris<sup>9</sup>
- Predefining of prospective roles and function of the stakeholder’s involvement in debris management
- Establishing of a hierarchy of debris management, such as controlling, reuse, recycling and landfilling
- Enhancing of the institutional capacities
- Identifying local resources; plant, equipment, budget, expertise and material processing options
- Establishing of commercial relationships for resource recovery activities<sup>10</sup>

These recommendations beg for greater understanding and investigation of the economic streams of disaster debris recyclability and recycled content products, described in the following section.

### 6.1.3 *Economizing Recyclability of Disaster Debris*

After a disaster, specific value shifts of materials will occur. Construction materials will be in high demand, and markets for reprocessed debris can fill needs for new construction material. Although econometrics is grazed in the scope of this research, E.K. Lauritzen provides a financial perspective on recycling of construction and demolition waste relevant to this work. Lauritzen states that “from a purely economical point of view, recycling of building waste is only attractive when recycled products are competitive with natural resources for what concerns cost and quality. Recycled materials will normally be competitive where there is a shortage of both raw materials and suitable deposit sites. With the use of recycled materials, economical savings in transportation of building waste and raw materials can be

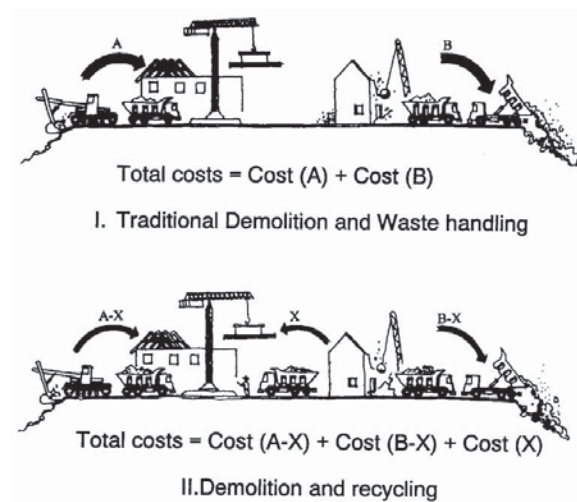
---

8 Friesen, Harder and Rifer, 1994, as cited by Phillips, 125

9 Reinhart, Planning tools for Disaster Debris Management

10 Ardani *et al.* as cited by Karunasena

obtained [Figure 6.1.3A].”<sup>11</sup>



**Figure 6.1.3A. Economic model of (I) traditional demolition and waste handling without recycling and (II) demolition and waste handling including recycling of materials. A; amount of natural materials and transportation; B; amount of transportation and disposal of waste materials; X; amount of recycled materials.**

Source: E.K. Lauritzen, 1998.

In larger post-disaster reconstruction projects, (such as Kobe, Japan) the economy will be dominated by the transportation costs. These transportation costs involve the removal of demolition products and the supply of new building materials. In these cases, the use of recycled materials becomes very attractive.<sup>12</sup>

Localizing supply chains in northern California can increase demands for Recycled Content Products (RCP) used in reconstruction. The suggestion here is to establish the framework for local RCP suppliers prior to a large-scale disaster such that the learning curve is reduced and local materials remain competitive throughout the recovery process. With the same sense, Transfer Stations or Material Recycling Facilities (MRFs) must be instated and operational on a broader, Bay Area level in a pre-earthquake, equilibrium state, for supply chains to be effective following a disaster. Simulation results attest to the benefits of increased Transfer Station/MRF capacity to the overall recyclability of disaster debris. They provide a staging, recovery, and processing ground such that useful material is diverted from landfills. Physical capacity has been discussed as being an obstacle for MRF prospectus; however, economic feasibility of these transfer stations must also be assessed. For MRFs to be economically viable, construction and demolition recycling should be a routine measure, which in San Francisco has been proven to be a successful means to recovering construction and demolition waste. If MRFs become competitive with landfills, with equal or less expensive tipping fees, then contractors will have no reason to give preference to landfilling rather than to depositing material to a recycling facility. Such incentives should be conceptualized and implemented before an imposing event, such that post-disaster operations are efficient.

Production and supply for RCP building materials depends on sufficient demand within the

11 E.K. Lauritzen, *Emergency Construction Waste Management*, 1998, 9-11

12 De Pauw and Lauritzen, 1994; Lauritzen, 1994 as referenced by E.K. Lauritzen 1998

region. Various actors can promote RCP demand based on their specified role to the recycling or rebuilding process. The type of reuse and recycling will establish demand from one of the following:

- Government department procurement directives
- The building owner, developer, client
- Members of the design team
- Persons who write specifications
- Main or specialist contractors

These actors will only specify RCPs if there is a good reason to do so. As always, “the foremost reason in many stakeholders’ perspective is that of cost. There are already many examples of reclaimed or reconditioned goods and RCPs that are most cost effective than virgin material, especially if they are locally processed. Cost alone, however, is not the only aspect that affects decisions about building design and construction. Other influences can also determine the demand for RCP processing and supplying. Some of these include:

- Legislation, especially related to the responsibility for and the cost of waste disposal
- Planning policy at the local authority level, which influences planning conditions, environmental design guidelines and waste targets
- Achieving credits in environmental assessment tools (such as LEED)
- The wishes of the client, perhaps encouraged by members of the project team

Such factors yet again justify the need for a broader city or regional based dialogue on usage of RCPs in the Bay Area. Many influential players can help make disaster debris recycling a viable option, including policy makers, disaster managers, and eco-industrial collaborators.”<sup>13</sup>

## **6.2 Future Work**

Applying system dynamics to a pre- or post-disaster framework has been a largely untapped method to assessing potential impacts to vulnerable communities. This methodology can present findings of relations and feedback loops that were not formerly anticipated or factored into the broader perspective of disaster management. For this reason, employing such a strategy for interpreting mitigation measures, humanitarian logistics, and recovery goals can be valuable for many hazard communities around the globe. The intent is to extend this type of research to cities that have faced a disaster and are in a reconstruction period, or cities that may require amplified mitigative actions.

Furthermore, this research will eventually continue to understand holistic Bay Area risks, and understand behavior of various factors attributing to recovery. Expansion of the model boundaries will require additional data mining, case studies, and consideration of built vulnerabilities.

### **6.3 Vision**

The overriding goal for this research is to unpack the variables influencing post-disaster effects. It bounds the research on aspects of disaster debris and housing, but could explore beyond these factors in the future. This research anticipates iterative evolution, and hopes that readers and stakeholders can contribute to data used for this work to foster understanding of the Bay Area's vulnerabilities. System models reveal great insight about processes that take place within a specified domain, and can influence policy decisions due to its temporal qualities. Applying such modeling to the San Francisco Bay Area can provide discernment to promote sustainable mitigative and recovery actions, and moreover, to encourage communities to participate in their resilience.



# APPENDIX



## APPENDIX A - DYNAMICS & RESULTS

### A1. Driving Model Equations Refer to 4B and 4C

“Anticipated Red-Tags” = 0.64

Units: Dmnl

64% of all red-tagged buildings are estimated to be damaged beyond habitation. These homes must go through the demolition/deconstruction line.

Construction = IF THEN ELSE ( Housing Units >= 330000, ( ( Construction Halt \* Units Under Construction ) / Time to Construct ) , ( ( ( ( Local RCP use Policy \* Imported Materials ) + ( 1 - Local RCP use Policy ) \* Recycled Content Building Materials ) ) \* “Unit/Ton” ) + Units Under Construction ) / Time to Construct ) \* Construction Halt )

Units: Units/Month

Converting recycled building material into constructed housing stock.

Construction Halt = 1 + STEP ( -1, 12 ) + RAMP ( ( 1 / 60 ) , 15, 75 ) + STEP ( -0.005, 75 )

Units: Dmnl

The halt in construction up to 3 months after earthquake.

Deconstructed Units = INTEG( MAX ( 0, Deconstruction Rate ) , 0 )

Units: Units

The number of deconstructed units over a specific time period.

Deconstruction Rate = IF THEN ELSE ( Units to be Demolished Deconstructed <= 0, 0, ( ( ( 500 + Post Earthquake Effects on Rate

\* Policy for Deconstruction \* Units to be Demolished Deconstructed ) / Delay in Deconstructing ) ) )

Units: Units/Month

The number of units per month that are destroyed via deconstruction. An estimated 30% of all building units are deconstructed.

Delay in Deconstructing = 4

Units: Month

About 4 months for processing and physically deconstructing unit .Typically twice the time of demolition.

Delay in Demolishing = 2

Units: Month

About 2 months for processing and physically demolishing a unit.

Demolish Rate = IF THEN ELSE ( Units to be Demolished Deconstructed <= 0, 0, ( ( ( 500 + Post Earthquake Effects on Rate

\* Percent Demolished \* Units to be Demolished Deconstructed ) / Delay in Demolishing ) ) )

Units: Units/Month

On Average, it is estimated that it takes 0.6 months (or 18 days) to demolish a building in an urban environment. The reciprocal of this is 1.64 units/month. An approximated 60%

of all units are demolished.

Demolished Units =  $\text{INTEG}(\text{MAX}(0, \text{Demolish Rate}), 0)$

Units: Units

The number of demolished units over a specified time frame.

Earthquake =  $(\text{Pulse Quantity} / \text{TIME STEP}) * \text{PULSE}(\text{Pulse Time}, \text{TIME STEP})$

Units: Units/Month

Effect of earthquake on system.

End of Life Rate =  $4.167 + \text{STEP}(-4.167, 12)$

Units: Units/Month

50 units per year (As per San Francisco Dept. of Building Inspection)

Housing Units =  $\text{INTEG}(\text{Construction} - \text{End of Life Rate} - \text{Units destroyed by Earthquake}, 330000)$

Units: Units

Number of existing units in San Francisco is about 330,000 residential. (CAPSS, ATC 52-1, page 9)

Import Delay = 2

Units: Month

From local foundry in Oakland, it takes about 2 months to ship recovered and processed materials back to the states upon order. These are bulk orders, and as such, must have enough of an order for it to be worthwhile to import to the Bay Area.

Imported Materials =  $\text{INTEG}(\text{Rate of Import}, 0)$

Units: tons

The rate of import is estimated to be 10,000 tons for all material.

Local RCP use Policy = 0.25

Units: Dmnl

The percent of local RCP vs. Imported material used in construction. Value above is multiplier for Imported product use.

Percent Demolished =  $1 - \text{Policy for Deconstruction}$

Units: Dmnl

100%- the percent of homes deconstructed equals the number of homes demolished per month.

Policy for Deconstruction = 0.001

Units: Dmnl

Estimated that 40% of buildings are deconstructed per month.

Post Earthquake Effects on Rate =  $\text{Lookup for Unit Destruction}(\text{Time})$

Units: Dmnl

Deconstruction and Demolition processes affected Post-Earthquake.

Pulse Quantity = 85000

Units: Units

Number of units destroyed by 7.2M earthquake (projected by ATC 52-1)

Pulse Time = 12

Units: Months

Time in simulation at which earthquake strikes.

Rate of Import = IF THEN ELSE ( Housing Units >= 330000, 0, ( 10000 / Import Delay ) )

Units: tons/Month

10,000 tons imported per month (approximate) and affected by delay time.

Rate to Deem Unsafe = IF THEN ELSE ( Uninhabitable Units <= 500, 0, 1000 \* Surveying )

Units: Units/Month

Surveying process to deem a building unsafe.

Recycled Content Building Materials = Recycled Building Materials \* "Pre-EQ" \* Effect of Lookup on Increased RCP Use

Units: tons

It is assumed that prior to the EQ, no recycled building products are used.

SF Housing Start Rate = 18.425 \* Construction Halt

Units: Units/Month

Number of Units started Per Month, Federal Reserve Statistics. This means 8.375 housing starts x 2.2 units/housing (average) = 18.425 .

Surveying = 1 + STEP ( 1, 12 ) + RAMP ( - ( 1 / 21 ) , 15, 36 )

Units: Dmnl

This value shows the acceleration of the surveying process after the earthquake to deem buildings safe/unsafe.

TIME STEP = 1

Units: Month

The time step for the simulation.

Time to Construct = 3.4 + STEP ( 2, 12 ) + RAMP ( - ( 2 / 15 ) , 25, 40 )

Units: Months

6 to 9 months for construction, average of 7.5 months. 7.5/2.2 units per home (Census 2010) about 3.4 months per unit.

Uninhabitable Units = INTEG( Units destroyed by Earthquake + End of Life Rate - Rate to Deem Unsafe , 0 )

Units: Units

Number of Uninhabitable Units needing some method of deconstruction/demolition.

"Unit/Ton" = 1 / 34.5

Units: unit/ton

As per calculations, one unit uses 34.5 tons/unit.

Units destroyed by Earthquake = Earthquake \* "Anticipated Red-Tags"

Units: Units/Month

Housing Units destroyed by earthquake, but not collapsed. These units are considered

“uninhabitable”

Units to be Demolished Deconstructed = INTEG( Rate to Deem Unsafe - Demolish Rate - Deconstruction Rate

, 0)

Units: Units

Number of Uninhabitable Units needing some method of deconstruction/demolition.

Units Under Construction = INTEG( MAX ( 0.001, SF Housing Start Rate - Construction ) , 0)

Units: Units

Units under Construction is an accumulation stock from San Francisco Housing Start Rate.

“Amount of C&D Recyclable (Avg.)” = 0.725

Units: Dmnl

Percentage of Classified Demolition/Deconstruction Waste that is recyclable. See Appendix D.

