Assessing the Scale of Environmental Impacts from a Major California Earthquake Recovery

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Abstract

The Economic Input-Output Life Cycle Assessment (EIO-LCA) method was used to gauge the regional energy resource consumption and environmental emissions that could result from the repair and replacement construction activities that would follow a major California earthquake. In 2002, the ShakeOut Scenario study (Jones et al.) was carried out to assess the physical, social and economic consequences of a magnitude 7.8 earthquake on the Southern San Andreas Fault. This study utilized the economic loss results from the ShakeOut Scenario to assess the resource requirements and emissions associated with the recovery from the same event. Economic sectors were chosen from the EIO-LCA model that relate to the construction activities that are likely to be carried out following the scenario event. To obtain the distribution of impacts among the various economic sectors, an assessment was done for six archetype buildings which included the three predominant construction classes that are found in Southern California (concrete, steel and wood). Greenhouse gas emissions, energy consumption, particulate matter emissions and water consumption impact categories are considered both for the building specific and regional assessments.

To better understand their scale within broader environmental sustainability, impact estimates obtained in this study were measured against other commonly referenced sources of emission and resource consumption. The study also explored whether or not this impact can be meaningfully reduced through seismic retrofit and improved seismic design, providing some context for examining the role of earthquake engineering in the sustainable building movement.

The study found that at the time of the event, the ensuing recovery would result in substantial environmental impacts that are comparable to annual impacts from other commonly referenced major California sources such as transportation greenhouse gas emission and home energy use. However, if the impacts brought about by the earthquake recovery are annualized based on an estimated return period for the event, the numbers are only a fraction of a percent of other major sources. The study also found that the implementation of several retrofit techniques that are commonly used in wood-frame buildings could reduce earthquake-related environmental impacts by approximately 40%.

Introduction

It has long been established that the construction and use of buildings and other civil infrastructure contribute significantly to resource consumption and other environmental impacts. In the United States, buildings account for approximately 39% of total energy use, 12% of the total water consumption, 68% of the total electricity consumption and 38% of the carbon dioxide emissions (US EPA, 2010). With increasing concerns over climate change and other environmental issues, there has been an expanded focus on reducing environmental burden and resource consumption in the construction industry. Current efforts like Leadership in Energy and Environmental Design (LEED) largely focus on developing more sustainable building materials, operation systems and construction practices.

One tool that is becoming increasingly useful is Life Cycle Assessment (LCA) which provides a framework for performing a comprehensive evaluation of the resource consumption and environmental burden of a product throughout its life. The methodology involves an inventory analysis of the material and energy inputs as well as waste output for each phase of the product life cycle as shown in Figure 1. This is followed by an evaluation of the impacts associated with this inventory. The results of the inventory analysis and impact assessment phases are interpreted in accordance with the objectives of the study. The International Organization for Standardization (ISO) 14040 provides a framework for Life Cycle Assessment. In the construction industry, LCA is typically used to evaluate alternative products, design or construction strategies, marketing (Green

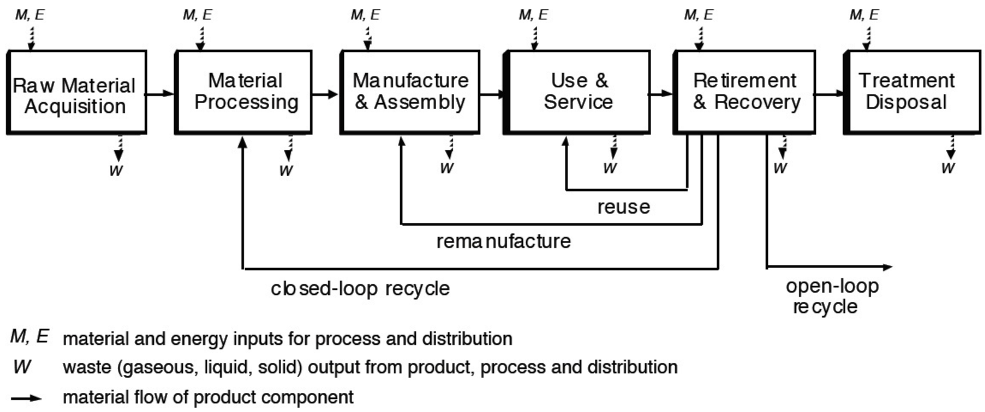

Figure 1 – Life Cycle Phase Diagram

Buildings) and identification of opportunities to reduce building life cycle impacts.

In California, there has been a growing debate over the role of earthquake engineering in improving the environmental sustainability of buildings. Many in the earthquake engineering community have asserted that seismic design has an important role to play in the sustainable building movement. Over the last decade, a Performance-based earthquake engineering (PBEE) methodology has been developed to allow stake holders to make informed decisions based on expected losses due to earthquake repair and replacement activities over the life of a building. The methodology, which is shown in Figure 2, was developed by the Pacific Earthquake Engineering Research (PEER) Center. It relies on integrating models and knowledge from seismology, structural engineering and the social sciences to obtain probabilistic predictions of seismic hazard, structural response, damage, economic losses and casualties (Deierlein, 2004). It has been argued that reducing expected earthquake losses through performance-based earthquake engineering also results in a net reduction in life cycle environmental impact due to reduced earthquake-related repair and replacement. While this argument has some merit, the question has been raised whether the scale of this earthquake-related environmental impact warrants any consideration. This study attempts to answer this question by using the Economic Input-Output Life Cycle Assessment (EIO-LCA) to assess the environmental impact that would result from construction activity due to earthquake related repair and replacement following a major California earthquake.

The LCA approach outlined earlier, which is based on the ISO 14040 Standard, is known as process-based LCA. Process-based LCA is desirable because the results are process specific and it allows for highly specific product comparisons. However, the difficulty in process-based LCA arises in selecting what processes will be included in the analysis. There are numerous processes involved in the construction of a building, principally when material acquisition and manufacturing processes are considered. As a result, performing a process based life cycle assessment on multiple building types is a very complex and time-consuming endeavor. EIO-LCA is an alternative to the process based approach.

