Seismic Performance Assessment of Buildings

Volume 4 – Methodology for Assessing Environmental Impacts

FEMA P-58-4 / December 2012

FEMA

nehrp

FEMA P-58-4 / December 2012

Seismic Performance Assessment of Buildings Volume 4 – Methodology for Assessing Environmental Impacts

Prepared by

APPLIED TECHNOLOGY COUNCIL
201 Redwood Shores Parkway, Suite 240
Redwood City, California 94065
www.ATCouncil.org

Prepared for

FEDERAL EMERGENCY MANAGEMENT AGENCY
Erin Walsh, Task Monitor
Michael Mahoney, Project Officer
Robert D. Hanson, Technical Monitor
Washington, D.C.

ATC MANAGEMENT AND OVERSIGHT
Christopher Rojahn (Project Executive)
William T. Holmes (Project Technical Monitor)
Jon A. Heintz (Project Manager)

PROJECT MANAGEMENT COMMITTEE
Anthony B. Court (Project Technical Director)
Peter Morris
Kathrina Simonen
Wayne B. Trusty
Mark Webster
Jon A. Heintz*

*ex-officio

ATC-58 PROJECT REPRESENTATIVES
Ronald O. Hamburger
John D. Hooper

Notice

Cover photograph – Collapsed building viewed through the archway of an adjacent building, 1999 Chi-Chi, Taiwan earthquake (courtesy of Farzad Naeim, John A. Martin & Associates, Los Angeles, California).

Preface

Beginning in 2010, under a "Seismic and Technical Guidance Development and Support" contract (HSFEHQ-08-D-0726) with the Federal Emergency Management Agency (FEMA), the Applied Technology Council (ATC) was awarded a series of tasks entitled "Environmental Benefits of Retrofitting," designated the ATC-86/ATC-86-1 Projects. The purpose of this work was to develop a methodology for assessing environmental impacts associated with earthquakes. The idea for this work was directly related to the development of the FEMA P-58 *Seismic Performance Assessment of Buildings, Methodology and Implementation*, which is a general methodology and recommended procedures for assessing the probable seismic performance of individual buildings based on their unique site, structural, nonstructural, and occupancy characteristics.

In the FEMA P-58 methodology, performance is measured in terms of the probability of incurring casualties, repair and replacement costs, repair time, and unsafe placarding. These performance measures, however, do not capture the potential environmental benefits related to improved seismic design of new buildings, or seismic retrofit of existing buildings, in terms of standard environmental metrics currently in use. These include climate change (global warming) potential, ozone depletion potential, acidification potential, non-renewable energy and material resource depletion, waste generation, and a broad range of human health impacts. Development of the FEMA P-58 methodology has resulted in a tool that can be adapted to assess environmental consequences associated with earthquake damage on a probabilistic basis, and quantify environmental benefits associated with improved seismic resistance.

This report, FEMA P-58-4, *Seismic Performance Assessment of Buildings, Volume 4 – Methodology for Assessing Environmental Impacts*, has been adopted as the fourth volume in the FEMA P-58 series of products. It describes a recommended methodology for incorporating assessment of environmental impacts, along with other consequences, that are associated with the repair of damage caused by earthquake shaking, and is intended to inform the further development and future enhancement of the FEMA P-58 methodology.

This work is the result of many individuals involved in the development of the methodology and recommended procedures. ATC is indebted to the leadership of Tony Court, who served as Project Technical Director, and Peter Morris, Kate Simonen, Wayne Trusty, and Mark Webster, who served on the Project Management Committee responsible for performing the work. ATC would also like to acknowledge Ron Hamburger and John Hooper who guided the work at key developmental stages for consistency and compatibility with the FEMA P-58 methodology, and members of the SEAOC Sustainable Design Committee and the ASCE/SEI Sustainability Committee who reviewed and commented on the developing report. The names and affiliations of all who contributed to this report are provided in the list of Project Participants.

ATC also gratefully acknowledges Erin Walsh (FEMA Task Officer), Michael Mahoney (FEMA Project Officer), and Robert Hanson (FEMA Technical Monitor) for their input and guidance in the conduct of this work, and Bernadette Hadnagy, Jon P. Kiland, and Peter N. Mork, for ATC report production services.

Jon A. Heintz
ATC Director of Projects

Christopher Rojahn
ATC Executive Director

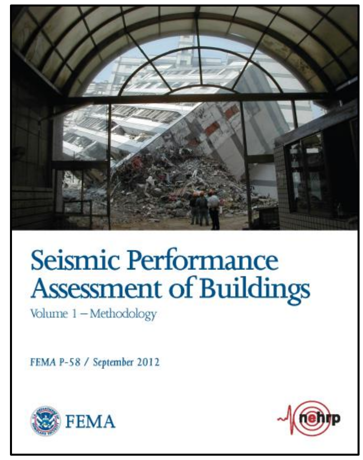
Table of Contents

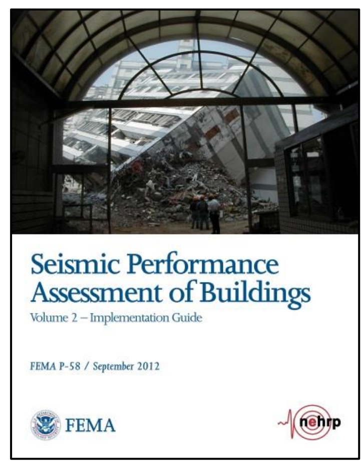
List of Figures

Chapter 1

Introduction

1.1 Background and Purpose





The Applied Technology Council (ATC), under contract with the Federal Emergency Management Agency (FEMA), recently completed the development of next-generation seismic performance assessment procedures under the ATC-58/ATC-58-1 Projects. The fundamental products of this 10-year developmental effort are the FEMA P-58 series of reports:

- FEMA P-58-1, *Seismic Performance Assessment of Buildings, Volume 1 – Methodology* (FEMA, 2012a)
- FEMA P-58-2, *Seismic Performance Assessment of Buildings, Volume 2 – Implementation Guide* (FEMA, 2012b)
- FEMA P-58-3, *Seismic Performance Assessment of Buildings, Volume 3 – Supporting Electronic Materials and Background Documentation* (FEMA, 2012c)

This series of reports describes a general methodology, recommended procedures, and background information for assessing the probable earthquake performance of individual buildings based on unique site, structural, nonstructural, and occupancy characteristics. Performance measures include potential causalities, direct economic losses (building repair or replacement costs), and potential loss of use (due to repair time or unsafe placarding), which are characterized on a probabilistic basis. The FEMA P-58 methodology and procedures are applicable to performance-based design of new buildings, and seismic performance assessment or upgrade of existing buildings.