“C&D from Destructed Buildings” = IF THEN ELSE ( Housing Units >= 330000, 1, ( ( Deconstruction Rate + Demolish Rate ) \* Tons per Unit ) )

Units: tons/Month

The amount of material generated from deconstruction and demolition practices.

“C&D from EQ” = Tons per Unit \* ( Units Collapsed by Earthquake )

Units: tons/Month

Units collapsed by earthquake multiplied by tons per unit gives the amount of CD debris generated from buildings that have immediately collapsed.

“C&D MRF Capacity” = INTEG( Capacity Growth - Decline , 367500)

Units: tons

WIP of Transfer Station sites in/near SF.

“C&D on Site” = INTEG( “Rate of C&D Accumulation” - Transfer , 0)

Units: tons

“C&D to be Reused/Sorted” = INTEG( Transfer - Rate of Separation - To Landfill , 0)

Units: tons

This stock represents the material that is ready to be sorted. It includes all materials that are not Hazardous Household Wastes that are discarded via incineration, etc.

Capacity Growth = IF THEN ELSE ( “C&D MRF Capacity” >= 700000, 0, ( 10000 \* Effect of Capacity on Growth Rate

\* Normal Fractional Growth Rate ) / “Delay in C&D Capacity Growth” )

Units: tons/Month

Number of Tons in capacity growth per month with a constant 10 ton increase per month, and a maximum allowable of 700,000 tons.

Decline = “C&D MRF Capacity” \* Normal Fractional Decline Rate

Units: tons/Month

The natural decline rate of C&D Capacity.

“Delay in C&D Capacity Growth” = 9

Units: Months

9 months to increase capacity growth by at least 10,000.

Delay in Processing = 6

Units: Month

Delay in processing C&D materials into recycled, See Appendix D.

Effect of Capacity on Growth Rate = Lookup for Transfer Station Capacity Increase ( Fraction Used )

Units: Dmnl

Fraction Used gives the effect of Capacity Increase on the Transfer Station growth.

“Effect of Debris De/Acceleration” = “Rate De/Acceleration” ( Time )

Units: Dmnl

Effect of Debris De/Acceleration as per federal help (Army Corps of Engineers).

Effect of TS Capacity = “C&D MRF Capacity” / Maximum TS Capacity

Units: Dmnl

Ratio of TS capacity to rate of separation.

Effect on Transfer Rate = Look up for Transfer Rate ( Time )

Units: Dmnl

Look up for effects on Transfer Rate.

Fraction Used = IF THEN ELSE ( “C&D on Site” <= 0, 0, ( “C&D on Site” / “C&D MRF Capacity” ) )

Units: Dmnl

Fraction of Transfer Station Capacity indicates the amount of C&D materials/total Transfer Station capacity. 367,500 tons is estimated equilibrium capacity of Transfer Stations.

Landfill Accumulation = INTEG( To Landfill , 0)

Units: tons

SF Gate quotes 5 million tons to Yuba City in 10 years. This is about 500,000 tons of material that is expected to be generated each year.

Lookup for Transfer Station Capacity Increase ( [(0,0)-(10,20),(0,1),(0.5,1),(0.75,1.5),(0.978593,2)

, (1.1,4),(1.5,6),(2,8),(3,9),(4,10),(4,12),(5,14),(6,16),(7,16),(8,16),(9,16),(10,16),(11,16)

, (12,16),(12.844,16),(120,16),(150,16)], (0,1),(0.397554,1.31579),(0.636086,1.92982),(1.03364,3.3

3333)

, (1.23242,4.73684),(1.43119,6.40351),(1.59021,8.33333),(1.70948,10.5263),(2.02752,12.5439)

, (2.66361,14.386),(3.61774,15.7018),(4.77064,15.8772),(6.16208,16.0526),(6.24159,16.1404)

, (6.59939,15.9649),(7.51376,15.9649),(8,16),(9,16),(10,16),(11,16),(12,16),(12.844,16),(250,16)

)

Units: Dmnl

Table Lookup for capacity vs. number of Transfer Stations.

Maximum TS Capacity = 367500

Units: tons

367500 tons/month

Normal Fractional Decline Rate = 0.005

Units: 1/Month

Half a percent of the Transfer Station capacity declines each month due to normal degradation.

Normal Fractional Growth Rate = 0.2

Units: 1/Month

Normal fractional growth rate of each Transfer Station to start as 1/5 months or 0.2

“Percent C&D Recovered (Mandated)” = 0.65

Units: Dmnl

Per San Francisco Environmental Code Ch 14 and C&D Debris Recovery Ordinance, a minimum of 65% of C&D waste must be recovered.

“Percent C&D to Landfill” = MAX ( 0.2, 1 - “Percent C&D Recovered (Mandated)” )

Units: Dmnl

Per SF Environmental Code Ch 14 and C&D Debris Recovery Ordinance, a minimum of 65% of C&D waste must be recovered. The rest will presumably go to landfill.

Policy for Amount Processed Per Month = 0.4

Units: Dmnl

Minimum amount of recycling per month, estimated at 40% for little demand of recycled building products from local C&D demolition sources (SF has few demolition projects per month, therefore, recycling as building material may not initially have much demand).

“Rate of C&D Accumulation” = “Tons/Month of C&D from source” + “C&D from EQ” + “C&D from De-structed Buildings”

Units: tons/Month

From HDMT, 2008 data shows that SF generates 1600 tons of C&D waste, out of a nearly 5,400 ton solid waste transfer each day.

Rate of Recycling = IF THEN ELSE ( Recovered Materials <= 0, 100, ( ( Recovered Materials \* “Amount of C&D Recyclable (Avg.)”

\* Policy for Amount Processed Per Month ) - ( 0.1 \* “Amount of C&D Recyclable (Avg.)”

\* Recovered Materials \* Policy for Amount Processed Per Month ) ) / Delay in Processing )

Units: tons/Month

The rate of recycling is dependant on the Recovered Materials diverted from landfill, the amount of C&D recyclable, the percent of Recovered Material that actually becomes building materials, the delay in processing of this material, and a nominal amount of material lost in processing (0.074).

Rate of Separation = IF THEN ELSE ( “C&D to be Reused/Sorted” <= 0, 0, ( ( ( “C&D to be Reused/Sorted” ) - ( 0.1 \* ( “C&D to be Reused/Sorted” ) ) ) / “Time to Separate C&D” ) \* “Percent C&D Recovered (Mandated)”

\* Effect of TS Capacity \* “Effect of Debris De/Acceleration” ) )

Units: tons/Month

Approximate tonnage separated at SF C&D mixed recycling site. Quoted at 75 tons/hour or 1200 tons/day. Subtraction of 0.1 x C&D to be Reused/Sorted is to show that some material is



lost in process of separation.

Recovered Materials = INTEG( Rate of Separation - Rate of Recycling - Unrecyclable , 0)

Units: tons

Amount of C&D material recovered from Transfer Stations.

Recycled Building Materials = INTEG( Rate of Recycling - Sold to Market , 0)

Units: tons

Tons of Building Materials produced from recycled C&D material.

Road Clearance = 1 + STEP ( -0.5, 12) + RAMP ( ( 1 / 24) , 13, 25)

Units: Dmnl

This is the value of the amount of roads that may be impeded after an earthquake. In its equilibrium state, the RC = 1. Based off of GIS calculations and ABAG data, the number of miles of road that are affected due to the earthquake are about 25% of the total mileage. From the Loma Prieta earthquake, it is noted that on average, it took 134 days to clear the roads (rounded to one year for simulation).

Sold to Market = IF THEN ELSE ( Recycled Building Materials <= 2000, 0, 1000)

Units: tons/Month

The amount of recovered building materials that are sold per month.

“Time to Separate C&D” = 1.23

Units: Month

Takes 5 weeks or 1.23 month to separate one month’s worth of C&D. Approximation.

To Landfill = IF THEN ELSE ( “C&D to be Reused/Sorted” <= 0, 0, ( ( “Percent C&D to Landfill” ) \* ( “C&D to be Reused/Sorted” ) / Transfer Delay to LF ) \* “Effect of Debris De/Acceleration” ) )

Units: tons/Month

1057 x 30 = 31 710

Tons per Unit = 34.5

Units: tons/unit

600 sq ft and 750 sq ft footprint Single Family and Multifamily Homes, respectively. See Appendix B.

“Tons/Month of C&D from source” = 5760 + STEP ( -5670, 12) + RAMP ( ( 5670 / 66) , 14, 80)

Units: tons/Month

5760 Tons of C&D created on site per month: (1600-1800 tons of refuse/day x 30 day/month, with 12-30% C&D; lower bound represented. 5760 = 1600 x .12 x 30 CD in SF waste stream.

Transfer = IF THEN ELSE ( “C&D on Site” <= 20000, 5000, ( 20000 \* Road Clearance \* Effect on Transfer Rate

\* Effect of TS Capacity ) / Transfer Delay )

Units: tons/Month

As per calculations from Tri-Ced recycling CEO Richard Valle, about 20 large trucks in SF working at 15 tons/truck over one month is nearly 10,000 tons. Over 2 months will be 20,000 tons.

Transfer Delay =  $1 + \text{STEP}(-0.99, 12) + \text{RAMP}\left(\left(1 / 12\right), 13, 25\right)$

Units: Month

Two Months to move 20,000 tons of debris.

Transfer Delay to LF =  $1.1 + \text{STEP}(1, 12) + \text{RAMP}\left(-\left(1 / 35\right), 15, 50\right)$

Units: Month

About 1.1 month to transfer 1 months worth of landfill (to Livermore).

Units Collapsed by Earthquake =  $\text{Earthquake} * 0.36$

Units: Units/Month

36% of units will collapse on onset of earthquake.

Unrecyclable =  $\text{Recovered Materials} * \left(1 - \text{"Amount of C\&D Recyclable (Avg.)"}\right)$

Units: tons/Month

Assume the material that is not recovered each month is sent to landfill.

## GRAPHICAL SNAPSHOTS OF STOCKS

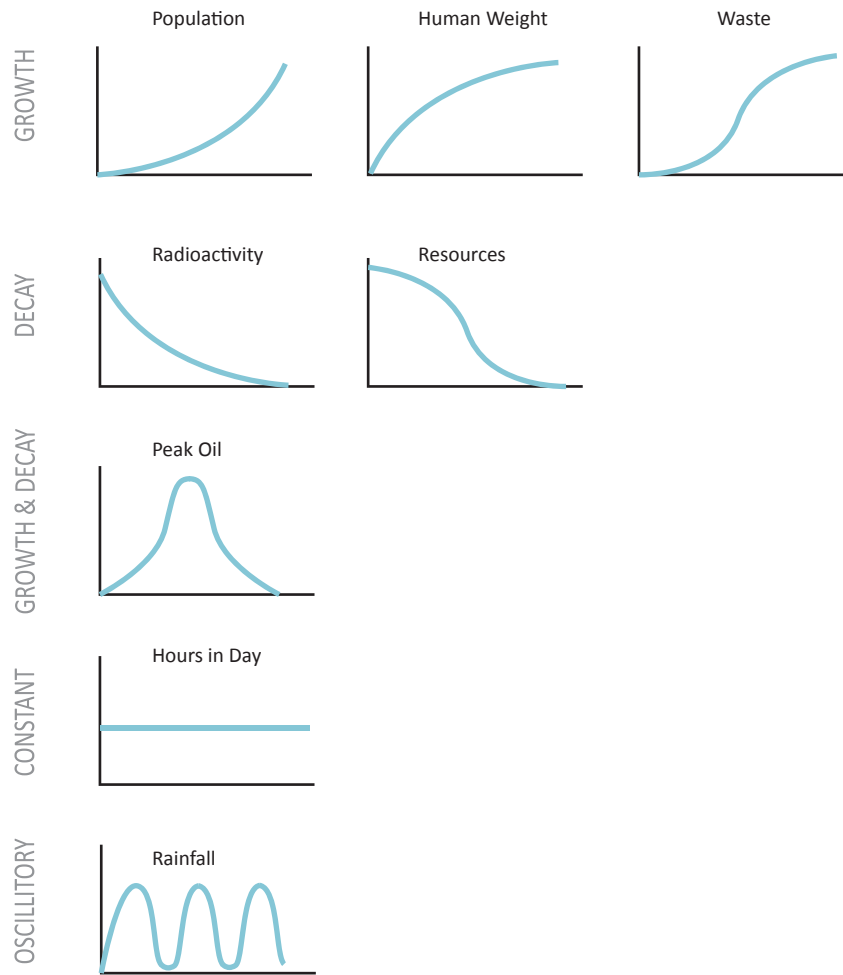
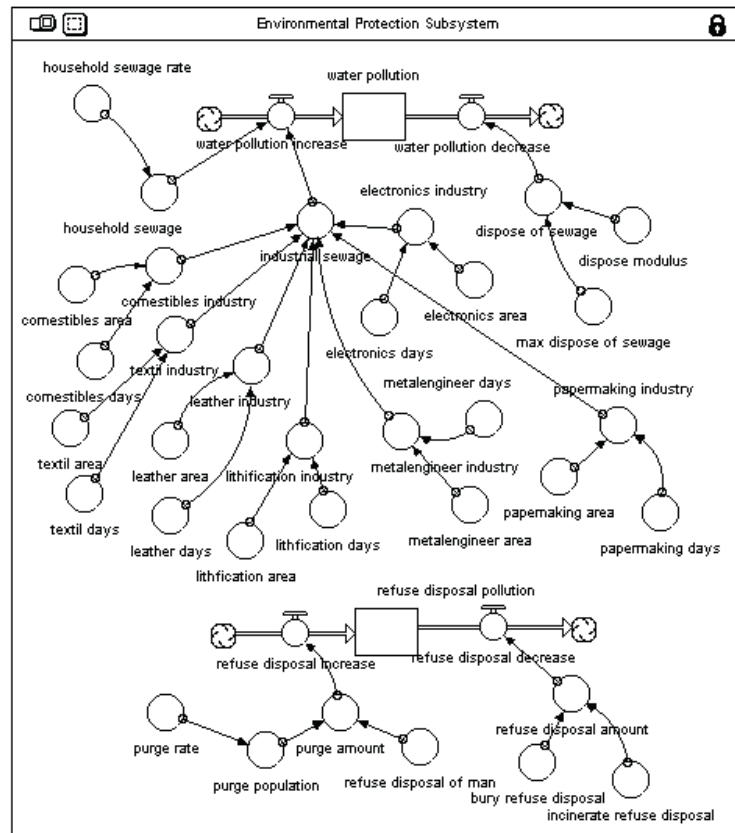


Figure A2. Various Behaviors of Stocks



**Figure A3. Environmental System Systems Model, Taichung City Earthquake.**  
Source: Ho, Lu and Wang, 2006

### Retrofit Cost

The following equation provides homeowners with a basic calculation when deciding for housing retrofit. It compares the cost of retrofitting to the associated risk of housing, as well as the risk of damage even after a retrofit has been completed. Since only 6% of retrofits are done accurately and thoroughly, chances of damage following housing retrofit is a possibility.