Economic input-output life cycle assessment (EIO-LCA) is a methodology that traces economic transactions, resource requirements, and emissions associated with providing a product or service to quantify the environmental impact of these activities from raw material extraction to final provision of the product or service. This approach links monetary transactions among economic sectors comprising manufacturing, transport, raw material extraction, and related life cycle stages to environmental inflows and outflows from these sectors. Ultimately, it is possible to trace the life cycle environmental impacts of purchasing final products or services based on their final producer prices.

EIO-LCA begins with the construction of an input-output transactions matrix that represents the flow of purchases among the economic sectors participating in the life cycle of the product or service (Hendrickson et al., 1998). Economic sectors are defined using designations from the US Economic Census. When linked with final economic demand, this matrix results in the total input and total output of all active economic sectors. After normalizing each sector to sector transaction by the total sector inputs, a direct requirements matrix, [D], is created that quantifies total economic inputs required across all sectors to marginally increase the economic output (e.g. increase final demand) of any one sector.

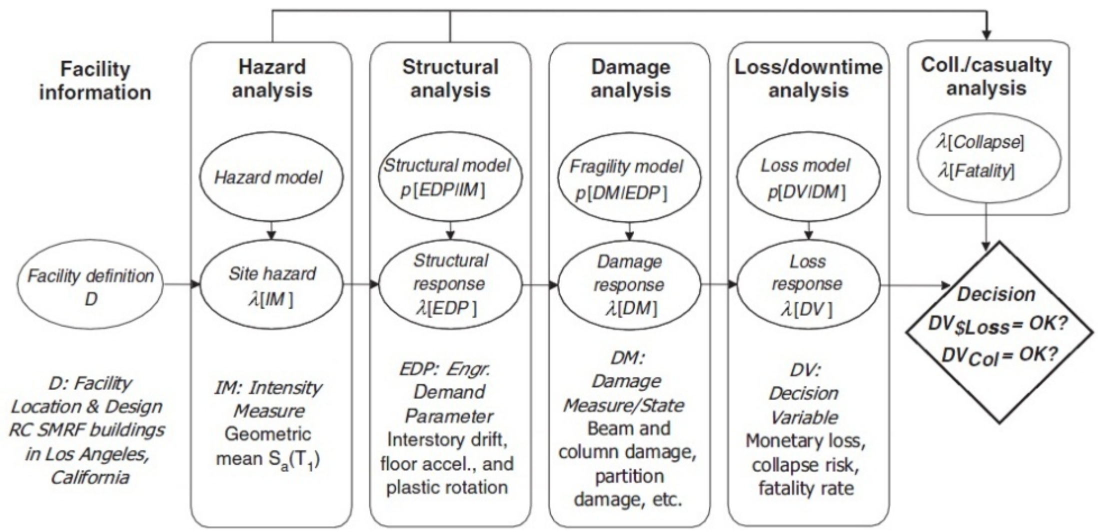

Figure 2 – Schematic of PBEE Methodology (Porter 2003)

This is shown in Equation 1.

$$\{X\}_{direct} = [I + D]\{F\} \qquad (1)$$

where, $\{X\}_{direct}$ is the economic output of all sectors directly supplying the sector meeting increased final demand, [I] is the identity matrix, and {F} is the final demand vector that quantifies economic final demand from each industrial sector.

However, the representation shown in Equation 1 only captures direct inputs into the sector supplying increased final demand. Sectors indirectly supplying final demand are accounted in Equation 2 through application of the Leontief Inverse.

$$\{X\} = [I - D]^{-1}\{F\} \qquad (2)$$

where, {X} is the economic output of all sectors involved with meeting increased final demand.

Separate from the creation of the input-output transactions matrix and the direct requirements matrix [D], an environmental impact matrix, $[R_I]$ is created that has diagonal elements comprised of the environmental impact per dollar of output for each economic sector. A variety of environmental burdens have been included in these matrix formulations including resource inputs (electricity, fuels, ores, and fertilizers) and environmental outputs (toxic emissions by media, hazardous waste generation and management, conventional air pollutant emissions, global warming potential, and ozone-depleting substances).

The change in environmental impact from each economic sector, $\{B_I\}$, involved with meeting changes in final demand is then calculated by multiplying the environmental impact matrix, $[R_I]$ with the economic activity matrix, {X]}, as shown in Equation 3.

$$\{B_I\} = [R_I]\{X\} = [R_I][I - D]^{-1}\{F\} \qquad (3)$$

where, $\{B_I\}$ is the vector of environmental impacts from each economic sector resulting from meeting final demand {F}, $[R_I]$ is the environmental impact matrix.

Using this approach, a monetary increase in final demand (measured using final producer prices) can be related to the associated increase in environmental impacts due to increased product activities throughout the economy. Thus, increased final demand in construction-related sectors resulting from repair and replacement of losses following a major seismic event can be related to the expected environmental impacts from carrying out the repair and replacement construction activities.

One major advantage of the EIO-LCA approach is that it effectively accounts for upstream input and processes that may otherwise be excluded from a process-based LCA. There are, however, some limitations to the EIO-LCA approach:

- There is a high level of aggregation of resource and environmental impacts which leads to uncertainty in how well specific industry sectors are modeled

- EIO-LCA models are based only on data which is publicly available and therefore may include only a limited number of environmental effects

- Using monetary value as an indicator of environmental impact can distort the physical relations between industries due to price inhomogeneity

While these limitations are significant, the EIO-LCA approach is employed in this study to take advantage of the numerous studies that have been done in the past on earthquake-related economic losses both on the building specific and regional levels.