Development of the FEMA P-58 methodology created a framework that can be adapted to capture other performance measures, including environmental impacts associated with earthquake damage. Examples of environmental impacts associated with earthquake damage include the energy expended, resources used, and environmental emissions created during the repair of earthquake-induced damage. In support of this objective, FEMA funded a separate, but related series of projects, designated the ATC-86/ATC-86-1 Projects, to review available environmental assessment methodologies and to investigate ways of incorporating environmental impacts into the FEMA P-58 methodology.

The ultimate purpose of this work was to develop an environmental impact assessment methodology for integration into the FEMA P-58 methodology. Using currently available environmental assessment procedures as a starting point, work included definition of a conceptual framework and development of recommendations for implementing environmental impact assessments within the FEMA P-58 methodology and associated products.

The building industry in the United States contributes significantly to total accumulated energy and resource use, and to total environmental emissions and their impacts. Architecture 2030 (2011b) estimates that the building industry consumes nearly 49% of the energy, and contributes nearly 47% of the CO_2 equivalent emissions relative to the entire U.S. economy. Architecture 2030 (2011b) also estimates that of the total building energy consumption, approximately 88% is currently attributable to building operations (e.g., HVAC and lighting) compared to only 12% attributable to building construction and materials. However, the ratio of "operational impacts" to "embodied impacts" is rapidly changing as buildings are made more operationally efficient, to the point that embodied impacts are becoming a major contributor to the overall environmental impact. Hence, interest and demand are growing for improved sustainable design tools to measure and reduce embodied impacts. Development of the FEMA P-58 methodology presents an opportunity to combine sophisticated seismic performance prediction capabilities with "embodied" environmental impact assessments to provide a powerful tool for sustainable seismic design.

The target audience for an eventual methodology assessing environmental impacts associated with earthquakes includes practicing engineers, researchers, other design professionals, and their clients who are interested in making environmentally conscious design decisions. The intended audience for this report includes FEMA, practicing engineers, researchers, and developers of the FEMA P-58 methodology, who may wish to begin testing the potential effectiveness of the recommended procedures, or who will implement the recommendations for incorporating environmental impacts into the FEMA P-58 methodology and associated products.

In the long term, the methodology for assessing environmental impacts is intended to help designers and their clients make more informed sustainable design decisions considering the probable environmental consequences associated with earthquake risk. The procedures and tools described herein are intended to provide effective ways of measuring the environmental benefits of seismically resistant construction. They should enable comparisons between alternative designs and between retrofitted and un-retrofitted buildings, and also provide tools to evaluate the potential benefits of rehabilitating or retrofitting older or earthquake-damaged buildings rather than demolishing and reconstructing them. They will likely encourage green building rating systems (e.g., LEED and Green Globes) in recognizing and rewarding improved seismic design and seismic retrofits that minimize environmental impacts considering the full building life cycle and probable consequences of earthquake damage.

1.2 Overview of Proposed Methodology

Life cycle assessment (LCA) procedures account for the environmental impacts of a product or building over its full life cycle, considering impacts related to building materials extraction, production and fabrication, the construction processes, building operations and maintenance, and eventual building demolition, disposal, or recycling. Until recently, life cycle assessments have not typically considered the effects of earthquakes or other natural hazards, or the advantages of designs intended to limit damage caused by these types of events. Building life cycle assessment provides a natural framework for adding probable seismic impacts. In order to assess these impacts, a prediction of the probable earthquake intensities expected over a considered building life, and a prediction of the probable earthquake damage and repairs are needed.

FEMA P-58 currently provides a methodology for predicting the potential consequences of damage to individual buildings located at specific sites. The FEMA P-58 methodology and associated products estimate probable losses in terms of repair costs, repair time, casualties, and unsafe placarding for a given intensity, scenario, or probabilistic earthquake event. The methodology enables users to estimate the consequences of material damage to a specific building design, and to predict the potential improvement in seismic performance, and reduction in earthquake damage, that can be expected from improved seismic design.

Using similar procedures, the FEMA P-58 methodology can be enhanced to assess probable environmental impacts associated with earthquake damage. Environmental impacts can be based on a limited set of metrics, or a full set of metrics, as described in ISO 21930, *Sustainability in Building Construction – Environmental Declaration of Building Products* (ISO, 2007). A limited set of metrics, for example, can consist of climate change potential (global warming) alone. Alternatively, the set of metrics can be expanded to also include primary energy consumption, natural resource consumption, waste streams, or other measures of interest.

Economic input-output (EIO) procedures, bill-of-materials (BOM) based unit process procedures, or hybrid procedures can be used to assess the environmental impacts of earthquake damage. Environmental impact assessments can proceed on a component basis or a full building basis, and can be based on the total magnitude of repair costs or on a bill-of-materials. Total seismic environmental impacts can be quantified in the same probabilistic manner as repair costs within the FEMA P-58 methodology. Seismic environmental impact assessments can be added to independent non-seismic life cycle assessments to generate total building seismic and non-seismic life cycle assessments. Assessment procedures can be repeated and compared for alternative design schemes to select environmentally effective seismic designs. Similarly, alternative seismic retrofit schemes can be compared to each other and to the un-retrofitted condition of a building to determine the potential benefits of seismic retrofit on an environmental basis.

1.3 Limitations

The recommended methodology for assessing environmental impacts relies on the FEMA P-58 seismic performance assessment methodology and associated tools for predicting probable earthquake damage. Based on the predicted damage, methods for quantifying environmental impacts associated with the repair actions necessary for reverting a building to its pre-earthquake condition are provided.

Assessment of building performance in future earthquakes involves significant uncertainty in earthquake hazard characterization, structural response and damage prediction, and estimation of repair costs and other consequences. Assessment of environmental impacts involves significant additional uncertainty related to the scope and extent of earthquake damage and repair, the means and methods of repair, and the quantification of the environmental impacts associated with the damage and repair actions. Selection of environmental metrics, and prioritization of procedures used to characterize environmental impacts, should consider this additional uncertainty in implementing the recommendations contained in this report.