If

$$\text{Cost of Retrofit} + \left( \text{Cost of Rebuild} \times \text{\% chance Rebuild following Retrofit} \right) > \left( \text{Cost of Rebuild} \times \text{\% chance Rebuild without Retrofit} \right)$$

Then

**Don't retrofit**

Example (data from ATC 52-1, 52-3)

Cost to retrofit Scheme 1 (\$6.60/sq ft)

Cost to rebuild (approx.) \$250/sqft)

If all units were to be retrofitted to scheme 1

Percentage collapse would go down to 8% from 31%

Assume a unit is 1500 sq ft

Then

$$1500 \times 6.60 + (1500 \times 250 \times 0.08) = 40,000$$

$$1500 \times 250 \times 0.31 = 116,250$$

40k < 116.3K therefore, this homeowner should retrofit.

### A4- Retrofit Calculation

## Hauling and CO<sub>2</sub> 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 CO<sub>2</sub>/gallon (EPA)

Calculate the CO<sub>2</sub> 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

$$100 \text{ miles} / 3 \text{ miles/gallon} = 34 \text{ gallons per truck}$$

$$34 \text{ gallons per truck} \times 22.3 \text{ lbs CO}_2/\text{gallon} = 758.2 \text{ lbs CO}_2/\text{truck}$$

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:

$$1.096\text{M tons LANDFILLED} / 15 \text{ tons/truck} = \mathbf{73,066 \text{ trucks}}$$

$$73,066 \text{ trucks} \times 758.2 \text{ lbs CO}_2/\text{truck} = 55,399,147 \text{ lbs CO}_2 = 27,700 \text{ tons CO}_2 \text{ for diesel fuel}$$

Reduce by 90% for CNG estimate:

$$\mathbf{2770 \text{ tons CO}_2 \text{ WITH RECOVERY}}$$

Account for recovered material added to landfill material:

$$1.096\text{M} + 1.5\text{M} = 2.596\text{M}$$

$$2.596\text{M tons} / 15 \text{ tons/truck} = 173066.67 \text{ trucks}$$

$$17,3067 \text{ trucks} \times 758.2 \text{ lbs CO}_2/\text{truck} = 131219399.4 \text{ lbs} = 65609.6997 \text{ tons}$$

$$\text{Reduce by 90\%} = \mathbf{65,610 \text{ tons CO}_2 \text{ if NO RECOVERY}}$$

$$65,610 - 2770 \text{ CO}_2 = \mathbf{62,839 \text{ tons CO}_2 \text{ SAVED if recovery implemented over 6.8 years}}$$

Source: [www.informinc.org/fact\\_ggt.php](http://www.informinc.org/fact_ggt.php)

## A5- Hauling and CO<sub>2</sub> Emissions

## APPENDIX B - HOUSING

### Simulated Housing starts versus Projected

Using a 18,425 housing unit start per month from Federal Reserve Statistics<sup>1</sup> for driving model and comparing it to data from California Building Industry Association<sup>2</sup>, we find that the 2010 data projects an estimated 18 housing unit starts per month, showing negligible difference to the estimation used for this research.

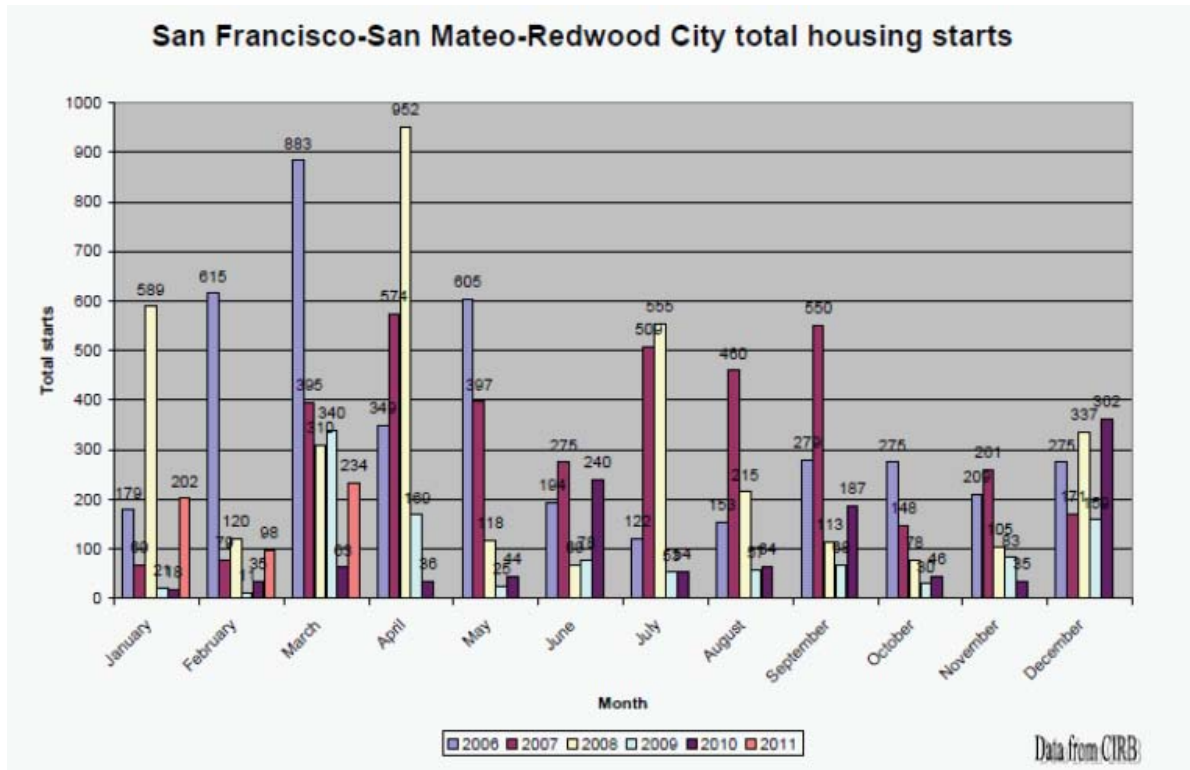


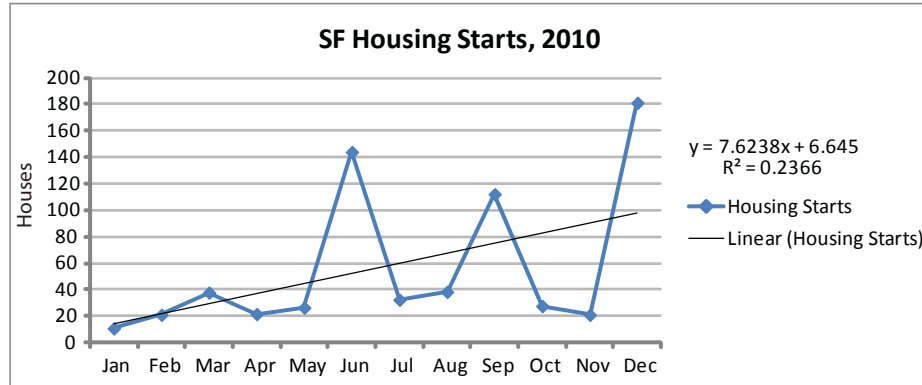
Figure B1. Total single family and multi-family housing starts for San Francisco, San Mateo and Redwood City

1 <http://www.federalreserve.gov/econresdata/statisticsdata.htm>

2 "Housing Starts," California Building Industry Association, 2010, California Building Industry Association, 11 Nov. 2011 < <http://www.cbia.org/go/newsroom/housing-statistics/housing-starts/>>.

Housing Starts, 2010, CBIA		
Month	Total, San Francisco, Redwood City, San Mateo	2010 San Francisco
Jan	18	10.8
Feb	35	21
Mar	63	37.8
Apr	36	21.6
May	44	26.4
Jun	240	144
Jul	54	32.4
Aug	64	38.4
Sep	187	112.2
Oct	46	27.6
Nov	35	21
Dec	302	181.2
<b>AVE</b>		<b>56.2</b>
CBIA, California Building Industry Assoc.		

**Table B2. Disaggregated Housing Start Data for San Francisco City**



**Figure B3. 2010 Housing Starts with Regression Analysis**

Using the above graph, an extrapolation of data using the regression equation yields nearly 18 housing unit starts per month, reinforcing the value used for simulation modeling.



### Destruction Permits Issued, 2011, San Francisco

MONTH	Permits for Destruction (Units)
January	8
February	4
March	12
April	2
May	16
June	1
July	2
August	1
September	3
October	0
November	0
December	1
Total Destroyed	
	50
Average Destroyed	
	4.17

**Table B4. Destruction Permits Issued, 2011.**  
**Source: San Francisco Department of Building Inspection**

## **Vulnerable Structures, as defined by California Action Plan for Seismic Safety, Report 52-1, 2010**

### *Concrete Buildings Built Before 1980*

Older reinforced concrete buildings can experience dramatic and deadly collapses during earthquakes. Such collapses are responsible for many of the casualties in earthquakes around the world. However, any older concrete buildings might remain standing but suffer a great amount of damage. Inside the columns, beams, walls and floor slabs of reinforced concrete buildings lay steel reinforcing bars. Ideally, these bars allow reinforced concrete buildings to not only carry loads from gravity, but also to withstand the side-to-side shaking caused by earthquakes. Older reinforced concrete buildings may not have enough steel inside them or may not have steel in adequate configurations to survive the level of shaking that will occur in San Francisco earthquakes.

The design and construction of Californian reinforced concrete buildings improved significantly in the mid-to-late 1970's. Engineers learned from dramatic failures of these buildings during the 1971 San Fernando earthquake in Southern California and other earthquakes. It took some years for these lessons to be reflected in building codes and new construction projects. This study assumes that all reinforced concrete buildings constructed before 1980 may have design problems. This date was chosen to be consistent with a focused earthquake hazard reduction program—the Concrete Coalition—that is working to study this type of building.

Many older concrete-frame buildings have unreinforced masonry walls filling the space between columns and floors to form walls for the exterior, elevator shafts, and stairwells. The masonry can help these buildings to remain standing during earthquakes, but the walls, being brittle, can crack and fall into or out of the building, creating significant dangers to those on sidewalks and causing damage that would be expensive and time-consuming to repair. Some of these buildings also have a softstory at the ground level, and could collapse. It is costly and difficult to reinforce these buildings before an earthquake and to repair them when they are damaged. There are older reinforced concrete buildings in San Francisco being used as apartment buildings, private schools, office buildings and warehouses. Thousands of people use these buildings daily. What is not known is which specific concrete buildings are most dangerous, and identifying the dangerous ones is challenging. Typically, it requires engineers with specific skills to conduct invasive and costly tests and analyze performance.

### *Unreinforced Masonry Bearing Wall Buildings*

Unreinforced masonry bearing wall buildings have long been recognized as one of the most dangerous types of buildings in earthquakes. These buildings are constructed with brick walls that bear the weight of the building. They typically have six or fewer stories and were built before the mid-1930's, when building codes were changed to prevent this type of construction. They perform very poorly in earthquakes. Building parapets and sections of walls can fall outward, and some buildings can collapse in even moderate shaking. This building type has been responsible for many deaths in past earthquakes.

San Francisco has been working to improve the safety of its unreinforced masonry bearing wall buildings for decades, first through an ordinance requiring parapets to be anchored, and later through an ordinance requiring most of these buildings to be retrofitted. As of the writing of this report, 90 percent (1,526 out of 1,699) of the buildings on the City's list of unreinforced masonry buildings had been retrofitted or demolished, and a remaining 10 percent were in process of becoming compliant with the ordinance, or were referred to the City Attorney's Office for enforcement. It is important to note that retrofitted unreinforced masonry buildings remain highly vulnerable to earthquakes. When exposed to strong shaking, it is likely that retrofitted buildings would cause significantly fewer casualties than those that have not been retrofitted, but many buildings could be damaged beyond repair, displacing their occupants and requiring demolition. A few hundred

masonry buildings were exempted from the City's retrofit ordinance, including buildings used only as residences with four or fewer units. It is likely that many of these remain unretrofitted.