To allow for comparison among various forms of resource consumption, emission outputs, and toxic releases, environmental impacts quantified within life cycle assessment are aggregated into a select number of impact indicators. These indicators can be calculated using one of the available impact assessment protocols including EDIP (Wenzel, Hauschild and Alting, 1997 and Hauschild and Wenzel, 1998), ReCiPe (Goedkoop et al., 2009), or TRACI (Bare, 2003). To better understand the results of this work, the broader environmental and social ramifications of the indicators chosen for study should be clear. In addition to economic loss, which needs no explanation, indicators of greenhouse gases, energy consumption, PM2.5 emissions, and water consumption are quantified in this study.

Greenhouse Gases

The impact category of greenhouse gas emissions (also known as global climate change) refers to the potential change in the Earth's climate caused by the buildup of chemicals that trap heat that would have otherwise passed out of the atmosphere (Bare, 2003). The emissions included within this analysis include anthropogenic sources and sinks of greenhouse gas emission, but do not include non-anthropogenic sources and sinks. Carbon dioxide contributes a large majority of the total normalized value for global warming emissions. Emissions of methane and nitrous oxide are the next largest contributors.

Energy Consumption

The energy consumption category is characterized by the potential depletion of fossil fuels: primarily coal, natural gas, and oil. Fossil fuels may be from domestic or foreign sources. Unfortunately this analysis fails to take into account the fact that continued extraction and production of fossil fuels tends to consume the most economically recoverable reserves first, so that (assuming fixed technology) continued extraction will become more energy intensive in the future.

PM2.5 Emissions

Ambient concentrations of particulate matter (PM) are strongly associated with changes in background rates of chronic and acute respiratory symptoms, as well as mortality rates. Ambient particulate concentrations are elevated by emissions of primary particulates, measured as total suspended particulates, particulate matter less than 10mm in diameter (PM10), and particulate matter less than 2.5mm in diameter (PM2.5).

Water Consumption

Water use has been tracked in simple mass terms without subsequent characterization analysis that would weight different usage flows to take into account important differences among source types and usage locations. Rather than trying to capture the emission of water pollutants into the environment, this impact category is structured to capture only the significant use or consumption of water without regard to its consumption in areas of low availability.

Methodology

The 2002 EIO-LCA benchmark model was used for this study. The economic model is built upon the inter-sector input-output transactions of the US economy as compiled by the Bureau of Economic Analysis of the US Department of Commerce. Emission and resource use data from various public sources have been combined with the economic part of the model to produce the EIO-LCA model. The EIO-LCA model receives as input, the monetary value of economic activities that comprise seismic repair product or process and provides as output, the associated emission and resources for this repair work.

The ShakeOut Scenario study (Jones et al., 2002) was carried out to assess the physical, social and economic consequences of a magnitude 7.8 earthquake on the Southern San Andreas Fault. The study utilized FEMA's loss estimation program HAZUS, to simulate the scenario earthquake and obtain estimates of physical damage and associated economic losses. The study region included Imperial County, Kern County, Los Angeles County, Orange County, Riverside County, San Bernardino County, San Diego County and Ventura County.

Table 1 – Buildings used in building-specific impact assessment

Building Type	Occupancy	Construction
C1	Office Building	90,000 ft^2, 4-story concrete moment frame
S1	Office Building	65,000 ft^2, 3-story steel moment frame
W1	Single Family Dwelling	1200 ft^2, single story wood frame house
W2	Single Family Dwelling	2400 ft^2, 2-story wood frame house
W3	Single Family Dwelling	2000 ft^2, 2-story wood frame townhouse
W4	Multi-Family Dwelling	10850 ft^2, 3-story wood frame apartment building

The economic sectors used in the EIO-LCA model were based on the construction activity associated with the repair and replacement of damaged infrastructure reported in the ShakeOut Scenario. To obtain a more accurate distribution of impacts among the various economic sectors that were selected, an assessment was done for six archetype buildings that include the three predominant construction classes that are found in Southern California. A description of these buildings is presented in Table 1.

Building C1 is an archetypical 90,000 ft^2, 4-story concrete moment frame office building designed by Haselton and Deierlein (2007) in accordance with the 2003 International Building Code and related ACI and ASCE provisions with an assumed location at a site in the Los Angeles basin, south of downtown Los Angeles. Miranda and Ramirez (2009) evaluated the seismic induced losses for this building using their Building-Specific Loss Estimation Methodology for PBEE. Economic losses were summed by sub-contractor categories to produce normalized dollar losses at different spectral acceleration levels as well as expected annual losses. For this study presented in this paper, the economic losses associated with the Design Basis Earthquake (DBE) was used and disaggregated into sub-contractor activities. The loss associated with each sub-contractor category was broken down further into the appropriate economic sectors provided in the EIO-LCA. The relative distribution of sub-contractor category losses to the various economic sectors was based on construction cost distributions obtained from RS Means. The sub-contractor categories and associated economic sectors for the building-specific impact assessment are presented in Tables 2 and 3. These economic sectors and their associated dollar amounts were used as input for the EIO-LCA model. It should be noted that the loss estimation study for building C1 by Miranda and Ramirez (2009) considered only structural and non-structural components. Content loss was not considered. As a result, content related impacts are not considered for the individual building assessments but will be addressed on the scenario earthquake level discussed later.

Building S1 is a 65,000 ft2, 3-story Pre-Northridge steel moment frame office building designed for the SAC Steel Project in accordance with the 1994 Uniform Building Code and related AISC and ASCE provisions with an assumed location in Los Angeles. Valdez (2010) evaluated the seismic induced losses for this building also using the Building-Specific Loss Estimation Methodology for PBEE developed by Miranda and Ramirez (2009). The goal of that study was to compare the economic benefits of the Self Centering Rocking Frame System to a traditional Pre-Northridge Steel Moment Resisting Frame. The methodology discussed earlier in this paper was used to obtain the emissions and resource consumption associated with the DBE for building S1.