1.4 Report Organization and Content

In this report, life cycle assessment concepts and procedures for evaluating environmental impacts of buildings are introduced, consideration of impacts resulting from earthquake damage are described, and the seismic performance assessment procedures of the FEMA P-58 methodology are summarized. Alternative methods for assessing environmental impacts and procedures for implementing environmental impact assessments in the FEMA P-58 methodology are presented and described.

Chapter 2 introduces life cycle assessment procedures. It discusses the life cycle stages, environmental impact metrics, methods for conducting life cycle assessments, interpretation of results, and inherent uncertainties in the procedures.

Chapter 3 discusses issues related to assessing environmental impacts associated with earthquakes.

Chapter 4 presents an overview of the FEMA P-58 methodology and the associated *Performance Assessment Calculation Tool* (PACT) as background and context for recommendations on incorporating assessment of environmental impacts.

Chapter 5 describes a general methodology for adding assessment of environmental impacts to the FEMA P-58 methodology. It identifies key issues that need to be addressed and reviews tools and databases currently available to assist in assessing environmental impacts.

Chapter 6 describes recommended procedures for adding environmental impact assessment capabilities to PACT or its successor programs. Both an economic input-output approach and a detailed bill-of-materials based unit process approach are presented.

Chapter 7 discusses how environmental impact assessment fits into the overall seismic design decision-making process for new building design, seismic retrofit design, and post-earthquake repair or demolition.

Chapter 8 summarizes overall conclusions and recommendations. It discusses potential trade-offs between ease of implementation versus accuracy for the recommended approaches.

Appendix A presents a preliminary analysis of selected component damage state repair estimates that was undertaken to test procedures for developing unit process based environmental impact assessments.

Appendix B summarizes currently available data sources and tools for assessing environmental impacts that are available in the public and private domain.

A Glossary, defining key environmental terminology, and a list of References, including a Bibliography of additional resources and information, are provided at the end of this report.

Chapter 2

Life Cycle Assessment of Environmental Impacts

2.1 Introduction

Life cycle assessment (LCA) is a procedure for comprehensively measuring the environmental impacts of products or buildings over their full life cycle. It can measure and report environmental impacts using a set of metrics that typically include climate change potential (global warming), ozone depletion potential, acidification potential, non-renewable energy and material resource depletion, waste generation, and a broad range of human health impacts. While building life cycle assessment has not traditionally included impacts related to earthquake damage, the procedure is well-suited to the task of measuring such impacts and integrating them into the full life cycle assessment. Recently, there have been multiple professional and academic efforts to integrate environmental impacts and seismic performance metrics.

The International Standards Organization (ISO) provides life cycle assessment guidelines for tracking the environmental impacts of a product or process throughout its full life cycle. Buildings can be assessed as products, using ISO 14044 procedures (ISO, 2006a; ISO, 2006b), in which buildings are taken as large products with long and uncertain lives. Significant effort is ongoing through ISO, ASTM, and the European Committee for Standardization (CEN), to further develop and clarify methods for life cycle assessment specifically for buildings and building products.

Several proprietary life cycle assessment tools and services have been developed based on ISO guidelines that are currently available for commercial use. These include the Athena Impact Estimator (Athena, 2012b), SimaPro (Pré Sustainability, 2011), GaBi (PE International, 2012), and CEDA (Climate Earth, 2010). Of these only the Athena Impact Estimator is designed specifically to perform assessments of complete buildings, while others can be adapted for application to buildings or building products. Additionally, new proprietary tools have recently been developed (e.g., Comber et al., 2012; Sarkisian et al., 2012b) to integrate seismic consequences considering selected environmental impacts.

2.2 ISO 14044: Components of Life Cycle Assessment

ISO 14044, *Environmental Management – Life Cycle Assessment – Requirements and Guidelines* (ISO, 2006b), defines four components of life cycle assessment relevant to buildings: (1) goal and scope definition; (2) life cycle inventory analysis; (3) life cycle impact assessment; and (4) interpretation.

Goal and Scope. Goal and scope definition sets the goals and boundaries of the life cycle assessment by defining questions to be answered, alternatives to be compared, intended uses of the results, quality of data and peer review requirements, and acceptable levels of uncertainty in input and output. The goals statement addresses why the assessment is being performed, what is to be learned, who is the audience and what is the functional unit for comparison. The scope statement addresses what is included in the assessment, what is excluded, what are the boundaries, and what are the life cycle impact assessment data sources.

In the context of the FEMA P-58 methodology, the goal will typically be to assess the impacts of probable earthquake damage, or to compare different seismically resistant designs, or retrofitted versus un-retrofitted options, considering functionally equivalent buildings.

Life Cycle Inventory Analysis. Life cycle inventory analysis lists and quantifies all the energy and material flows associated with the building during its life cycle. This inventory includes the input flows from nature and the output flows back to nature throughout the stages of the building life. In the context of the FEMA P-58 methodology, this inventory includes input and output flows for the bill-of-materials (e.g., pounds of steel) and construction processes (e.g., welding) associated with earthquake damage clean-up, repairs, or building replacement. A life cycle inventory analysis is illustrated in Figure 2-1.

Life Cycle Impact Assessment. Life cycle impact assessment defines the summary environmental impacts to be measured, quantifies the impacts per unit of material (e.g., kilograms of CO_2 equivalents per pound of portland cement or cubic yard of concrete) and summarizes the impacts over the building life cycle. In the context of the FEMA P-58 methodology, life cycle impact assessment would be conducted using one of the methods discussed in Chapter 5. The environmental factors to be measured would be selected in general accordance with the prioritized metrics discussed in Section 5.2.1.