#### *Welded steel moment frame buildings*

The welds connecting columns and beams in steel moment frame buildings built before 1994 can crack in earthquake shaking, leading to a reduction in their capacity to support the building. Before this vulnerability was discovered, this construction type was thought to have excellent seismic performance and, therefore, was popular for large office buildings. The 1994 southern California Northridge earthquake revealed this weakness. A number of San Francisco's downtown high-rises are welded steel moment frames.

#### *Concrete tilt-up buildings*

These buildings have precast concrete panels that are raised in place to form the building walls. If the walls are not adequately connected to each other and to the roof, they can separate when shaken by an earthquake, causing the roof to collapse on the occupants and contents of the building. This structure type is often used for industrial purposes, but may also be used for some grocery stores or other commercial purposes. There are an estimated 200 of these buildings in San Francisco.

#### *Older steel buildings with masonry infill walls*

San Francisco has many steelframe buildings from the early part of the last century with masonry walls filling the space between columns and floors to form walls for the exterior, elevator shafts, and stairwells. The steel is often encased in concrete for fireproofing purposes, making the building appear to be a concrete frame to a casual observer. The masonry walls in these buildings can crack up and fall into or out of the building, creating significant dangers to those on sidewalks and causing damage that would be expensive and time-consuming to repair. These buildings are used as residences and offices, and many have beautiful period architectural detailing.

#### *Hillside Buildings*

San Francisco's characteristic hills have led to many buildings that have more stories on one side than the other. For example, it is common to see buildings with one or two stories of street frontage, but three or four stories when seen from the back. Structurally, buildings with irregular heights can be especially vulnerable to earthquake shaking, particularly if the lower levels have a soft-story or other structurally deficient condition.

#### *Cladding, Finishes and Chimneys*

Buildings of all structural types have elements that can fall off during earthquakes, particularly if their connections have deteriorated due to age or corrosion. These elements can hurt people or affect the functionality of a building. They include cladding (outside finishes of glass, brick, stone, or other materials), and decorative elements. Masonry chimneys are brittle and often lack reinforcing steel. During earthquakes they can snap at the roof or pull away from a building. Falling bricks can crash through roofs or onto the ground below.

### **B5- Vulnerable Housing Type Description**

### *Falling hazards and utility failure*

There are a variety of non-structural issues that can lead to deaths and injuries, or make buildings unusable. These include tipping of heavy furniture and equipment and falling light fixtures or objects on shelves. Falling hazards can be serious, even in buildings that are structurally sound. For example, studies following the 1999 Kocaeli earthquake near Istanbul, Turkey found that nearly half of the casualties were caused by non structural elements rather than damage to the building structure. A variety of non-structural issues can also make buildings unusable, such as inoperable elevators or destruction of furniture due to water damage.

**Estimated Damage to Wood-Frame Soft-Story Buildings in Various Earthquake Scenarios**

Scenario	Dollar Loss* (\$Billions)	Estimated Distribution of 2,800 Buildings with Large Openings by Post-earthquake Safety Tagging Category			
		Green Tag (% of Buildings)	Yellow Tag (% of Buildings)	Red Tag – No Collapse (% of Buildings)	Red Tag – Collapse (% of Buildings)
Magnitude 6.9 Hayward Fault	\$3.2	33 - 49	19 - 27	18 - 30	6 - 18
Magnitude 6.5 San Andreas Fault	\$3.6	22 - 42	17 - 27	23 - 39	8 - 23
Magnitude 7.2 San Andreas Fault	\$4.1	6 - 35	9 - 23	32 - 54	11 - 31
Magnitude 7.9 San Andreas Fault	\$4.4	1 - 33	2 - 18	37 - 62	12 - 35

\* The total estimated value of these buildings and their contents is approximately \$14 billion. This excludes the value of the land.

M: Magnitude

**Table B6. Red-Tag Estimates**

64% damaged beyond repair is an average of high values between columns 3 and 4;  $31/85 = 36\%$  collapse on impact and  $54/85 = 64\%$  are red tagged for demolition/repair. Source: California Action Plan for Seismic Safety, 2010.

### Estimated Damage to Housing, HAZUS Study

Scenario	Retrofit	SPUR Performance Level Among 2,800 Buildings (%)				
		A	B	C	D	E
Magnitude 6.9 Hayward Fault	As-is	15%	18%	19%	30%	18%
	1	50%	22%	18%	8%	2%
	2	68%	16%	10%	6%	0.3%
	3	72%	16%	9%	3%	0.2%
Magnitude 6.5 San Andreas Fault	As-is	9%	13%	17%	39%	22%
	1	38%	23%	23%	13%	4%
	2	56%	20%	15%	9%	1%
	3	59%	20%	15%	6%	0.3%
Magnitude 7.2 San Andreas Fault	As-is	2%	5%	9%	54%	31%
	1	17%	19%	28%	28%	8%
	2	35%	22%	24%	18%	1%
	3	44%	23%	21%	12%	0.7%
Magnitude 7.9 San Andreas Fault	As-is	0%	1%	2%	62%	35%
	1	4%	8%	21%	52%	14%
	2	10%	14%	26%	47%	3%
	3	13%	15%	26%	44%	3%

Note: SPUR performance levels are color-coded to indicate an equivalency with the ATC-20 UNSAFE placard/tag (red), RESTRICTED USE placard/tag (yellow), and INSPECTED (apparently safe) placard/tag (green).

**Table B7. Housing Damage by Earthquake Magnitude.**  
**Source: California Action Plan for Seismic Safety, 2010**

### Residential Building and Dwelling Units and Value Used in CAPSS Report

Size of Building	Number of Buildings <sup>a</sup>	Number of Dwelling Units <sup>b</sup>	Value <sup>c</sup> (\$ Billions)
Single-Family houses	112,000	112,000	\$53
Two unit residences	19,000	38,000	\$22
Three or more unit residences <sup>d</sup>	23,000	180,000	\$45
Total <sup>e</sup>	150,000	330,000	\$120

a. These numbers are estimates for 2009.

b. Note that dwelling unit counts may vary from what is presented in other tables due to different source materials. The counts presented in this table represent a best effort using all available data sources to match building counts with unit counts.

c. These figures represent an estimate of the cost to replace or reconstruct a building in 2009. They do not include the value of the land the building sits on or a building's contents. Replacement values are significantly different than real estate prices or assessed valuation. Building value is based on square footage from the San Francisco Assessor's Tax Roll, not the estimated number of buildings.

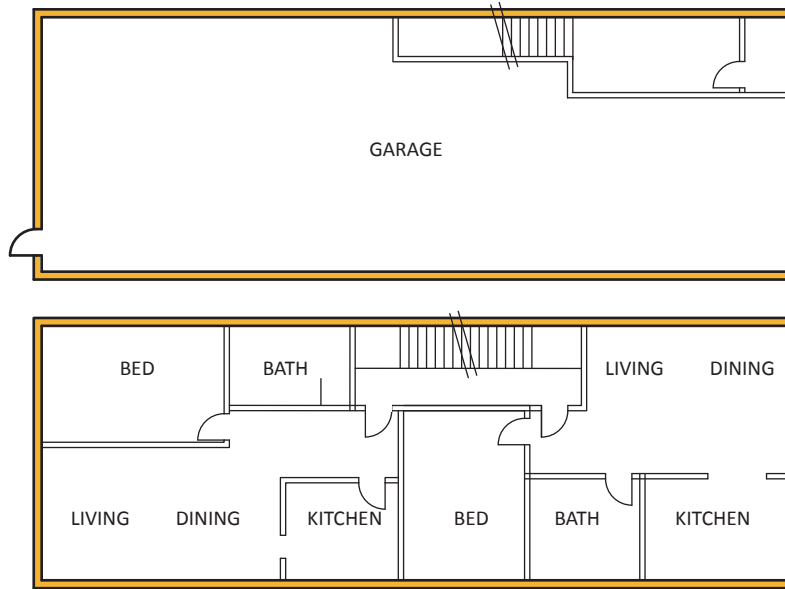
d. Note that wood-frame residences with three or more stories and five or more units, discussed in the companion CAPSS report *Earthquake Safety for Soft-Story Buildings* (ATC 52-3 Report), are a subset of these buildings. That report discusses that there are an estimated 4,400 of those buildings built before May 1973, with 45,000 units, valued at about \$14 billion. Many, but not all, have a soft-story condition.

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

Sources: This study, San Francisco Assessor's Tax Roll, Census data, San Francisco Planning Department, and San Francisco Department of Building Inspection.

**Table B8. Residential Building and Dwelling Units and Value. Source: California Action Plan for Seismic Safety, 2010**

### Average Housing Unit, San Francisco



Scale 1/128" = 1'-0"

**Figure B9. Average Housing Unit, Floor Plan**

**Note:** Dimensions are 21.2' x 63.6' and is typically within a 4 storey building. Assumed four units per floor.



**Figure B10. Example Multi-Family Unit. Source California Action Plan for Seismic Safety, 2010**

### SIMPLIFIED MATERIAL COMPOSITION IN HOUSING UNITS

Material In Housing	Percentage (%)
Concrete	78.25
Drywall	2.42
Wood	17.28
Asphalt	0.7
Steel	1.35
	100

**Table B11. Material in Housing. Simplified and average calculation from RS Means calculation of single-family and multi-family units.**

**Tonnage per Unit, Single-Family Unit in San Francisco**

ASSEMBLY TYPE	MATERIAL	UNITS	QTY	SINGLE FAMILY UNIT 3 STY 1 UNIT 1800	Cubic Feet	Cu. Yd	Multiplier from Debris Mgmt Plan from Cu Yd to Tons*	Tons	Percentage (%)
<b>Foundation</b>				<b>600 SQ FT FOOT PRINT</b>					
01. Footing System									
	8" Thick x 18" Wide Concrete	C.Y.	0.04	24		24	1	1	78.25
	1/2" Steel Rebar	Lb.	1.38	828			1	0.414	1.35
<b>Framing</b>									
01. Floor Framing Systems									
	2"x10" 16" O.C. Wood Joists	L.F.	1	600	83.33	3.08	0.4	1.232	4.02
	5/8" CDX Plywood Sheathing	SQ. FT.	1	600	31.25	1.15	0.4	0.46	1.50
02. Exterior Wall Framing System									
	2"x6" @16 O.C. Wood Studs	L.F.	1	600	50	1.85	0.4	0.74	2.41
	1/2" CDX Plywood Sheathing	SQ. FT.	1	600	25	0.9259	0.4	0.37036	1.21
03. Gable Roof Framing System									
	2"x4" @16 O.C. Ceiling Joists	L.F.	1	600	33.33	1.23	0.4	0.492	1.60
	2"x6" @16 O.C. Wood Rafter	L.F.	1.17	702	58.5	2.16	0.4	0.864	2.82
	1/2" CDX Plywood Sheathing	SQ. FT.	1.17	702	29.25	1.083	0.4	0.4332	1.41
04. Partition Framing System									
	2"x4" @16 O.C. Wood Studs	L.F.	1	600	33.33	1.23	0.4	0.492	1.60
<b>Exterior Wall Cladding</b>									
01. Wood Siding System									
	1/2"x 6" Beveled Siding	SQ. FT.	1	600	12.5	0.4629	0.4	0.18516	0.60
<b>Roofing Cladding</b>									
01. Gable Roofing System									
	Asphalt Shingles	SQ. FT.	1.16	696	14.5	0.537	0.4	0.2148	0.70
<b>Interiors</b>									
01. Drywall Wall System									
	1/2" Sheet Rock	SQ. FT.	1	600	25	0.9259	0.4	0.37036	1.21
	3/4"x6" Wood Baseboard	L.F.	0.125	75	2.34375	0.086	0.4	0.0344	0.11
02. Drywall Ceiling System									
	1/2" Sheet Rock	SQ. FT.	1	600	25	0.926	0.4	0.3704	1.21
								<b>30.67 Tons / Unit</b>	<b>100</b>

Single Family Unit Construction - RS Means  
 \* Multiplier as cited in San Francisco Debris Management Plan

**Table B12. Tonnage per Unit, Single-Family Unit**



### Tonnage per Unit, Multi-Family Unit in San Francisco

ASSEMBLY TYPE	MATERIAL	UNITS	QTY	Multi Family Unit 4 STY 3 UNITS 3000SQFT	Cubic Feet	Cu. Yd		
Foundation				750 SQ FT FOOT PRINT*				
	01. Footing System							
	8" Thick x 18" Wide Concrete	C.Y.	0.04	30.00		30.00	1.00	30.00
	1/2" Steel Rebar	Lb.	1.38	1035.00			1.00	30.00
								0.52
Framing								
	01. Floor Framing Systems							
	2"x10" 16" O.C. Wood Joists	L.F.	1.00	750.00	104.17	3.84	0.40	1.54
	5/8" CDX Plywood Sheathing	SQ. FT.	1.00	750.00	39.06	1.44	0.40	0.58
	02. Exterior Wall Framing System							
03. Gable Roof Framing System	2"x6" @16 O.C. Wood Studs	L.F.	1.00	750.00	62.50	2.30	0.40	0.92
	1/2" CDX Plywood Sheathing	SQ. FT.	1.00	750.00	31.25	1.15	0.40	0.46
							0.40	
	2"x4" @16 O.C. Ceiling Joists	L.F.	1.00	750.00	41.67	1.53	0.40	0.61
	2"x6" @16 O.C. Wood Rafters	L.F.	1.17	877.50	73.13	2.70	0.40	1.08
04. Partition Framing System	1/2" CDX Plywood Sheathing	SQ. FT.	1.17	877.50	36.56	1.35	0.40	0.54
							0.40	
	2"x4" @16 O.C. Wood Studs	L.F.	1.00	750.00	41.67	1.53	0.40	0.61
	Exterior Wall Cladding							
01. Wood Siding System								
	1/2"x 6" Beveled Siding	SQ. FT.	1.00	750.00	15.63	0.58	0.40	0.23
	Asphalt Shingles	SQ. FT.	1.16	870.00	18.13	0.67	0.40	0.27
Roofing Cladding								
	01. Gable Roofing System							
Interiors								
	01. Drywall Wall System							
	1/2" Sheet Rock	SQ. FT.	1.00	750.00	31.25	1.15	0.40	0.46
	3/4"x6" Wood Baseboard	L.F.	0.13	93.75	2.93	0.11	0.40	0.04
02. Drywall Ceiling System							0.40	
	1/2" Sheet Rock	SQ. FT.	1.00	750.00	31.25	1.15	0.40	0.46
								38.32
								34.50 Tons / Unit