Buildings W1, W2, W3 and W4 are residential buildings that were used as part of the CUREE Caltech Wood-frame Project. Porter et al. (2002) evaluated the seismic induced losses for 19 specific wood-frame buildings of varying ages, size, configuration, quality of construction and retrofit and redesign conditions using the Assembly Based Vulnerability (ABV) methodology also developed by Porter et al. (2001). The buildings that were evaluated represent variations on four basic floor plans also referred to as index buildings which include a small house (W1), a large house (W2), a town house (W3) and an apartment building (W4). The ABV framework is similar to the building-specific loss estimation methodology developed by Miranda and Ramirez (2009) in that it utilizes damage fragility functions for individual building structural and non-structural components. One key difference between the two approaches is that Porter el al. considered only 46% of the building components by cost to be damageable while Miranda and Ramirez considered 84% of the building components to be damageable. This inconsistency between the two methodologies was considered in the interpretation of the impact distribution for the

Table 2 – Structural Sub-Contractor Categories and Associated Economic Sectors

Concrete	Steel	Wood
Non Metallic Mineral (Limestone) Mining (212390*)	Iron Ore Mining (212210)	Forest/Wood Acquisition (113A00)
Sand/Gravel Mining (212320)	Iron and Steel Mills (33110)	Engineered Wood Member Manufacture (321213)
Cement Manufacture (327310)	Custom Roll Forming (332114)	Maintenance and Repair (230301)
Ready-mix Concrete Manufacture (327320)	Maintenance and Repair (230301)	
Maintenance and Repair (230301)		

*Economic sector identification number used in EIO-LCA model

Table 3 – Non-Structural Sub-Contractor Categories and Associated Economic Sectors

Finishes	Doors/Windows/Glass	Mechanical	Electrical
Gypsum Product Manufacture (3274A0)	Sand/Gravel Mining (212320)	Plumbing Fixture Manufacture (332913)	Lighting Fixture Manufacture (335120)
Painting and Coating Manufacture (325510)	Forest/Wood Acquisition (113A00)	Pipe Fixture Manufacture (326122)	Electric Power and Specialty Transformer Manufacture (335311)
Miscellaneous Manufacturing (33999A)	Flat Glass Manufacture (327211)	Heating Equipment Manufacture (333414)	Motor and Generator Manufacture (335312)
Maintenance and Repair (230301)	Wood Windows and Doors Manufacture (321910)	AC/Refrigeration Manufacture (333415)	Miscellaneous Electrical Equipment Manufacture (335999)
	Miscellaneous Manufacturing (33999A)	Air Purification & Ventilation Equipment Manufacture (33341A)	Switchgear and Switchboard Apparatus Manufacture (335313)
	Maintenance and Repair (230301)	Maintenance and Repair (230301)	Maintenance and Repair (230301)

different building types. For each of the four index buildings, the study by Porter et al. provides the normalized losses for each building as a function of damped elastic spectral acceleration. Also provided was the average fraction of total repair cost represented by each of five categories of assembly type: paint, water heater, glazing, gypsum board, stucco walls and shear walls. These assemblies were incorporated into the sub-contractor categories and economic sectors shown in Tables 2 and 3.

The ShakeOut Scenario provides economic losses associated with physical damage to buildings and selected lifelines (pipelines and highways) both from earthquake ground motions and subsequent fire. The EIO-LCA approach was used to assess impacts from losses due to earthquake ground motion damage to buildings. These losses were divided among the following occupancies:

Table 4 – Inventory distribution of building occupancies among primary structural material types for San Francisco County

	Residential	Commercial	Industrial	Other
Concrete	0.3%	13.2%	66.7%	39.4%
Steel	0.2%	10.2%	33.3%	28.6%
Wood	99.4%	71.5%	0.0%	18.3%
Masonry	0.1%	5.1%	0.0%	13.6%

- Single Family Residential
- Multi-Family Residential
- Commercial
- Industrial
- Other (Agricultural, Education, Religious and Utility)

The loss provided for each occupancy type was further broken down among structural components, non-structural components and content.

The distribution of structural losses among the various construction classes or primary structural materials was needed to assess environmental impacts associated with structural components, however, this information was not provided in the ShakeOut Scenario study. Several key assumptions were used to disaggregate structural losses provided for the various occupancy types into the primary structural materials.

Table 4 shows the inventory distribution of building occupancies into construction class/structural materials for San Francisco County. For the study presented in this paper, the loss distribution for each occupancy type among the different construction classes/structural materials was assumed to be the same as the inventory distribution shown in Table 4. 100% of structural losses identified as being associated with slight or moderate building damage in the ShakeOut Study was assigned to the structural material used in the lateral force resisting system e.g. 100% of structural losses associated with buildings that have a steel lateral force resisting system with slight or moderate damage were assigned to steel. Structural losses identified as being associated with extensive or complete building damage was divided among the various structural materials based on replacement cost distributions used in building-specific environmental assessments. Structural losses associated with masonry were allocated to the concrete subcontractor category.

The results of the building-specific impact assessment study were used to distribute non-structural losses from the ShakeOut Scenario into subcontractor categories.

As noted earlier, content related losses and environmental impacts were not evaluated as part of the building-specific assessments. The ShakeOut Scenario provides a distribution of content losses among the various occupancy types but no detail is provided regarding the types of contents. Trying to assess the type and distribution of contents for the various occupancy types would be a very time consuming endeavor and was not done for this study. The economic sectors in the EIO-LCA model that could be associated with building content replacement are presented in Table 5. These have been categorized according to those that can be associated with residential buildings and those that can be associated with commercial and other types of buildings. The regional emissions and resources due to content replacement was assessed based on the average impact of the contents considered. In other words, it was assumed that all contents listed in Table 5 contributed equally to the total impact due to repair and replacement.

The environmental impacts from fire damage and damage to lifelines were estimated by scaling the impacts from building damage due to earthquake ground motions based on the dollar losses.