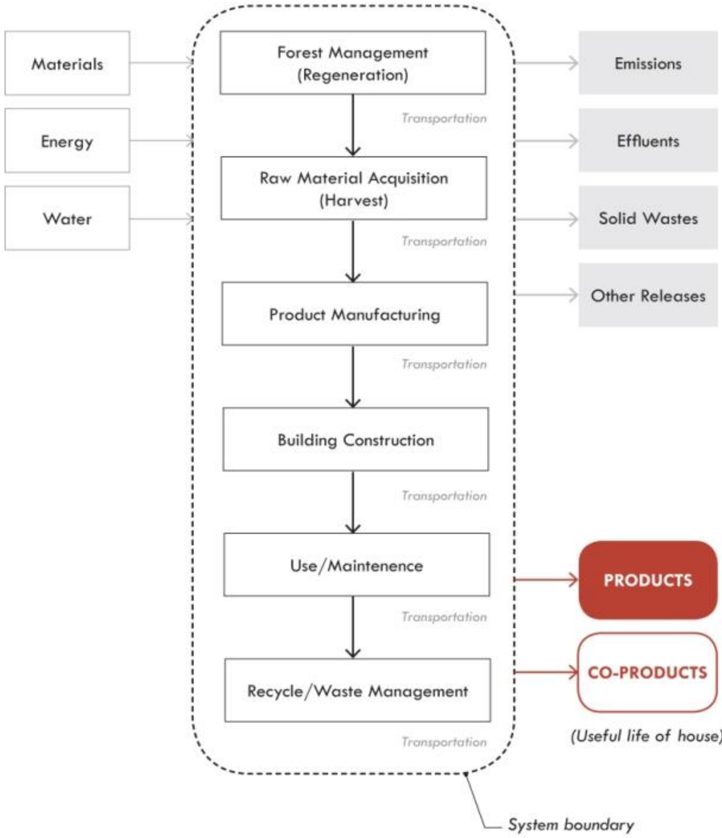


Figure 2-1 Illustration of life cycle inventory analysis (Simonen and Haselbach, 2012).

Interpretation. Interpretation involves evaluating the results of the life cycle assessment. Evaluation should include identifying major contributing processes and materials, assessing environmental inventory data quality and uncertainty, and comparing results between alternative designs. A challenge for implementation in the performance-based design process is to ensure that appropriate supporting information is provided to enable users to interpret environmental impact assessments in a way that effectively informs design decision-making.

2.3 Stages of Life Cycle Assessment

A building life cycle includes several distinct stages. Illustrated in Figure 2-2 and Figure 2-3, these stages can be generally identified as the material extraction and production stage, the construction stage, the building use stage, and the demolition or end-of-life stage. Building life cycle stages are discussed in the following sections.

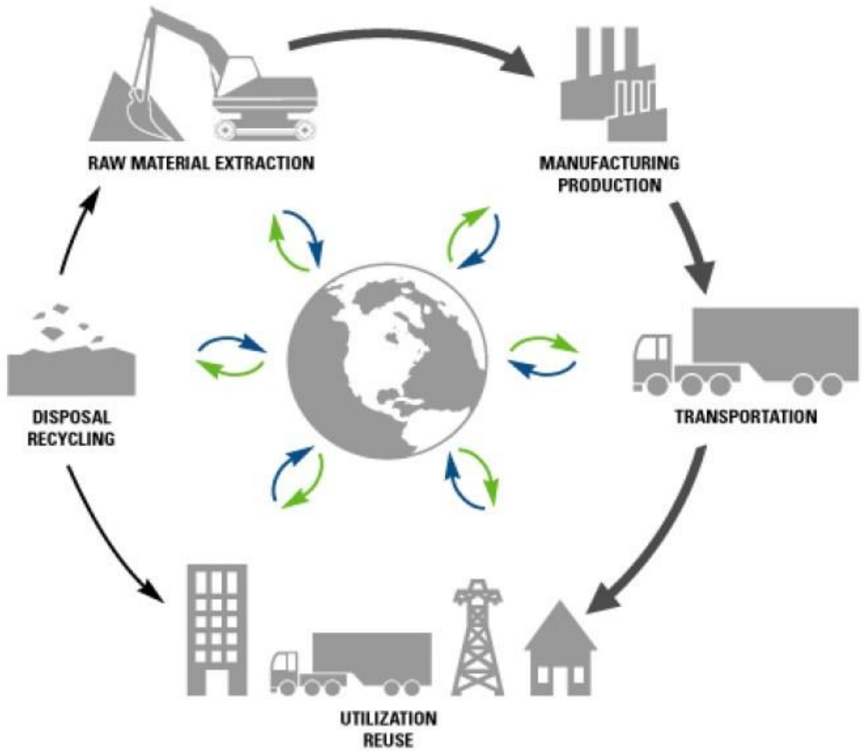


Figure 2-2 Life cycle assessment stages for buildings or building products (NIST, 2008).

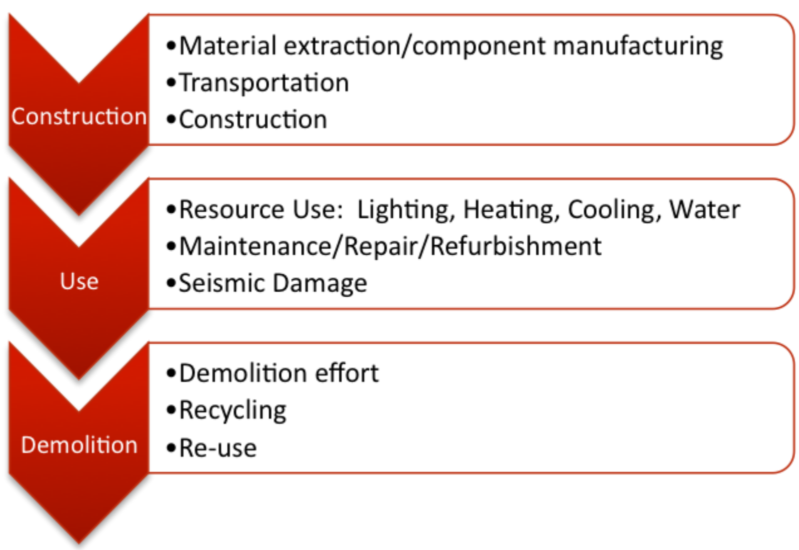


Figure 2-3 Simplified building life cycle assessment stages.

For new construction, or seismic retrofit of existing construction, impacts for each of these stages would be accounted for in the life cycle assessment process. Earthquake damage impacts, however, do not clearly fit into one of these stages. Instead, earthquake damage repairs can be treated as supplemental construction that can be assessed separately through a similar set of life cycle stages. The life cycle impacts of earthquake damage can then be added to the impacts of the original construction, as discussed in Chapter 7.

2.3.1 Material Production Stage

The material production stage involves raw material extraction (e.g., mining or harvesting), transport of materials, processing, and manufacturing. Each of these steps incurs environmental impacts. These impacts are typically accounted for through a detailed unit process procedure. The U.S. Life Cycle Inventory (LCI) Database (NREL, 2011) has been established to report industry average life cycle inventories, and remains in development. Some primary building materials are currently represented in this inventory.

Other material production inventories exist in both public and proprietary databases that can be adjusted to report impacts reflecting regionally specific energy and material sources and production methods. These databases continue to be updated and refined. For original construction, this stage is accounted for as part of the non-seismic life cycle assessment. For earthquake damage repairs, this stage would be accounted for within the environmental impact portion of the seismic performance assessment.