Single Family Unit Construction - RS Means

\*Multiplier is occupiable floor area per unit

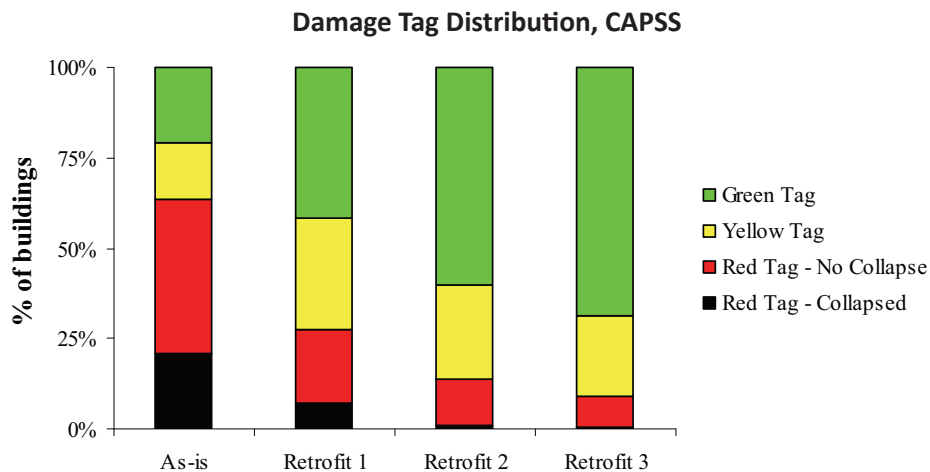
\*\*\* Multiplier as cited in San Francisco Debris Management Plan

Table B13. Tonnage per Unit, Multi-Family Unit

### Retrofits Examined, CAPSS

Retrofit Scheme	Description
1	Retrofit 1 targeted SPUR Level D as the intended performance. This was approached by identifying and retrofitting the specific exterior wall lines that were clearly vulnerable. This approach assumed that by addressing the obvious vulnerability, the performance of the building would increase to match the performance of similar buildings without the obvious vulnerability. Typical retrofit measures included steel moment frames and oriented strand board (OSB) shear walls being added in the ground story.
2	Retrofit 2, like Retrofit 1, typically involved use of steel moment frames and OSB shear walls. A greater extent of OSB shear wall was provided in Retrofit 2 than in Retrofit 1.
3	This was approached by replacing the steel moment frames with steel cantilevered columns, while maintaining the seismic force level used for proportioning the system. Because the cantilevered columns are designed using an R factor of 2.5 rather than the moment frame R of 8, their use led to lower deflections, which should translate to a lower cost of repair.

**Table B14. Retrofit Schemes. Source: California Action Plan for Seismic Safety, 2010**



**Figure B15. Distribution of Damage Tags Before and After Retrofit Schemes. Magnitude 7.2 earthquake on San Andreas Fault. Corresponding to schemes described in Table B14. Source: California Action Plan for Seismic Safety, 2010**

## **APPENDIX C - DEBRIS & WASTE**

### **Definitions of Construction and Demolition Waste**

**by California Integrated Waste Management Board, Waste Characterization Study, 2008, 117-118.**

Concrete means a hard material made from sand, aggregate, gravel, cement mix and water. Examples include pieces of building foundations, concrete paving, and concrete/cinder blocks.

Asphalt Paving means a black or brown, tar-like material mixed with aggregate used as a paving material.

Asphalt Composition Shingles means composite shingles composed of fiberglass or organic felts saturated with asphalt and covered with inert aggregates. Does not include built-up roofing. Commonly known as three tab roofing.

Roofing Tar Paper/Felt means a heavy paper impregnated with tar or a fiberglass or polyester fleece impregnated with tar and used as part of a roof for waterproofing.

Roofing Mastic means a paste-like material used as an adhesive or seal in roofing applications.

Built-up Roofing means other roofing material made with layers of felt, asphalt, aggregates, and attached roofing tar and tar paper normally used on flat/low pitched roofs usually on commercial buildings.

Other Asphalt Roofing Material means any other roofing material containing asphalt that cannot be put into any of the other roofing material types.

Clean Dimensional Lumber means unpainted new or demolition dimensional lumber. Includes materials such as 2x4s, 2x6s, 2x12s, and other residual materials from framing and related construction activities. May contain nails or other trace contaminants.

Clean Engineered Wood means unpainted new or demolition scrap from sheathed goods such as plywood, particleboard, wafer board, oriented strand board, and other residual materials used for sheathing and related construction uses. May contain nails or other trace contaminants.

Clean Pallets and Crates means unpainted wood pallets, crates, and packaging made of lumber/engineered wood.

Other Wood Waste means wood waste that cannot be put into any other material type. This type may include untreated/unpainted scrap from production of prefabricated wood products such as wood furniture or cabinets, untreated or unpainted wood roofing and siding, painted or stained wood, and treated wood.

Clean Gypsum Board means unpainted gypsum wallboard or interior wall covering made of a sheet of gypsum sandwiched between paper layers. Examples include used or unused, broken or whole sheets. Gypsum board may also be called Sheetrock, drywall, plasterboard, gypboard, Gyproc, or wallboard. Painted/Demolition Gypsum Board means painted gypsum wallboard or interior wall covering made of a sheet of gypsum sandwiched between paper layers. Examples: This type includes used or unused, broken or whole sheets. Gypsum board may also be called Sheetrock, drywall, plasterboard, gypboard, Gyproc, or wallboard.

Rock, Soil and Fines means rock pieces of any size and soil, dirt, and other matter. Examples include rock, stones, sand, clay, soil, and other fines. This type also includes non-hazardous contaminated soil.

Remainder/Composite Inerts and Other means inerts and other material that cannot be put in any other type. This type may include items from different types combined, which would be very hard to separate. Examples include brick, ceramics, tiles, toilets, sinks, and fiberglass insulation. This type may also include demolition debris that is a mixture of items such as plate glass, wood, tiles, gypsum board, and aluminum scrap.

#### **C1- Definitions of C&D Waste**

#### **Materials Recovery Facility Cost versus Landfilling Cost**

MRF	Landfill
Construction Cost	Contract Cost
\$1.4M - \$2.2M	\$6.6M
Savings	up to \$4.4 Million

**TABLE C2. Adapted from Handbook: Material Recovery Facilities for Municipal Solid Waste, Peer Consultants, P.C. and CalRecovery, Inc., 1991.**

**Note:** Values for MRF construction cost are not including variable cost or equipment cost; an increase of 70,000 tons/month will result in up to \$2.2M in construction costs. Landfill contract cost is based on a \$22 M contract for 10 years, 3 landfill years equals \$6.6 M. Source: Material Recovery Facility, TN, 2003.

### Debris Generated by 7.9 Magnitude San Andreas Earthquake

Wood/Brick/Other Area (mi)	Low (Tons)	Amount/Area (Tons/Sq Mi)	x1000 (Tons)
0.19	120.00	120	
3.06	50.00	16.34	
16.59	20.00	1.21	
17.83	5.00	0.28	
5.38	0.00	0	
Total Sq Miles Affected	Average 195.00	137.83	
43.05			
	Avg. x Total Sq Mi	5,933.40 tons	5,933,402.46
Concrete/Steel Area (mi)	Low (Tons)		x 1000 (Tons)
2.062	210.00	101.84	
1.73	120.00	69.36	
7.79	50.00	6.42	
29.07	5.00	0.17	
5.1	0.00	0	
Total Sq Miles Affected	Average 385.00	177.8	
45.75			
	Avg. x Total Sq Mi	8,134.59 tons	8,134,591.98
		Total	14,067,994.44

**Table C3. Debris Generated by 7.9 Magnitude San Andreas Earthquake.**  
Source: San Francisco Disaster Debris Management, 2010

### Debris Generated and Material Required for Reconstruction

SF Debris Management Guide (Debris from buildings due to shaking and liquefaction of 7.9M)	Low average	Normalized to 7.2M earthquake generating 6.8M tons generated (tons)	Percentage Material Needed for Recovery	Debris Generated Residential Wood Frame Only: Number of Units destroyed x tons/unit = 85k x 34.5 (tons)
Brick/Wood/Other Debris tons	5,900,000	2,400,000	0.358	
Concrete & Steel Debris tons	8,100,000	4,400,000	0.647	
<b>Total</b>	<b>14,000,000</b>	<b>6,800,000</b>	<b>1</b>	<b>2932500</b>

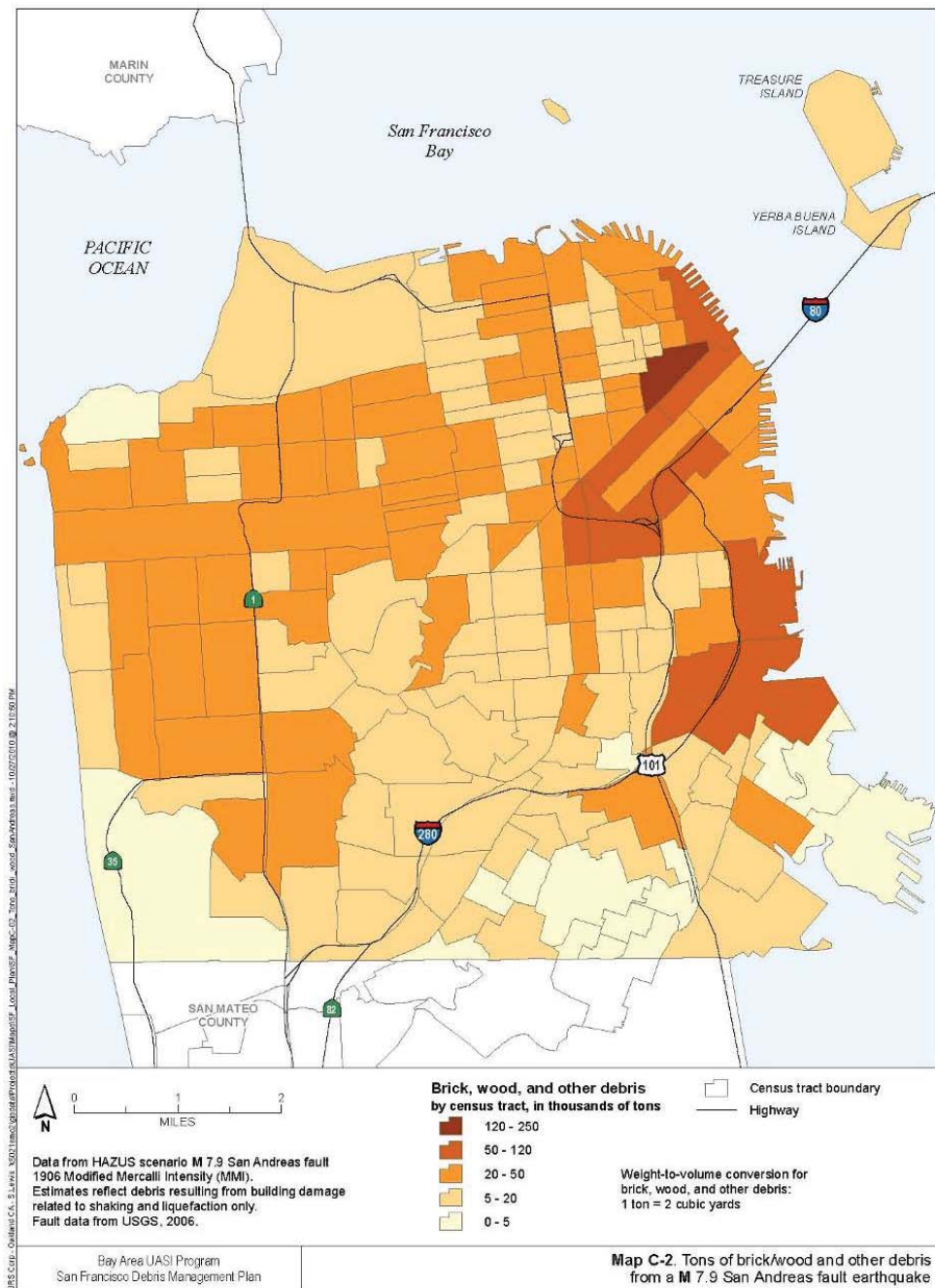
**Table C4. Debris Generated and Material Required for Reconstruction.**

### Debris Estimates for the Four CAPSS Scenarios

Type of Debris	Amount of Debris in Million Tons			
	San Andreas M6.5	Hayward M6.9	San Andreas M7.2	San Andreas M7.9
Light Debris: Brick, Wood and Other Debris	1.5	1.2	2.4	4.1
Heavy Debris: Concrete and Steel	2.4	2.2	4.4	8.7
<b>Total</b>	<b>3.9</b>	<b>3.4</b>	<b>6.8</b>	<b>12.8</b>

**Table C5. Debris Estimates for San Francisco.**  
Source: California Action Plan for Seismic Safety, 2010

## Tons of Brick/Wood and Other Debris from 7.9 San Andreas Earthquake



**Figure C6. Tons of Brick/Wood and Other Debris.**  
Source, San Francisco Debris Management Plan, 2011

Map C-3. Tons of concrete/steel from a M 7.9 San Andreas fault earthquake

Bay Area UASI Program  
San Francisco Debris Management Plan

Data from HAZUS scenario M 7.9 San Andreas fault  
1906 Modified Mercalli intensity (MMI).  
Estimates reflect debris resulting from building damage  
related to shaking and liquefaction only.  
Fault data from USGS, 2006.