This study also explores whether or not environmental impact due to earthquake ground motion damage can be meaningfully reduced through seismic retrofit and/or improved seismic design. This is done by evaluating the loss reduction that would result for retrofitted or improved design variations of the wood-frame residential buildings (W1, W2, W3 and W4) used in the individual building impact assessment. The buildings used in the CUREE Caltech Study identified as buildings W1 through W4 in this study represent “typical quality” homes in southern California as described by Porter et al. The following is a description of the structural features of the index buildings (Porter et al. 2002):

Table 5 – Economic sectors used for content losses

Residential	Non-Residential
Electronic Computer Manufacture (334111*)	Electronic Computer Manufacture (334111)
Computer Storage Device Manufacture (334112)	Computer Storage Device Manufacture (334112)
Computer Terminals and Other Peripheral Equipment (33411A)	Computer Terminals and Other Peripheral Equipment (33411A)
Telephone apparatus and Manufacture (334210)	Telephone apparatus and Manufacture (334210)
Broadcast and Wireless Communications Equipment (334220)	Broadcast and Wireless Communications Equipment (334220)
Other Communications Equipment and Manufacture (334290)	Other Communications Equipment and Manufacture (334290)
Audio Video Equipment Manufacture (334300)	Audio Video Equipment Manufacture (334300)
Wood Kitchen Cabinet and Countertop Manufacture (337110)	Wood Kitchen Cabinet and Countertop Manufacture (337110)
Upholstered Household Furniture Manufacture (337121)	Institutional Furniture Manufacture (337127)
Non-Upholstered Wood Household Furniture Manufacture (337122)	Metal and other Non-Upholstered Furniture (33721A)
Metal and other Non-Upholstered Furniture (33721A)	Custom Architectural Woodwork and Millwork (337212)
Custom Architectural Woodwork and Millwork (337212)	Showcases, Partitions, Shelves and Lockers (337215)
Mattress Manufacture (33791)	Office Furniture Manufacture (33721A)
Blind and Shade Manufacture (337920)	Blind and Shade Manufacture (337920)
All Other Miscellaneous Manufacture (33999A)	Laboratory Apparatus and Furniture Manufacture (339111)
	Surgical and Medical Equipment (339112)
	Surgical Appliances and Supplies Manufacture (339113)
	Dental Equipment and Supplies (339114)
	Office Supplies (Except Paper) Manufacture (339940)
	All Other Miscellaneous Manufacture (33999A)

*Economic sector identification number used in EIO-LCA model

- Small House (W1) – Single story with stucco exterior walls, framed floor with perimeter unbraced cripple walls and post and pier interior under floor supports. Gypsum wall board for interior finish

- Large House (W2) – Two stories with slab on grade and spread footings. Exterior walls have stucco finish, interior walls finished with gypsum. Not all walls have structural sheathing

- Townhouse (W3) – Two stories with garage under part of the living area. Slab on grade and spread footings. Exterior walls have stucco finish, interior walls finished with gypsum. Many but not all walls have structural sheathing

- Apartment Building (W4) – Three stories with two levels of residential space located above the ground-level tuck under parking. Slab on grade and spread footings. The second and third floors and roof are wood framed. The walls are wood framed at all levels. Exterior walls have stucco finish, interior walls finished with gypsum. Many but not all walls have structural sheathing. The longitudinal front wall is open to provide access to parking

Table 6 – Economic losses (millions of dollars) in ShakeOut Scenario due to building damage related to earthquake ground motions (Jones et al. 2002)

	Residential	Commercial	Others	Total
Structural	2,935	2,738	1,056	**6,729**
Non-Structural	14,508	7,349	4,140	**25,997**
Content	4,035	3,788	2,469	**10,292**
Total	**21,478**	**13,875**	**7,665**	**43,018**

Porter et al. (2002) assessed the reduction in seismic induced losses as a percentage of the replacement cost for several improved variations (either through retrofit or improved seismic design) of the index buildings described earlier. The structural features of the improved variants are described as follows:

- Small House Retrofitted (W1A) – Braced Cripple Walls
- Large House Improved Design (W2A) – Redesigned for immediate occupancy performance
- Townhouse Improved Design (W3A) – Redesigned for limited drift by using thicker sheathing and foundation sills to produce more-uniform interstory drifts
- Apartment Retrofitted (W4A) – Retrofit with steel moment frames at garage openings

Detailed individual building impact assessments were not done for the improved variants of the index buildings. Reductions in emissions and resource consumption were estimated by scaling the impacts with the reduced economic losses. These reductions were then extrapolated to the regional impact assessment.

Results

The EIO-LCA methodology was used to assess the environmental impact due to the recovery related construction activities that follow a magnitude 7.8 earthquake on the Southern San Andreas Fault. Greenhouse gas emissions, energy consumption, particulate matter emissions and water consumption impact categories were considered.

In the ShakeOut Scenario, it was estimated that $43 billion will be needed to repair and replace buildings damaged by ground motions from the magnitude 7.8 scenario earthquake. The largest building losses due to earthquake ground motion damage were sustained by residential occupancies which made up 50% of the total loss. Non-structural components dominate losses for all occupancy categories making up 60% of all building related earthquake losses. Table 6 provides a summary of the losses associated with building damage due to earthquake ground motions.

Building-Specific Impact Assessment

A distribution of the economic loss and environmental impacts between subcontractor categories for buildings C1, S1 and W1 is presented in Figures 3a through 3c. Finishes, which includes gypsum board partitions, paint, ceiling and floor finishes dominate economic loss for all building types ranging from 55% for the concrete office building (C1) to 65% for the small house (W1). There is an escalation in the contribution of finishes going from economic losses to greenhouse gas emission. For example, in the concrete building (C1) there is a 35% increase in the contribution made by finishes when moving from economic loss to greenhouse gas emission. The contribution of finishes to greenhouse gas emission is dominated by the manufacture of the gypsum board used in partitions and ceilings. For the economic sectors that were considered in this study, only cement manufacture had a higher greenhouse gas emission than gypsum board manufacture per unit cost. Structural contributions to greenhouse gas emission and energy consumption are on par with economic loss for the concrete and steel buildings. For all wood-frame buildings, there is a reduction in the contribution of the structure moving from economic losses to greenhouse gas emission. This is not surprising since economic sectors that account for the acquisition of raw materials and manufacturing processes for wood generally have a lower carbon footprint than those for concrete and steel. For the concrete and steel buildings, there is 60-70% reduction in the contribution of mechanical and electrical components when moving from economic loss to greenhouse gas emissions. They each contribute on the order of 5% of the greenhouse emissions. The distribution of energy intensity is similar to those for greenhouse gas emission.