2.3.2 Construction Stage

The construction stage includes transportation of materials to the building site, construction processes and equipment usage, power usage, fuel usage, construction waste disposal, runoff, and dust particle generation. For original construction, this stage is accounted for as part of the overall life cycle assessment. For earthquake damage repairs, this stage would be accounted for as part of the environmental impact portion of the seismic performance assessment.

2.3.3 Use Stage

The building use stage can include impacts related to operational energy usage (e.g., heating and lighting), building component maintenance, (e.g., repair, replacement, and refurbishment), and resource inflow and waste outflow (e.g., water and utility usage and waste disposal) during operations. These impacts can be significant, and are typically accounted for as part of a standard non-seismic life cycle assessment. They are, however, usually not significant in comparisons between seismic design alternatives, provided that seismic damage and repair impacts are assessed separately from the use stage.

2.3.4 End-of-Life Stage

The end-of-life stage includes building de-construction or demolition, transport of waste or salvaged materials, and processing and disposal (including stockpiling for recycling or re-use) of these materials. Also included are demolition equipment usage and power usage, dust and runoff abatement, and other related activities.

The end-of-life impacts for the original construction of a building are accounted for once in the non-seismic life cycle assessment process, and should not be counted again in the environmental impact portion of a seismic performance assessment. Earthquake damage repairs, however, represent incremental new construction that will have incremental end-of-life impacts that should be considered in a seismic performance assessment. Also, if the useful life of a building is shortened by an earthquake, then the shortened lifespan should be accounted for in the assessment.

2.4 Environmental Metrics

ISO 21930, *Sustainability in Building Construction – Environmental Declaration of Building Products* (ISO, 2007), and current practices identify sets of environmental impact factors, and resource use factors, that are typically accounted for in a building life cycle assessment. These include common metrics, such as climate change (global warming) potential, primary energy use, and non-renewable resource use, and also include less familiar metrics, such as acidification of land and water resources, eutrophication potential, stratospheric ozone depletion potential, tropospheric ozone formulation potential, and human health impairment potential. While only some of these metrics may be of widespread interest at present, a longer list of potentially significant factors can be selected for consideration and future adaptation into a seismic environmental impact assessment methodology. Environmental metrics are discussed in the following sections, in general order of priority, considering current relevance and significance of the potential environmental impact.

2.4.1 Climate Change Potential

Climate change potential is the most widely recognized environmental impact metric. It is a measure of greenhouse gas emissions converted to units of kilograms of CO_2 equivalents, and includes contributions from carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perflourocarbons, and sulfur hexafluoride, among others. CO_2 equivalent emissions are generated in large quantities in, for example, cement production and other energy intensive materials production (e.g., virgin steel and aluminum manufacturing), carpet and other finish product production, and in energy consumption during the operating life of a building. Emissions can result from combustion of fossil fuels or from chemical reactions occurring during manufacturing processes.

2.4.2 Primary Energy

Primary energy includes all of the fossil fuel, nuclear, and renewable sourced energies consumed in the material production, construction, operation, and end-of-life stages of a building life cycle. Distinctions may be appropriate between fossil fuels and other energy sources, depending on the goals of the life cycle assessment.

2.4.3 Resource Depletion

Resource depletion is a measure of renewable (or non-renewable) resource use per functional unit (i.e., a building of a certain size and function in a certain environment). Non-renewable resource use is typically of greatest interest. Resource depletion is a measure of the depletion of rare or limited resources that, once expended, will no longer be available for use by future generations, or will be extractable only at a higher cost or environmental impact. Renewable resource use is not typically considered, but can be of interest when intensive use, at a rate above a sustainable production rate, limits other potential uses of the resource. Use of virgin resources contributing to depletion of readily available reserves is typically of greatest concern. Use of recycled materials reduces demand for limited virgin resources.

Resource use also produces many other consequences, such as energy consumption, climate change potential, and pollution effects, but these consequences can be directly accounted for using other metrics. Relative measures of resource depletion are an indicator of the relative environmental impacts of different buildings or seismic designs. Material use intensity (e.g., pounds of steel per square foot of building) can be a useful indicator of the relative resource usage rate and the comparative environmental impact of different buildings designed using the same structural systems.

2.4.4 Waste Generation and Disposal

Waste is generally measured in units of tons or kilograms. Waste generation occurs in material production, construction waste, and end-of-life building demolition. ISO impact categories distinguish between hazardous and non-hazardous wastes. Often, only total waste is tracked.

2.4.5 Photochemical Smog Potential (NOe)

Photochemical smog potential is measured in terms of nitrogen oxide (NO) equivalent emissions. Many chemicals contribute to this impact by reacting with atmospheric sunlight to cause visible haze, air pollution, and detrimental human health effects. Leading causes of detrimental human health effects include nitrogen oxide, volatile organic compounds, ozone and peroxacetyl nitrate (Environmental Protection Agency of South Australia, 2004)

2.4.6 Ozone Depletion Potential (N_2Oe)

Ozone depletion potential is measured in terms of nitrous oxide (N_2O) equivalent emissions. Nitrous oxide is released by fertilizer breakdown and many other industrial processes. Many complex chemicals including chlorofluorocarbons (CFCs) contribute to this impact by reacting with atmospheric sunlight to deplete ozone. With the phasing out of CFCs as part of the international Montreal Protocol agreement in 1987, nitrous oxide has become the leading man-made cause of ozone depletion, contributing more than twice the ozone depletion of any other source (NOAA, 2009).

2.4.7 Eutrophication Potential

Eutrophication refers to a process of releasing excess nutrients (e.g., nitrogen, phosphorous, and carbon) into bodies of water causing excessive algae growth, which results in a reduction in dissolved oxygen and inability to support aquatic plant or animal life. Buildings can contribute negatively in a number of ways, particularly if they use materials produced with the release of eutrophic substances (e.g., chemical fertilizers and detergents).

2.4.8 Acidification Potential

Chemical pollutants released into the air have caused widespread acid rain problems in industrialized areas, resulting in acidification of the land and water. This is a greater problem in the Eastern United States and in Europe, and is less of a problem in the Western United States (Environmental Protection Agency of South Australia, 2004).