Weight-to-volume conversion  
for concrete/steel:  
1 ton = 1 cubic yard

Concrete and steel debris  
by census tract, in thousands of tons

- 210 - 1200
- 120 - 210
- 50 - 120
- 5 - 50
- 0 - 5

Census tract boundary  
Highway

0 1 2  
MILES

N

MARIN COUNTY

San Francisco Bay

TREASURE ISLAND

YERBA BUENA ISLAND

PACIFIC OCEAN

80

101

280

92

94

SAN MATEO COUNTY

143

**MATERIALS AS PERCENTAGE  
OF WASTE STREAM**

Material	%age of waste stream by weight
Timber/Wood/ Lumber Waste	43
Brick	5
Asphalt Paving	1
Asphalt Roofing	6
Concrete	10
Gypsum	10
Remainder/Composite C&D	6
Rock soil and fines	11
Steel	8
Clay Tile Roofing	
Plastic	
GreenWaste	
Mixed Debris	
White Goods	
Treated Wood	
Urban Wood Waste	
Cardboard	
Total	100

**Table C8. C&D Materials in California Waste Stream. Adapted from California Integrated Waste Management Board Waste Characterization Study, 2004**

**Note:** Dark shaded materials are not included in simplified waste stream composition for this research.

### **Key Issues in Emergency Construction Waste Management**

*Principle of time-priority of the work*

- Rescue demolition in order to rescue trapped persons
- Emergency demolition and protection work in order to re-establish supplies and infra structures, save historic buildings, and secure unstable buildings
- Clearance and demolition work related to the planned reconstruction programs

*Principle of resources*

- Selective demolition and separation of waste
- Sorting of waste in main fractions with respect to recycling or disposal
- Optimal utilization of available waste treatment facilities and disposal sites
- Optimal use of natural and re-useable resources
- Minimum transport of materials for construction and wastes for disposal

*Principle of execution- demolition and waste planning and control*

- Damage and waste assessment and classification of damaged buildings
- Planning and implementation of demolition work and recycling facilities
- Waste stream control including assignment of suitable disposal sites
- Traffic planning and control
- Protection of buildings, etc., of historic or cultural value

**Source:** Adapted from Lauritzen 1998, Table 3, pp. 51

### **C9- Key Issues in Emergency Construction Waste Management**



## Debris by Event Type

Disaster Types	Debris Streams										
	Construction & Demolition (C&D)	Household Hazardous Waste (HHW)	Hazardous Waste	Vegetative	Personal Property (Household Items)	White Goods	Putrescent	Electronic Waste	Vehicles & Vessels	Soil, Mud & Sand	Sandbags
Wildfires	X	X	X	X	X	X		X	X	X	X
Floods	X	X	X	X	X	X	X	X	X	X	X
Earthquakes	X	X	X		X	X	X	X	X	X	
Tsunamis	X	X	X	X	X	X	X	X	X	X	X
Hurricanes/Typhoons	X	X	X	X	X	X	X	X	X	X	X
Tornadoes	X	X	X	X	X	X	X	X	X		
Severe Storms/High Winds	X	X	X	X	X	X	X	X	X	X	X
Acts of Terrorism*	X		X				X		X	X	
Ice Storms			X	X							

Table C10. Debris by Event Type

Source: Debris Management Overview, California Emergency Management Agency, 2010



## APPENDIX D - RECYCLABILITY

### Permitted Active Volume Transfer Sites near San Francisco

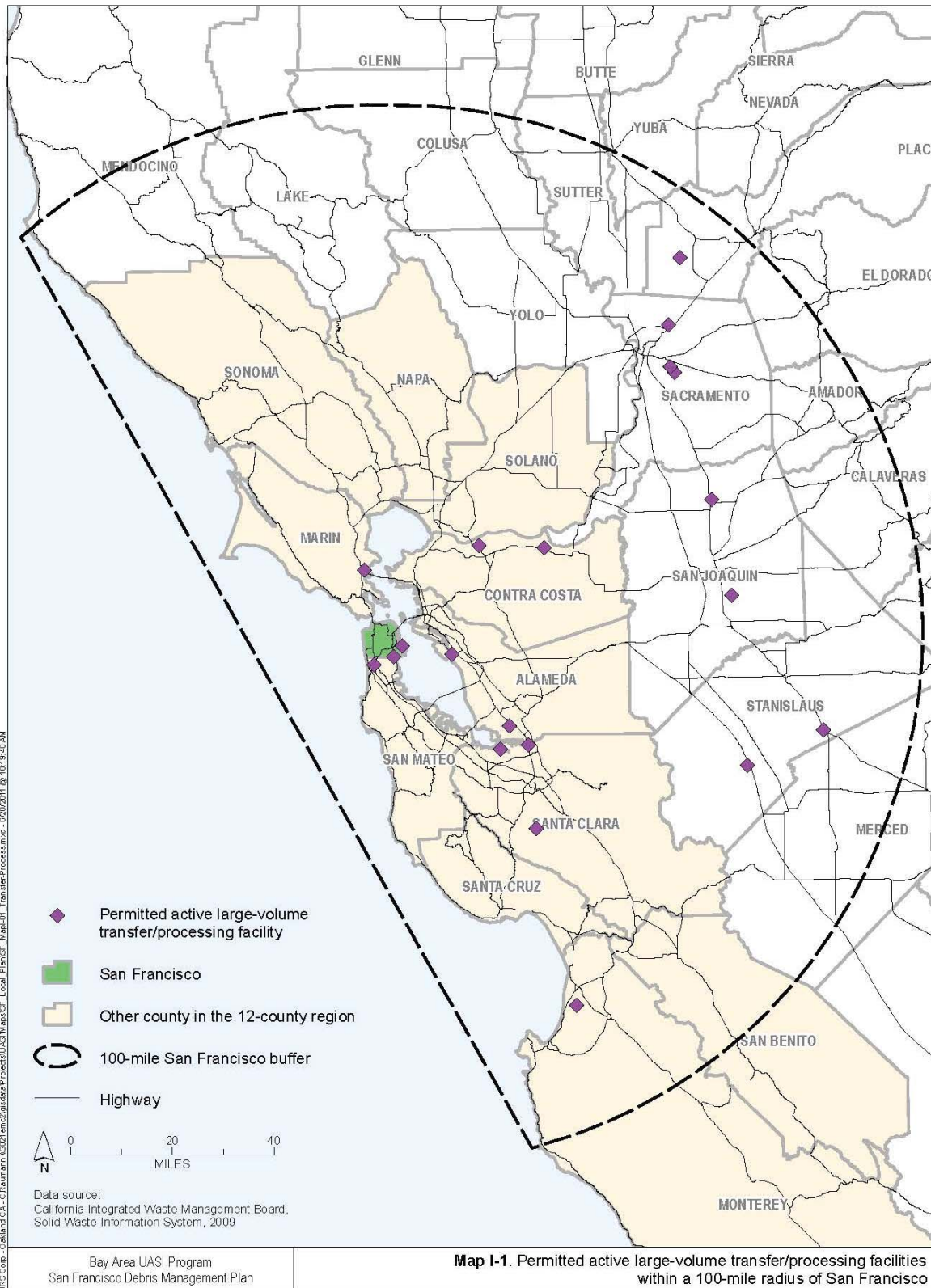


Figure D1. Permitted Active Large-Volume Transfer/Processing Facilities, SF Debris Management Guide

**SUGGESTED RECYCLABILITY  
OF MATERIALS**

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 D2. 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 D3.

## METHODS OF RECYCLABILITY OF DEBRIS MATERIAL

Material	Recycl-ability (%)	Second-life Uses
Timber/ Wood/ Lumber Waste	50%	<ul style="list-style-type: none"> <li>-Wood waste generated during site work can be ground up and recycled with greenwaste</li> <li>-Wood from the demolition process requires more labor-intensive disassembly of materials to remove fasteners and finishes and should be screened for lead paint</li> <li>-Recycled wood can be ground into wood chips or wood flour and used to make composite or engineered lumber products, mulch or composted</li> <li>-Unseparated waste wood is sometimes burned to produce waste electricity</li> <li>-Clean wood waste can be more easily used as feedstock for engineered lumber</li> <li>-Lumber and other wood products can be directly reused or ground and used for boiler fuel, mulch and engineered lumber. Care should be taken to separate lead-based paint coated wood and chemically treated lumber</li> <li>-Large timbers and dimensional lumber removed from demolition operations can be reused or recut for construction 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</li> <li>-Composite wood based thermoplastic products</li> </ul>
Brick	95%	<ul style="list-style-type: none"> <li>- Brick has a salvage value of \$400 per ton, clean and stacked on a pallet.</li> <li>-The process of cleaning mortar from brick, however, can be labor intensive, removing much of the profit from this process.</li> <li>-Brick remains, however, a very recyclable CD material that recyclers will often accept at no cost. Non-salvageable brick can be crushed and used as aggregate base or backfill material</li> <li>-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.</li> </ul>
Asphalt Paving	75%	<ul style="list-style-type: none"> <li>-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 purchased.</li> </ul>
Asphalt Roofing	75%	<ul style="list-style-type: none"> <li>-Recycling of Asphalt composition roofing results in aggregate base, asphalt pavement and pavement cold patch</li> <li>-Asphalt shingles can be recycled into new asphalt pavement mixes. They can also serve two purposes at a cement kiln: combustion of the shingles provided energy in the kiln and the remaining mineral components containing the limestone granules, serve as raw material for cement</li> </ul>
Concrete	80%	<ul style="list-style-type: none"> <li>-Crushed, screened and used as road base. Aggregates can be recovered from this process and used in the production of new concrete, in regions where aggregates are not readily available</li> <li>-Recycled concrete must be used with caution due to strength parameters</li> <li>-preferably for foundation and site work</li> </ul>
Gypsum	95%	<ul style="list-style-type: none"> <li>-Gypsum dry wall can be recycled into new drywall, cement and agricultural uses.</li> <li>-Drywall gypsum can be recycled 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</li> <li>-Potential markets for drywall waste: cement plants use large quantities of virgin gypsum to clinker, stucco additive, ; drywall wastes from demolition waste can be recycled for nonagricultural markets;</li> </ul>
Steel	85%	<ul style="list-style-type: none"> <li>-Steel C&amp;D is very recyclable due to its lack of contamination by dissimilar materials.</li> <li>-85% of C&amp;D steel is currently recycled by recyclers</li> <li>-Good markets exist for ferrous metals such as iron and steel, as well as other non-ferrous metals such as copper, brass and aluminum.</li> <li>-Metal is almost always recycled back into other metal products and recycling opportunities are available in virtually every area around the country</li> </ul>
Treated Wood	25%	<ul style="list-style-type: none"> <li>-Treated wood should be handled separately from vegetative debris being recycled</li> <li>-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 preservatives that can contaminate recycled wood products; these woods can be combusted in waste to energy facilities.</li> </ul>

**Table D3. Material Recyclability Methods**

## DEMOLITION DEBRIS RECYCLING OPTIONS

Demolition Material	Disposal/Recycling Options
Asphalt (paving and shingles)	Recycle into new asphalt pavement, disposal in bulky waste landfill, or use as clean fill on or off site if local and state regulations allow.
Earth/Soil	Recycle by incorporation into new asphalt pavement, disposal in bulky waste landfill, or use as clean fill on or off site if allowed by local and state regulations.
Electrical (fixtures and wiring)	Recycle metal components and dispose of remaining components in solid waste disposal area.
Insulation (non-asbestos, rigid polystyrene, fiberglass bat and roofing)	Disposal in bulky waste or solid waste disposal area as allowed by state and local regulations.
Masonry and Rubble (bricks, cinder blocks, concrete and mortar, porcelain, rock, stone, and tile)	Bulky waste landfill. May be used as clean fill and/or recycled if allowed by regulations; processing such as crushing may be required.
Metal (plumbing, electrical, gutters, sheet metal, structural steel, rebar and studs)	Recycle by selling to scrap metal dealer who will, in turn, sell the scrap to a smelter to be recycled.
Plastics (pipes, styrofoam, vinyl siding and laminate)	Dispose in bulky waste landfill or send to a recycler if local market exists.
Roof Materials ((non-asbestos shingles, built up roofing and tar paper)	Dispose in bulky waste landfill or recycle by use as an aggregate in asphalt pavements.
Vinyl (siding, flooring, doors, and windows)	Reuse if removed intact or dispose in bulky waste or solid waste disposal area as allowed by regulations.
Wood (treated and non-treated lumber)	Dispose in bulky waste landfill, reuse as structural timber as is or after remilling, recycle by processing and use as boiler fuel, landscaping, compost, animal bedding, or for engineered building products.
Wall Coverings (drywall and plaster)	Dispose in bulky waste landfill or grind up for use as a soil amendment or a substitute for lime on lawns (if regulations allow).
Glass	Dispose in a bulky waste landfill or collect and send to a glass recycling facility.