Like greenhouse gas emissions, particulate matter is also dominated by finishes making up 74-85% of emissions. There is a much higher contribution to PM2.5 emission from wood-frame structural components than those of concrete or

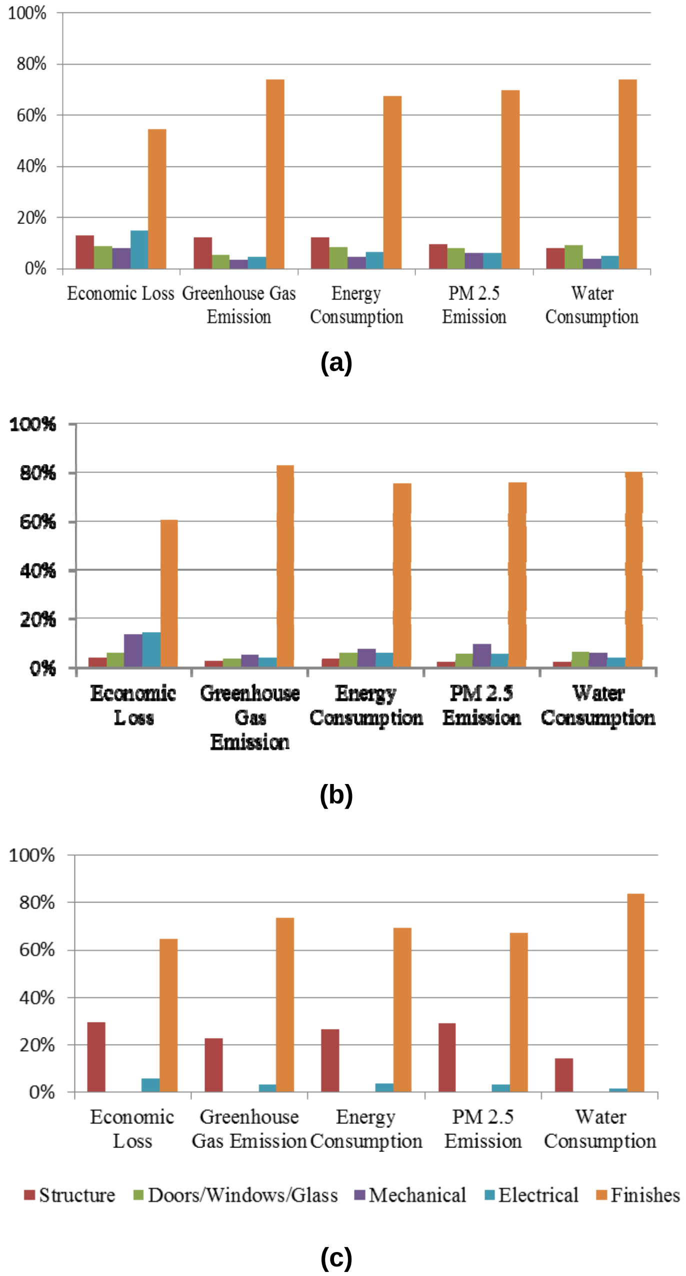

Figure 3 – Distribution of economic losses and environmental impacts due to design basis earthquake: (a) Building C1; (b) Building S1; (c) Building W1

steel. Acquisition of wood products has the highest PM2.5 emission per unit cost that any other economic sector considered in this study. With the exception of the contribution of structural components in wood-frame buildings, water consumption follows a similar distribution as PM2.5 emission being dominated by finishes. The contribution of wood-frame structural components to water consumption is on the order of half its contribution to PM2.5 emissions. Water consumption is dominated by the paint and coating manufacturing economic sectors that are part of the finishes subcontractor category.

The building-specific assessment results show that mechanical and electrical components have little or no contribution to economic losses and environmental impacts for residential buildings. However, this result is misleading since only 5% of the mechanical and electrical components by cost were considered damageable in residential buildings used in the CUREE Caltech study versus 88% in the concrete and steel buildings using the Miranda and Ramirez methodology.

Environmental Impact Assessment for the ShakeOut Scenario

Table 7 provides a summary of the greenhouse gas emissions associated with repair and replacement construction activities for buildings damaged by ground motions in the ShakeOut Scenario earthquake. These activities will result in an estimated 54 million metric tons of CO_2 -equivalents released into the atmosphere. The distribution of greenhouse gas emission for the different occupancy types is closely related to the economic loss distribution. Like economic losses, non-structural components dominate greenhouse gas emissions. There is a 20% increase in the contribution of non-structural components to greenhouse gas emission compared to economic losses as can be seen in Figure 4. This is not surprising given the observations in the building specific impact assessments. There is a 4% reduction in the contribution of structural components to greenhouse gas emission over economic losses. Emissions due to content replacement are 9% of the total, 24% less that its contribution to economic losses.