2.4.9 Other Factors

Other environmental factors related to buildings (some positive and some negative) have been identified and tracked, but these are typically of lower significance, or may not be easily measured. Such factors include water usage, particulates released into the atmosphere, hazardous waste disposal, radioactive waste disposal, exported energy (i.e., surplus energy generation), materials and components available for reuse, materials for recycling, materials for energy recovery, human health respiratory effects potential, and toxicity factors.

2.4.10 Data Sources for Environmental Metrics

The environmental footprint of a product or process can be measured in a life cycle assessment using the environmental factors listed above. Currently available tools and databases for assessing environmental impacts, which exist in both the public domain and private sector, are discussed in Chapter 5 and Appendix B. Use of available tools and databases in the life cycle assessment process is described below.

2.5 Life Cycle Assessment Methods

Environmental life cycle assessments can utilize one of several models for completing the inventory impact assessments, including a unit process method, an economic input-output (EIO) method, or a hybrid method that combines aspects of the unit process and the economic input-output approaches. These methods differ in the level of precision. The unit process method can be manufacturer, product, or region specific. The economic input-output method is based on national average data and broad industry sectors.

2.5.1 Unit Process Method

The unit process method is the traditional approach to life cycle assessment. It uses systematic and methodical procedures to research and quantify the complete inventory of all the energy and material flows. It includes the input flows from nature and the output flows back to nature throughout the stages of a product or building life, and then calculates the environmental impacts of those inventory flows.

The unit process method models the inputs from nature (e.g., iron ore or natural gas) and outputs to nature (e.g., methane emissions or particulate matter) for each of the individual processes (i.e., unit processes) that go into the extraction, processing, and manufacturing of materials or products. It draws an assessment boundary to define the limits of an analysis and to clarify, for example, whether ancillary material or laborer transportation to the construction site is included or excluded. The unit process method then typically utilizes life cycle assessment tools and databases, either public or proprietary, to calculate impacts based on the quantity of materials and energy consumed.

The strength of the unit process method is that it is the most detailed and precise of the methods. It can utilize the best available data for materials and processes, where specific data are available. It can also link to unique material and product data reports.

Weaknesses and limitations associated with the unit process method have historically included truncation error, missing data, or processes extending beyond the analysis boundaries. These issues are less valid today, as more life cycle inventory data have become available. However, the U.S. LCI database is incomplete, and LCA professionals must typically rely on private databases and customization of international life cycle inventory databases to reflect U.S. conditions. Also, the unit process method can require a high level of effort to generate the life cycle inventory and to analyze the impacts of specific items for which summary data are not currently available.

Unit process based assessments can be extremely laborious and costly if done from scratch, researching each constituent product, material, and process back to the source boundaries of the study. Instead, this procedure is usually expedited by identifying the key constituents of a product, as itemized in the bill-of-materials and construction processes for a building, and then drawing upon existing life cycle impact tools and inventory databases to track and tally the environmental impact measures for each constituent product and the whole building.

The level of detail in the unit process method is a reasonable match to the level of detail in the FEMA P-58 methodology for assessment of repair cost consequences. Assuming that the bill-of-materials and necessary life cycle inventory data are available, a unit process method can provide the most detailed and precise assessments. Where life cycle inventory datasets are not available, simplified economic input-output procedures can be used to approximate missing information. Alternatively, a knowledgeable LCA professional can often use similar life cycle inventory data to create approximate proxy data for materials or processes for which specific life cycle inventory data are not available.

2.5.2 Economic Input-Output (EIO) Method

The economic input-output (EIO) method is based on research conducted by Leontief from the 1940s through the 1970s. In his second edition textbook, *Input-Output Economics* (Leontief, 1986), the national economy is divided into a number of sectors (currently 430), and arrayed in a matrix that captures the inter-relationships, showing the dollar flows between each sector and all other sectors. This method was expanded by the Carnegie Mellon Green Design Institute (2008) and further refined by Suh and Lippiatt (2012) to estimate the environmental impacts per dollar of production (or service) for each sector. The enhanced mathematical matrix shows the estimated environmental impact per dollar of transaction per sector. To use this method, each dollar of economic activity expended for a building component must first be separated into labor, materials, and processes. The material and process portion can then be mapped to the contributing economic sectors, and the environmental impacts can be estimated.

The EIO method can be applied by LCA professionals with appropriate EIO expertise, and access to EIO databases. The U.S. Department of Commerce, and many foreign governments, maintains economic data for this method, updated on a cycle of approximately 5 to 10 years. Researchers take environmental impact data and develop links between dollars and environmental impacts. The CEDA, Comprehensive Environmental Data Archive (Climate Earth, 2010), is an EIO database that is integrated into several commercial tools, and the EIO-LCA dataset (Carnegie Mellon Green Design Institute, 2008) is available through an access license. Additional information on these and other data sources is provided in Appendix B.

The strength of the EIO method is that it is theoretically comprehensive, broadly covering all impacts and avoiding truncation error. It also links to dollars rather than material quantities, which is easier to interface with readily available economic data or construction costs.

A weakness of the EIO method is that the economic and environmental data are based on industry averages and are not tailored to specific products. Also the data are relatively old, dating from the U.S. Department of Commerce, Bureau of Economic Analysis, benchmark input-output accounts (BEA, 2002). Some products, services, or building components may not easily map into the predefined economic sectors. The EIO databases are cradle-to-gate and thus do not include transportation, on site construction, maintenance, and end-of-life impacts. A significant limitation of the EIO method is that it will generate relatively gross approximations of impacts that are not consistent with the level of detail included in the FEMA P-58 methodology for assessment of repair cost consequences. However, an EIO evaluation may be useful for in a preliminary assessment, and could serve as a screening tool to help identify major contributing items in life cycle assessments, which might then require more detailed analysis. It could also be used as part of a hybrid approach to fill in gaps in a unit process method.

2.5.3 Hybrid Method

Hybrid methods combine aspects of the unit process and economic input-output methods to capture the strengths of each approach. A hybrid method can start with a top-down (EIO) procedure, and then fill in detailed unit process data for items shown to be major contributors to the life cycle assessment analysis. This approach has the potential advantage of capturing the detail of unit process methods and the comprehensive scope of EIO methods. A hybrid method can also start with a bottom-up (unit process) procedure, and then fill in missing impact data for products or building components using EIO estimates. This method is not commonly used and presents challenges in developing data that are appropriately scaled to be compatible with unit process based life cycle inventory data.