**Table D4. Demolition Debris Recycling Options.**

**Adapted from Burgess and Giroux, 1997, Cited in Ardani, Table 3, 1999**

APPENDIX E - DELAYS

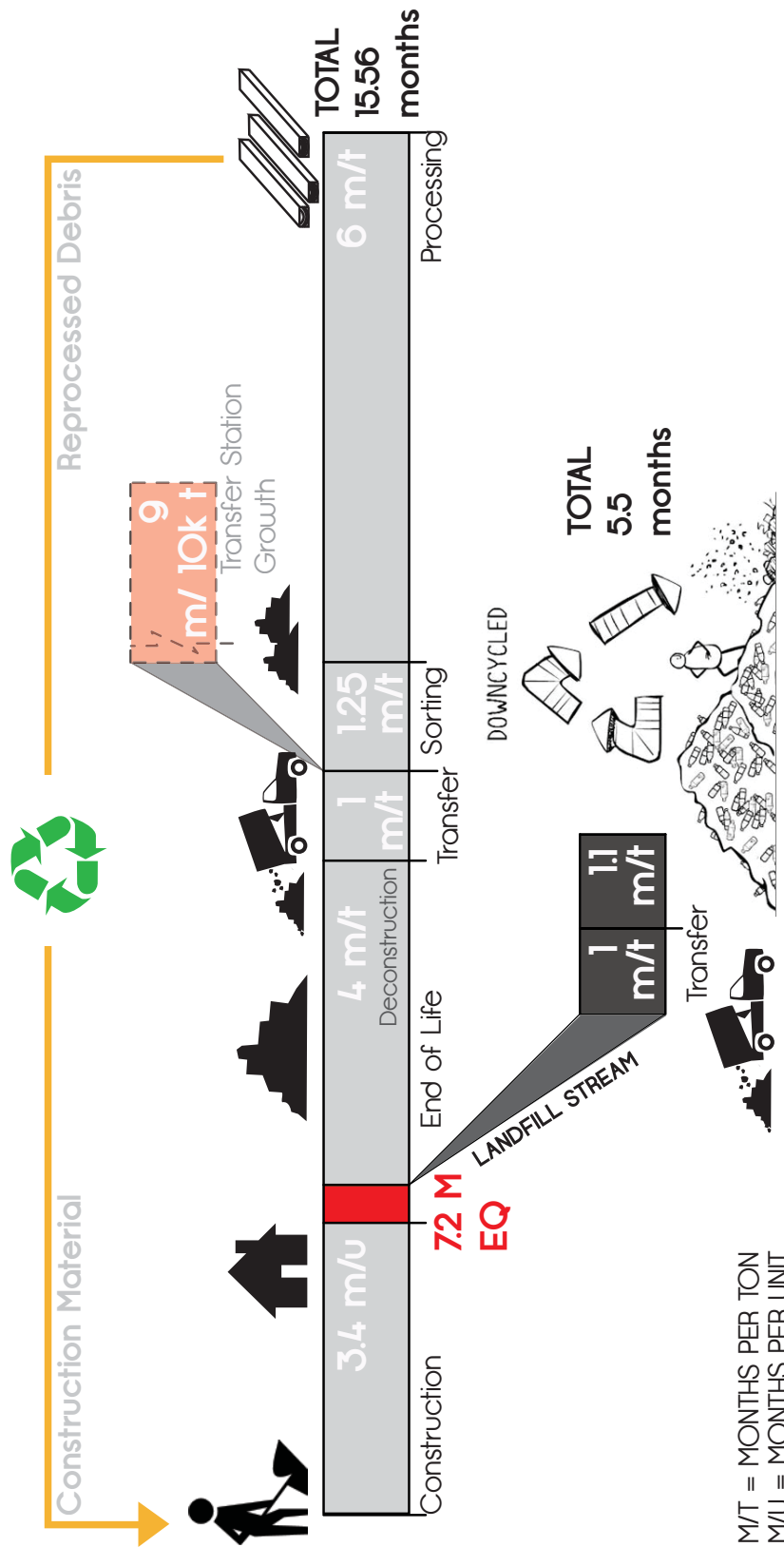
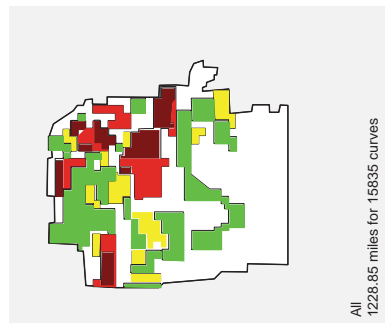


Figure E1. System Delays, Lumber Processing

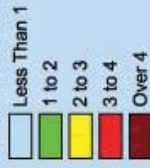
# Road Closure Delays, adapted from Associated Bay Area Governments



## ROAD CLOSURES

Model of the 1906 San Francisco Earthquake Magnitude 7.9

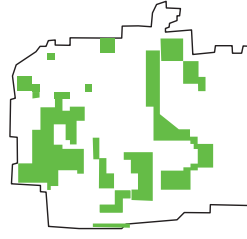
Number of Closures by Census Tract



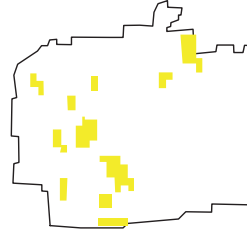
**HOW TO INTERPRET THESE MAPS:** These road closure maps are not intended to be site-specific. Rather, they depict the general risk within neighborhoods and the relative risk from community to community. Use these maps to estimate the level of disruption of the transportation system in a neighborhood, not to count road closures. Severity of disruption ranges from light blue, indicating insignificant disruption, to brown, indicating major disruption.

**Source: ABAG, 2003.**  
Current version of map available on Internet at <http://quake.abag.ca.gov/traffic>.

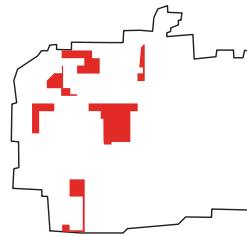
Extrapolated by z.saiyed



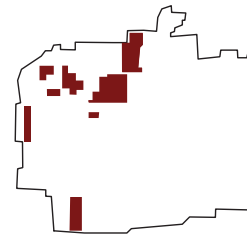
1-2 (Green) // 337.29 miles



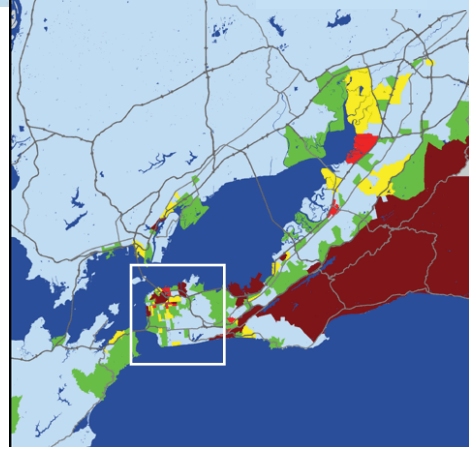
2-3 (Yellow) // 101.74 miles



3-4 (Red) // 127.09 miles



Over 4 (Dark Red) // 110.93 miles



[http://www.abag.ca.gov/bayarea/eqmaps/eqtrans/penm\\_rsl.html](http://www.abag.ca.gov/bayarea/eqmaps/eqtrans/penm_rsl.html)

Figure E2. Road Closures



APPENDIX F - RECOVERY

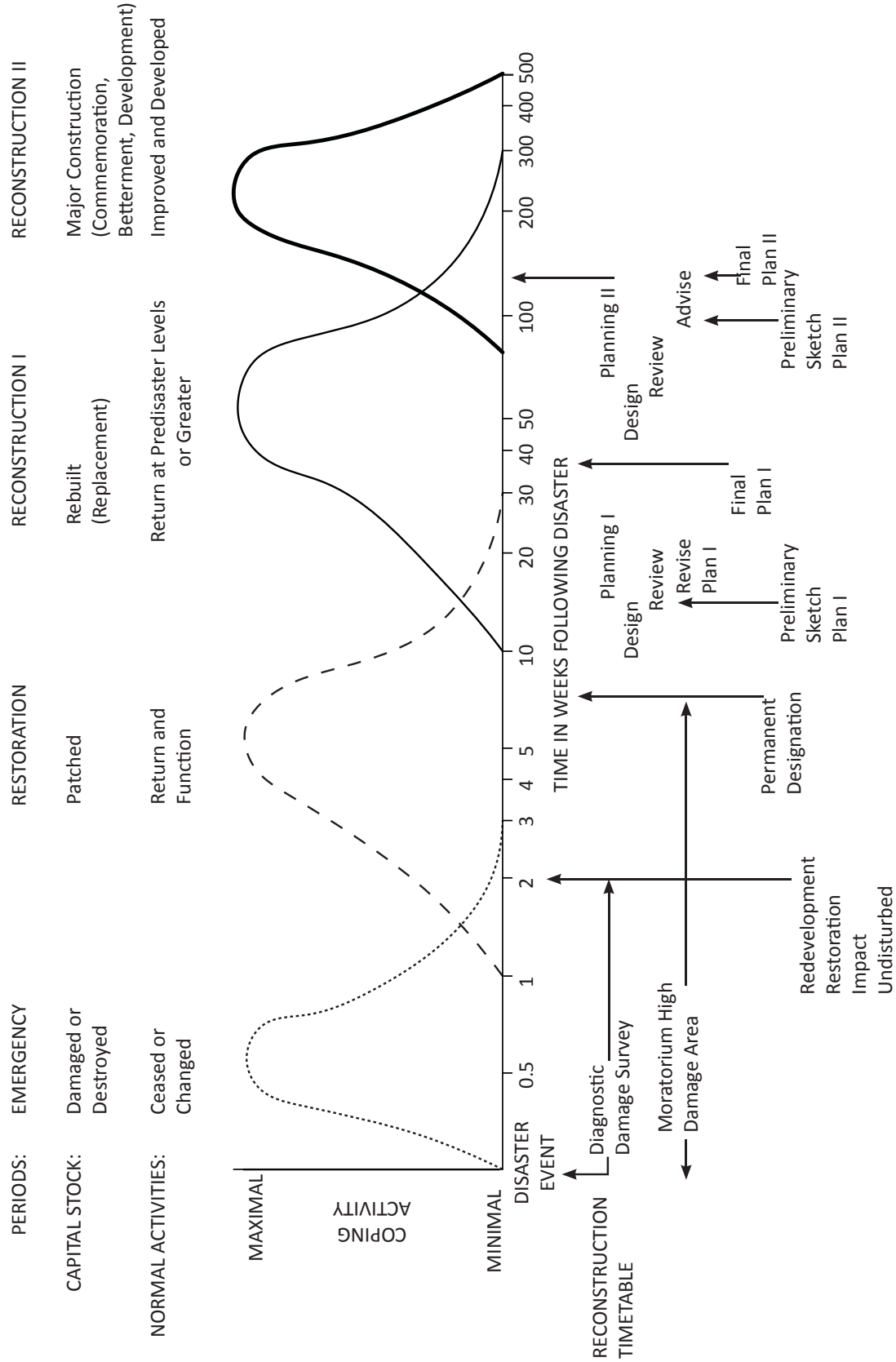
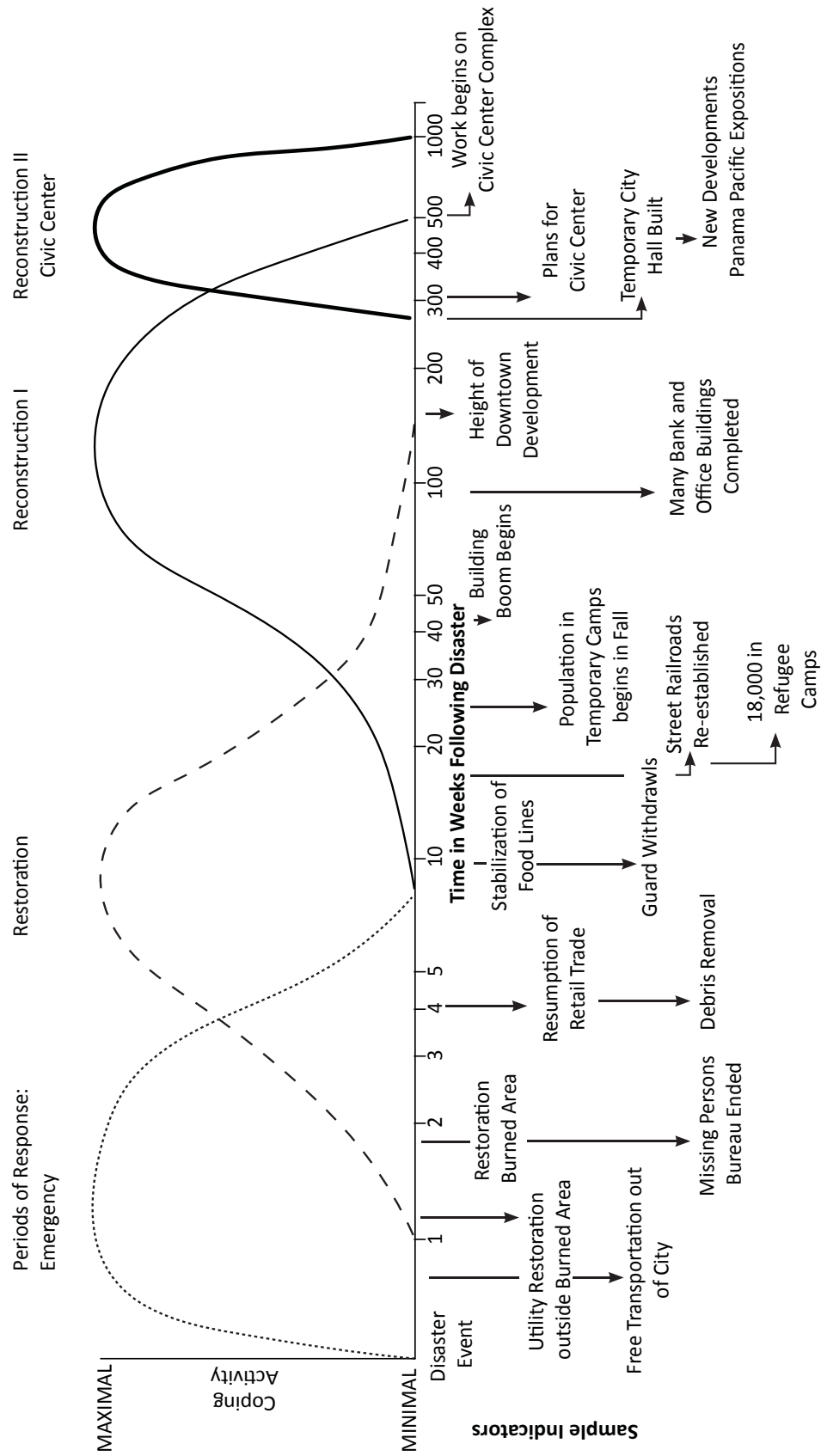