Table 7 – Greenhouse gas emissions due to repair of buildings damaged by earthquake ground motions (metric tons)

	Residential	Commercial	Others	Total
Structural	1,990,000	2,580,000	1,520,000	**6,090,000**
Non-Structural	22,400,000	15,700,000	5,060,000	**43,160,000**
Content	1,980,000	1,900,000	1,240,000	**5,120,000**
Total	**26,370,000**	**20,180,000**	**7,820,000**	**54,370,000**

Table 8 – Primary energy intensity due to repair of buildings damaged by earthquake ground motions (TJ)

	Residential	Commercial	Others	Total
Structural	29,100	33,400	17,300	**79,800**
Non-Structural	266,000	189,000	63,100	**518,100**
Content	30,900	30,400	19,900	**81,200**
Total	**326,000**	**252,800**	**100,300**	**679,100**

Table 9 – PM2.5 emission due to repair of buildings damaged by earthquake ground motions (kg)

	Residential	Commercial	Others	Total
Structural	5,570	4,810	1,370	**11,750**
Non-Structural	30,400	21,600	6,260	**58,260**
Content	4,000	4,410	2,880	**11,290**
Total	**39,970**	**30,820**	**10,510**	**81,300**

Table 10 – Water consumption due to repair of buildings damaged by earthquake ground motions (millions of gallons)

	Residential	Commercial	Others	Total
Structural	34,100	32,500	13,000	**79,600**
Non-Structural	253,400	180,000	59,800	**493,200**
Content	39,000	32,500	21,200	**92,700**
Total	**326,500**	**245,000**	**94,000**	**665,500**

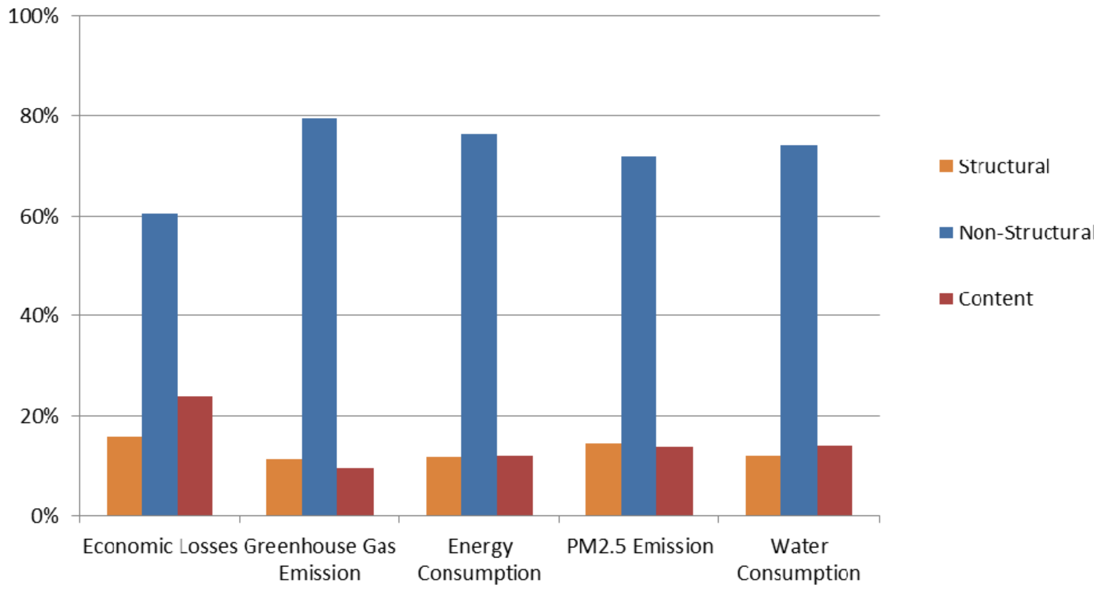

Figure 4 – Distribution of Economic Losses and Environmental Impacts for the Shake Out Scenario

The primary energy intensity associated with repair and replacement construction activities for buildings damaged by the earthquake ground motions is estimated to be 6.8 x 10^5 TJ. Table 8 provides a summary of the energy intensity impacts. The distribution of energy intensity among the various occupancy categories follows the same trend as economic losses and greenhouse gas emissions. Figure 4 shows that the primary energy intensity also follows the same trend in terms of increases in contribution of non-structural components and decrease in contribution of structural components when compared to economic losses.

A summary of the particulate matter emission is presented in Table 9. An estimated 8.2 x10^4 kg of particulate matter is released due to construction activities for buildings damaged by the earthquake ground motions. Unlike energy intensity and greenhouse gases, the contribution of structural components to PM2.5 emission is on par with its contribution to economic losses.

Water consumption for repair and replacement activities is presented in Table 10. The results show that 6.7 x 10^5 MGal will be consumed for construction activity. Figure 5 shows that water consumption follows the same trend as greenhouse gas emissions and energy intensity in terms of contribution of structural and non-structural components when compared to economic losses.

Including environmental impacts due to fire and damage to lifelines

The ShakeOut Scenario study also included economic losses due to fire subsequent to the earthquake and damage to select lifelines (water pipelines and highways). The study reports that fire related damage would result in an estimated \$40-\$100 billion in structural and non-structural building component losses and \$25 billion dollars in building content losses. The study also reports an estimated \$1.9 billion in losses from damage to pipelines and highway infrastructure. Fire and lifeline losses were not disaggregated by building occupancy and component type. Environmental impacts for these losses were computed by scaling the impacts from building damage to due earthquake ground motions. Environmental impacts from all direct losses are presented in Table 11 assuming an average value for fire related structural and non-structural losses (\$70 billion).