A hybrid method can be used with earthquake repair costs by first separating labor costs from the predicted total repair costs. Then EIO procedures can be applied to the remaining costs to estimate environmental impacts. Economic input output tables report emissions per dollar per industry sector. Repair material costs can be assigned to relevant sectors, and approximate emissions per dollar can be determined for relevant repair activities. Critical contributors can be identified and analyzed using unit process based data to refine an impact assessment. Adjustments may be required to achieve consistency between the EIO based impact estimates and the unit process based impacts.

A strength of hybrid methods is that a top-down approach is comprehensive (without the concern for boundaries and truncation errors) but it can also be refined to adequately capture significant contributors to environmental impacts. Hybrid methods can potentially be done with less work effort than unit process methods, and can help target the effort to critical contributors. A hybrid method might not be beneficial if a unit process method can be readily applied using available commercial tools.

A weakness of hybrid methods is that data compatibility must be tested between the unit process and EIO portions of the assessment. EIO data can integrate the entire supply chain, and can have higher inventory quantities than unit process based data. Care must be taken to scale results to be comparable. Also, a hybrid method could end up involving more work in the end if it starts with an EIO process and then ends up fully developing unit process inventory data for most of the items in the bill-of-materials.

A hybrid method also provides a mechanism for a two-step process involving a quick, preliminary EIO method, followed by a more detailed, targeted unit process method. This two-step process can be tailored to a limited developmental budget, whereas a full, unit process based method would be expected to require a larger developmental budget.

2.6 Interpreting Impact Assessments

Once a life cycle assessment including earthquake-related impacts is completed, results require evaluation and interpretation to be useful in design decision making. Evaluation should include identifying major contributing components, processes and materials, assessing environmental impact data quality and uncertainty, and comparing relative impacts for different designs. Results will typically indicate total impacts by different metrics (e.g., climate change potential, primary energy consumption, resource usage, emissions, effluents, and waste generation). Environmental impact metrics will need to be prioritized in order to comparatively evaluate different designs.

2.6.1 Total Impacts and Weightings

Total impacts in environmental metric categories can be directly compared between alternative designs. A variation of plus or minus 15% is generally considered to be the level of accuracy attained in life cycle assessments. Differences between alternative designs that are less than 15% are not likely to be statistically significant due to variability and uncertainty in material quantities and impact assessments. If a single environmental impact is selected as the deciding criterion, and the difference exceeds 15%, then environmental impact assessment can provide clear direction. If not, a combination of factors (e.g., environmental, economic, or other) may need to be considered in design decision making.

Different environmental impacts can be weighted relative to each other and summed to obtain a single number for total environmental impact, but this procedure is generally discouraged. ISO 14044 (ISO, 2006b) advises against weighting, stating that "weighting shall not be used in life cycle assessment studies intended to be used in comparative assertions intended to be disclosed to the public." Nonetheless, subjective criteria for combining impact factors might be used to aid decision making on individual projects. Subjective factors could be used to develop a weighted score that takes into account project-specific priorities.

2.6.2 Relative Impacts and Communicating Impact Measures

In order to more effectively communicate to end users and the public, environmental impacts can be quantified in meaningful terms. Such terms include familiar standard measures, such as tons of CO_2 equivalents, and in more accessible comparative terms, such as "number of cars taken off the road" or savings in "annual residential power usage units." In addition, seismic impacts will be more meaningful to decision makers if they are placed in the context of a full building LCA so that the relative magnitude of seismic impacts compared to initial construction and operations can be understood.

2.7 Uncertainties in Data Quality and Variability

There are many sources of uncertainty in the life cycle assessment process. There are uncertainties related to the material and construction process quantities, particularly with regard to predicted earthquake damage repair quantities. There are also uncertainties regarding the quality of life cycle inventory data and assumptions regarding regional variations, transportation distances, and product variations (e.g., different concrete mix designs). There are different ways to account for these uncertainties, ranging from professional judgment to statistical studies.

2.7.1 Material Quantity Variability

Quantities related to construction materials and construction processes cannot be known with certainty. In the case of new construction, material quantities can be estimated with reasonable accuracy, but construction waste, material and labor transportation, construction equipment usage, and energy usage can be only roughly estimated. In the case of earthquake damage repair, the predicted repair quantities can have significant variation. Even if the extent of damage is known, the quantity of finishes that need to be removed and replaced to access the work can vary widely and the environmental impacts of these finishes can be high.

2.7.2 Environmental Data Quality and Variability

The environmental impact assessments can vary significantly depending on available sources of information. Environmental impacts associated with building products vary widely between higher technology production techniques and lower technology production techniques. For example, steel produced by blast furnace has a different carbon footprint than steel produced by electric arc furnace. Transportation distances and local material availability can also vary from region to region.

Environmental data are typically based on plant or industry averages, and do not address marginal production or nonlinear steps in output levels. Data quality varies in precision, completeness, consistency, reproducibility, and in accounting for regional and technological differences.

Life cycle inventory data quality is typically assessed based on the following measures:

- **Technical representation.** The degree to which the data reflect the actual technology(ies) used.
- **Temporal representation.** The degree to which the data reflect the actual time (e.g., year) or age of the activity.
- **Geographical representation.** The degree to which the data reflect the actual geographic location of the activity (e.g., country or site).
- **Completeness.** The degree to which the data are statistically representative of the relevant activity. Completeness includes the percentage of locations for which data are available and used versus the total number of locations that relate to a specific activity. Completeness also addresses seasonal and other fluctuations in data.
- **Reliability.** The degree to which the sources, data collection methods, and verification procedures used to obtain the data are dependable.

2.7.3 Options for Considering Variability in Environmental Impact Assessments

Given the complexity of the problem, one option for considering variability is to accept the uncertainty and state that it is unknown, leaving it to the user to estimate the uncertainty (or to accept it). Another option is to use professional judgment to estimate uncertainty and incorporate it into the assessment process. This approach may make sense considering that individual users may not have sufficient expertise to estimate uncertainty. A third option is to attempt a precise statistical analysis of the uncertainty and variability. This approach would provide the best quantification but would require extensive research and investigation. Uncertainty and variability is further discussed in Chapter 5.

Chapter 3

Assessing the Environmental Impacts of Earthquakes

3.1 Life Cycle Assessment of Earthquake Impacts

Earthquake damage to buildings, and the associated repairs, results in environmental impacts that have not typically been accounted for in life cycle assessments. If potential earthquake damage and repair can be predicted and quantified, then the resulting impacts can be accounted for in the same way as other life cycle impacts using the life cycle assessment procedures discussed in Chapter 2.