Figure F1. Reconstruction Timetable  
Source: Adapted from Reconstruction Following Disaster, 1977



**Figure F2. Reconstruction Timetable, San Francisco after 1906**  
 Source: Vale and Campanella, 2005; Adapted from Reconstruction Following Disaster, 1977

# REFERENCES

- Addis, William. *Building with Reclaimed Components and Materials: A Design Handbook for Reuse and Recycling*. London Sterling, VA: Earthscan, 2006.
- Ajayi, O.M., A.A. Soyingbe, and Olandirn, O.J. "The Practice of Waste Management in Construction Sites in Lagos State: Nigeria." *RICS Construction and Building Research Conference*. London, 2008. 1-9.
- Alameda County Waste Management Authority. *Alameda County Disaster Waste Management Plan*. Alameda County Waste Management Authority with assistance from EMCON. , 1998.
- Applied Technical Council, 52-1 & 52-1A. *Here Today - Here Tomorrow: The Road to Earthquake Resilience in San Francisco*. Redwood City: ATC, 2010.
- Applied Technical Council. *Here Today—Here Tomorrow: The Road to Earthquake Resilience Earthquake Safety for Soft-Story Buildings* 52-3. Redwood City: ATC, 2009.
- Ardani, Kristen B., Charles C. Reith, C. Josh Donlan. "Harnessing Catastrophe to Promote Resource Recovery and Eco-industrial Development." *Journal of Industrial Ecology* (Yale University), 2009: 579-591.
- Association of Bay Area Governments. *Shaken Awake*. ABAG, 2011.
- Awotona, Adenrele. *Reconstruction After Disaster: Issues and Practices*. England Brookfield, Vt: Ashgate, 1997.
- Baycan, F. and M. Petersen. "Disaster Waste Management -C&D Waste." *ISWA, Annual Conference of the International Solid Waste Association*. Istanbul, Turkey, 2002. 117-125.
- Blakely, E. "Collaborating to Build Communities of Opportunity. ." *Roosevelt Institute Symposium*. New Orleans, 2007.
- Brunner, Paul. *Practical Handbook of Material Flow Analysis*. Boca Raton: CRC/Lewis, 2004.
- Burgoyne, Dan. *Construction & Demolition (C&D) Waste Diversion in California*. Department of General Services, California.
- California Emergency Management Agency. *Debris Forecasting and Estimating*. CAL EMA, 2010.
- . *Debris Management Overview*. California EMA, 2010.
- . *Debris Management Plan*. California EMA, 2010.
- . *Disaster Debris Management Concept of Operations*. California emergency Management Agency, Recovery Division Technical Assistance Programs, 2010.
- CalRecycle. *California Integrated Waste Management Plan*. CalRecycle, 1997.
- Carter, W. *Disaster Management: A Disaster Manager's Handbook*. Manila, Philippines: Asian Development Bank, 1992.
- Cheng, F.Y., Y.Y. Wang. *Post-Earthquake Rehabilitation and Reconstruction*. New York: Pergamon, 1996.
- City and County of San Francisco, Public Works and Engineering Annex. *Appendix B: Disaster Debris Management Plan*. San Francisco: City and County of San Francisco, 2010.
- City and County of San Francisco. *City and County of San Francisco Municipal Code: Environmental Code*.

Tallahassee, Florida: Municipal Code Corporation, 2006.

—. *Construction and Demolition Debris Recovery Program Ordinance No. 27-06*. City and County of San Francisco, 2006.

—. "Disaster Debris Management Plan, Appendix B of Public Works and Engineering Annex." San Francisco, 2011.

Coke, Janet L. "Recycling Program Diverts Debris from Earthquake Cleanup." *Public Works*, 1995: 50-51.

Comerio, M., Howard Blecher. "Estimating Downtime from Data on Residential Buildings after the Northridge and Loma Prieta Earthquakes." *Earthquake Spectra* (Earthquake Engineering Research Institute) 26 (2010): 951-965.

Comerio, Mary. *Disaster Hits Home: New Policy for Urban Housing Recovery*. Berkeley: University of California Press, 1998.

—. "Post-Disaster Housing." *The Great East Japan Earthquake and Disasters: One Year Later*. San Francisco: UCSF, 2012.

Deutz, P and D. Gibbs, 2004. "Eco-industrial development and economic development: Industrial ecology or place promotion." *Business Strategy and the Environment* 13(5) 347-362.

Dolan, P.J., Lampo, R.G. and Jacqueline C. Dearborn. *Concepts for Reuse and Recycling of Construction and Demolition Waste*. US Army Corps of Engineers, 1999.

Donovan, Sharon. "Hurricane Andrew: Waste Haulers and Managers Ease Crisis." *Waste Age*, 1992: 24,126.

DSM Environmental Services, Inc. *2007 Massachusetts Construction and Demolition Debris Industry Study*. Massachusetts Dept. of Environmental Protection, 2008.

Environmental Protection Agency. "Estimating Building-Related Construction and Demolition Material Amounts." 2003.

—. *Planning for Disaster Debris*. United States Environmental Protection Agency, 1995.

—. "Planning for Natural Disaster Debris." 2008.

—. *Waste Transfer Stations: A Manual for Decision-Making*. EPA.

—. *Public Assistance: Debris Management Guide*. FEMA-325, 2007.

—. *Estimating Building Related Construction and Demolition Materials Amounts*. EPA, 2003.

—. *Planning for Natural Disaster Debris*. EPA, 2008.

Ford, Andrew. *Modeling the Environment: An Introduction to System Dynamics Models of Environmental Systems*. Washington, D.C.: Island Press, 1999.

Franklin Associates. "Characterization of Building-Related Construction and Demolition Debris in the United States." Prairie Village, 1998.

Friesen, G., Harder, J. and W. Rifer. "Closing the loop after the storm." *Resource Recycling* , 1994: 37-44.

- Goumans, J.J.J. M, Guy R. Woolley, Peter John Wainwright. *Waste Materials in Construction: WASCON 2000*. Harrogate, England: Proceedings of the International Conference on the Science and Engineering of Recycling for Environmental Protection, 2000.
- Governor's Office of Emergency Services, Oakland, San Francisco, San Jose. "San Francisco Bay Area Regional Emergency Coordination Plan." 2008.
- Haas, J. Eugene, Robert W. Kates, Martyn J. Bowden. *Reconstruction Following Disaster*. Cambridge: MIT Press, 1977.
- Hinte, Ed van, Cesare Peeren, Jan Jongert. *Superuse: Constructing New Architecture by Shortcutting Material Flows*. Rotterdam: 010 Publishers, 2007.
- Ho, Yufeng, Chienhao Lu and Hsiao-Lin Wang. *Dynamic model for earthquake disaster prevention system: a case study of Taichung City, Taiwan*. Thesis, Taichung, Taiwan: Graduate School of Architecture and Urban Design, 2006.
- Jelsinki et al. *Industrial Ecology: Concepts and Approaches*. Murray Hill, New Jersey: AT&T Bell Laboratories, 1994.
- Jonsson, Robert, Ove Pettersson. *Timbre Structures and Fire: A Review of the Existing State of Knowledge and Research Requirements*. Stockholm: Swedish Council for Building Research, 1985.
- Karunasena, Gayani. "Sustainable Post-Disaster Waste Management: Construction and Demolition Debris." In *Post-Disaster Reconstruction of the Built Environment: Rebuilding for Resilience*, by Dilanthi, Richard Haigh Amaratunga. Chichester, West Sussex, UK Ames, Iowa: Wiley-Blackwell, 2011.
- Kirkwood, Craig W. "System Dynamics Methods: A Quick Introduction." College of Business, Arizona State University, 2010.
- Lauritzen, E.K. and C. de Pauw. *Disaster Planning, Structural Assessment, Demolition and Recycling (Rilem Report, 9)*. London: Spon Press; 1st edition, 1994.
- Lauritzen, E.K. "Emergency Construction Waste Management ." *Safety Science*, 1998: 45-53.
- Limbachiya, Dr. Mukesh, Professor John Roberts. "Sustainable Waste Management and Recycling: Challenges and Opportunities. Volume 2- Construction Demolition Waste." *Proceedings of the International Conference Organized by the Concrete and Masonry Research Group held at Kingston University- London* . London: Thomas Telford Publishing, 2004.
- Liu, Tony C., Chrisitan Meyer. *Recycling Concrete and Other Materials for Sustainable Development*. Farmington Hills, MI: American Concrete Institute, 2004.
- March, L. and D. M. Wiley. "Resourceful Debris Management." *Taskforce Newsletter* 1 1-2.
- Meadows, Donella. *The Limits to Growth: The 30 Year Update*. White River Junction, Vt: Chelsea Green Pub, Co., 2004.
- . *Thinking in Systems: A Primer*. White River Junction, Vt: Chelsea Green Pub, 2008.
- Mileti, Dennis. *Disasters by Design: A Reassessment of Natural Hazards in the United States*. Washington D.C.: Joseph Henry Press, 1999.

Office of Emergency Services, California. *Disaster Debris Management: Statewide Strategy and Guidance*. California Emergency Management Agency, 2004.

Olshansky, Robert B., Laurie A. Johnson, Kenneth C. Topping. *Rebuilding After the 1994 Northridge and the 1995 Kobe Earthquakes*. Urbana-Champaign, San Francisco: University of Illinois; Laurie Johnson Consulting, 2005.

Pawley, Martin. *Building for Tomorrow: Putting Waste to Work*. San Francisco: Sierra Club Books, 1982.

Peng, C.L., D.E. Scorpio, and Kilbert, C.J. "Strategies for Successful Construction and Demolition Waste Recycling Operations." *Construction Management and Economics*, 1997: 15,49-58.

Phillips, Brenda D. *Disaster Recovery*. Boca Raton, London, New York: CRC Press, 2009.

Quinn, David. *Modeling the Resource Consumption of Housing in New Orleans using System Dynamics*. Cambridge: Massachusetts Institute of Technology, 2008.

Rajib Shaw, Tran Phong. *Environment Disaster Linkages*. Bingley, U.K. : Emerald, 2012.

Ramezankhani, Atefe and Najafiyazdi, Mostafa. "A System Dynamics Approach on Post-Disaster Management: A Case Study of Bam Earthquake." *International Conference of the System Dynamics Society*. Athens, Greece, 2008.

Reinhart, Debra R., Philip T. McCreanor. *Disaster Debris Management- Planning Tools*. Orlando: University of Central Florida, 1999.

*Residential Cost Data*. R.S. Means Company, 1987.

Richardson, George P. and Alexander Pugh. "Introduction to System Dynamics Modeling." Waltham, MA: Pegasus Communications, 1981.

San Francisco Planning and Urban Research Association. *Safe Enough to Stay*. San Francisco: SPUR, 2012.

Security, Governor's Office of Homeland. *San Francisco All Hazards Strategic Plan*. Governor's Office of Homeland Security, 2008.

Solid Waste Association of North America. *Hurricane Katrina Disaster Debris Management: Lessons Learned from State and Local Governments*. SWANA, 2005.

Solis, Gabriela Y., H.C. Hightower, J. Sussex, and J. Kawaguchi. *Disaster Debris Management*. The Disaster Preparedness Resources Center, The University of British Columbia, 1996.

Sterman, John. "Business Dynamics." McGraw-Hill, 2000.

Tennessee, Recycling Marketing Cooperative for. *Material Recovery Facility*. RMCT, 2003.

University of Massachusetts, Amherst. *Debris Management Plan Workshop: Student Guide*. Amherst: University of Massachusetts Amherst, 2011.

Vale, Lawrence J., and Thomas J. Campanella. *The Resilient City*. New York: Oxford University Press, 2005.

Woolley, G.R., Goumans, J.J.J.M. and P.J. Wainwright. *Waste Materials in Construction, Volume 1: Science and Engineering of Recycling for Environmental Protection (Waste Management)*. Amsterdam, Oxford, New York: Pergamon, 2000.

Yahya, K. and Boussabaine, A.H. "Eco-costing of construction waste." *Management of Environmental Quality: An International Journal*, 2006: 17, 6-19.