Reducing of Environmental Impact from Residential Buildings through Retrofit and Improved Seismic Design

In addition to assessing the scale of the environmental impact from a major California earthquake recovery, this study also explored whether or not this impact can be meaningfully reduced through seismic retrofit and improved seismic design. This is done by evaluating the loss reduction that would result for retrofitted or improved design variations of the wood-frame residential buildings (W1, W2, W3 and W4) used in the individual building impact assessment. In the

Table 11 – Environmental impacts for all direct losses in ShakeOut Scenario Event

Loss Description	Economic Losses (millions of dollars)	Greenhouse Gas (metric tons)	Energy Consumption (TJ)	Water Consumption (MGal)	PM2.5 Emission (kg)
Building damage due to earthquake ground motion	43,018	54,370,000	679,100	665,500	81,300
Building damage due to fire	70,000	31,200,000	390,000	377,000	47,200
Building content damage due to fire	25,000	12,500,000	200,000	225,000	27,400
Lifeline damage due to earthquake ground motion	1,900	31,000,000	400,000	380,000	47,200
Total	**139,918**	**129,070,000**	**1,669,100**	**1,647,500**	**203,100**

EIO-LCA methodology, environmental impacts scale fairly linearly with dollar amounts. As a result, the reduction for all impact categories scales almost in direct proportion to the reduction in losses. As shown in Table 12, the retrofit and redesign improvements discussed in the methodology will result in an estimated 40% reduction in economic losses as well as all impact categories.

Interpretation of Results

The ShakeOut Scenario study predicts that a magnitude 7.8 earthquake on the southern San Andreas Fault would result in an estimated $140 billion in property damage. This includes losses due to building infrastructure and content losses due to the earthquake ground motions, subsequent fire damage and damage to highways and water/sewer lines.

This study estimates that approximately 130 million metric tons of greenhouse gas emission would result from the repair of all damaged property reported in the ShakeOut Scenario. This number is comparable to the emission from all California transportation activity in 2008 (California Air Resources Board, 2010). If we assume that the ground motions from the ShakeOut Scenario are representative of a design basis earthquake with an expected return period of 475 years, it can be said that the “average yearly” greenhouse gas emission is on the order of 270,000 metric tons per year which is less than 1% of the California transportation emissions in 2008.

The primary energy intensity of the repair and replacement activities reported in the ShakeOut Scenario is estimated to be on the order of 1.7 million TJ which is comparable to the energy used by all California homes in one year (US EIA). Again if we consider the expected return period of the event, the average yearly energy consumption related to the design basis earthquake is comparable less than 1% of the annual energy consumption by California homes.

An estimated 200,000 kg of PM2.5 emission is expected to result from the ShakeOut Scenario repair and replacement activities.

The water consumption for all repair and replacement activities reported in the ShakeOut Scenario is on the order of 1.6 trillion gallons. It should be noted that this includes the water that is consumed by the raw material acquisition, manufacture/processing and construction phases of the recovery effort. Much of the water consumed in the raw material acquisition and manufacture/processing phases is not likely to come from California sources. For comparison with other California sectors, only the construction phase water use will be considered and this is approximately 50% of all water consumed in the recovery effort (.8 trillion gallons). Irrigated agriculture in California applies consumes approximately ten times this amount of water per year (DWR, 1994a).

The study shows that the implementation of various common retrofit strategies on wood buildings can reduce environmental impacts due to the repair and replacement of residential buildings by approximately 40%. If we assume that this reduction can be applied across all occupancy types, this would result in a 52 million metric tons reduction in the greenhouse gas emission due to the ShakeOut Scenario event. This number is comparable to the annual reductions that are expected as a result of the implementation of the following climate action strategies by the state of California: Executive Order S-01-07 (January 2007) proposes a 10% reduction in carbon intensity of transportation fuels by 2020. This is expected to reduce yearly greenhouse gas emissions by approximately 18 million metric tons. Senate Bill 107 (2006) proposes that 33% of California electricity be acquired from renewable sources by 2020. This is expected to reduce yearly greenhouse gas emissions by approximately 13 million metric

Table 12 – Reduction in environmental impacts through retrofit/redesign of wood-frame structures

Description	Economic Losses (millions of dollars)	Greenhouse Gas (metric tons)	Energy Consumption (TJ)	Water Consumption (MGal)	PM2.5 Emission (kg)
Residential Impact before Retrofit	21,500	26,300,000	326,000	236,000	40,000
Residential Impacts after Retrofit	12,400	15,300,000	192,000	195,000	23,000
Impact Reduction	9,100	11,000,000	134,000	41,000	17,000

tons. The State of California also plans to decouple utility sales and revenue so that providers are indifferent to and not harmed by customer side efficiency. This is expected to contribute to a 15 million metric ton reduction in yearly greenhouse gas emission by 2020 (California Climate Action Team, 2010).

Conclusion

An EIO-LCA methodology was used to assess the environmental impacts from repair and replacement activities following a major California earthquake. Impact categories considered include, greenhouse gas emission, energy consumption, PM 2.5 emission and water use. Six individual building types were evaluated to obtain the distribution of impacts between the various economic sectors that are used in the EIO-LCA model for the scenario assessment. The results show that, like economic losses, environmental impacts are concentrated in the repair and replacement of finishes such as ceilings, partitions, floor finishes and painting. However, there is amplification in the contribution of finishes when moving from economic losses to environmental impact.

The results of the regional assessment show that at the time of the event, the ensuing recovery would result in considerable resource consumption and environmental emissions that are comparable with the annual impact of other commonly referenced major California sources such as annual household energy use and transportation related greenhouse gas emission. However, if the impact brought about by the earthquake recovery is annualized based an estimated return period for the event, the numbers are only a fraction of a percent of other major environmental impact sources.

This study also explored the extent to which environmental impacts due to earthquake recovery can be reduced through retrofit or improved seismic design. The study finds that for residential buildings, the implementation of commonly cited retrofit techniques for wood-frame buildings can result in an estimated 40% reduction in environmental impacts. If it is assumed that this level of reduction can be attained for all types of damage including other building occupancies, fire and lifeline damage, the resulting reduction in greenhouse gas emission for a single event is comparable to the target annual reductions for several proposed California Climate Action Strategies. However, if impacts are annualized based on the return period of the event, once again they would not be comparable to any major target reduction goals.

The focus of this study was to understand the regional resource consumption and environmental emissions of a major earthquake recovery effort in California. Future building-specific studies that compare earthquake related impacts to other building life cycle phases would also provide a meaningful contribution to the discussion on the intersection of earthquake engineering and environmental sustainability.

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