The FEMA P-58 methodology accounts for the seismic hazard exposure and unique characteristics of individual buildings to predict probable earthquake damage and consequences in terms of repair costs, casualties, and loss of use due to repair time or unsafe placarding. It can be expanded to assess probable environmental impacts associated with earthquake damage and repairs. These seismic impacts can then be added to non-seismic impacts to complete a full building life cycle environmental impact assessment.

Earthquake-related impacts can be compared to impacts associated with the original construction of the building to provide a sense of relative significance. A threshold for environmental reparability can be evaluated to assess the relative merits of repair and retrofit versus demolition and reconstruction.

Earthquakes, earthquake damage repairs, and their environmental impacts present several special issues not typically factored into traditional (non-seismic) life cycle assessments. These issues are discussed in the following sections.

3.2 Earthquake Probabilities and Design Service Life

The probability of damaging earthquakes occurring during the service life of a building significantly influences the environmental impact assessment. The damage potential of earthquake ground shaking varies as a function of intensity, duration, and frequency. The probability of damaging earthquakes occurring, and their damage potential, can range from very high to very low.

In seismically active areas, the earthquake damage probability is relatively high over the 50 to 100 year service life of a building. In less seismically active areas, earthquake damage probability can be very low over this time period. If a significantly longer service life is intended (e.g., several hundred years in the case of a monumental structure), then the probability of earthquake damage occurring over the service life increases accordingly. If the structure is a temporary structure with a very short design service life, the probabilities decrease significantly.

The FEMA P-58 methodology explicitly accounts for earthquake hazard probabilities. The methodology permits the use of intensity-based, scenario-based or time-based assessments. Time-based assessment permits consideration of the cumulative probability of different intensity earthquakes occurring over the life of the building, and fits well into a life cycle assessment. Intensity-based or scenario-based assessments can be used to provide insight into the likely environmental impacts of a specific earthquake intensity, or an earthquake of a specific magnitude and location with an expected probability of occurrence.

3.3 Structural Response and Probable Consequences

Building response to earthquakes can be characterized by a set of peak response parameters (e.g., story drift, floor velocity, and floor acceleration) occurring at different points throughout a structure. The probable structural response can be calculated using traditional seismic analysis procedures and a characteristic hazard function for the building site. The hazard function indicates the probability of different earthquake shaking intensities occurring over time.

Probable structural responses can then be related to probable consequences using the FEMA P-58 methodology and procedures. Environmental consequences result from demolition activities, waste transport and waste disposal, and construction of earthquake repairs. Environmental impacts can be measured in terms of climate change potential, primary energy use, or other metrics, as defined in Chapter 2. The FEMA P-58 methodology provides a means of accounting for these effects in probabilistic terms.

3.4 Change in Building Service Live and Annualized Impacts

Earthquake damage can affect the remaining service life of a building. Earthquake damage can result in collapse or abandonment (i.e., end of service life). Extensive repairs, including major tenant improvements, infrastructure upgrades, or architectural enhancements, can rejuvenate a building and extend its service life.

Annualized environmental impact measures can capture these consequences and communicate relative impacts between alternative designs. Annualized impacts can be expressed as the total life cycle impact divided by the expected service life, considering the probable occurrence of earthquakes that are likely to alter the service life of a building.

3.5 Building Collapse or Total Loss

Depending on when in the building life cycle an earthquake occurs, building collapse (or total loss) can result in significant life cycle impact or minimal impact. If a recently constructed building is destroyed by an earthquake, the incremental impact is the total life cycle impact minus the operational impact. If a building nearing the end of its service life is destroyed by an earthquake, the incremental environmental impact is essentially zero. Note that life cycle assessment studies often refer to the concept of a reference service life, but the prediction and quantification of building service life continues to be a focus of LCA research.

In a design stage life cycle assessment, the total loss scenario can be analyzed as a time-based probabilistic event. If the total loss has a 0.1% annual probability of exceedance, or a 10% life time probability of occurrence (assuming a 100-year expected life), the loss could be assumed to have a 10% probability of occurring at the mid-point of the building service life. If a total loss occurs in a scenario-based or intensity-based assessment, then the probability of the event occurrence needs to be considered in the assessment.

There may be cases in which a building is damaged to the extent that it is considered a total loss from an economic standpoint, but not from an environmental standpoint. For example, FEMA typically recognizes a repair cost ratio of 50% of the replacement cost as an economic threshold for demolition and replacement. Even at that level damage, it is possible that an environmental assessment could indicate that repair is preferable to replacement (i.e., the environmental impact of repair is less than the environmental impact of replacement). In cases where environmental impact considerations govern the decision, repair of the building might be considered, even when traditional measures for the economic viability of repair are exceeded.

3.6 Avoided Impacts

The concept of avoided impacts is also useful in evaluating design alternatives. Designs that avoid damage, and particularly that avoid collapse, also avoid the environmental impacts associated with repair or demolition and reconstruction. Impact avoidance may provide a compelling argument in favor of improved seismic design for new construction, or retrofit of existing construction, assuming that the probable impacts associated with design or retrofit for improved seismic performance are less than those associated with the repair of probable earthquake damage.

3.7 Regional Effects

Large earthquakes can cause damage over a widespread area with regional consequences that can change the environmental impacts for repair of individual buildings. Increased local demand, and disruptions in local supply chains, can extend material and labor transportation over greater distances, increasing environmental impacts. Disruptions to electrical power distribution services are likely to cause inefficient on-site power generation, also resulting in greater environmental impacts. An earthquake environmental impact methodology should provide options to account for regional disaster effects.

3.8 Labor Intensity Associated with Repairs

In contrast with new building construction, repair work tends to involve a higher proportion of labor relative to materials. This difference has several effects. Labor tends to have a high cost impact but a low environmental impact, therefore earthquake repair work tends to have a lower environmental impact per dollar than new construction. This is a contributing factor in the possibility that a building may be deemed economically unrepairable at a lower damage threshold than it is deemed environmentally unrepairable. Labor and material cost contributions to repair actions should be separated so that material-related environmental impacts are accurately accounted for.

3.9 Uncertainties in Seismic Performance Assessment

Uncertainties in the context of general life cycle assessment were presented in Chapter 2. Additional uncertainties arise in seismic performance assessments. These include: (1) uncertainty in prediction of probable earthquake ground motions, considering probability of occurrence, intensity, duration, and characteristic frequencies; (2) uncertainty in predicting the structural response, considering modeling assumptions, mass, stiffness, damping and non-linear characteristics; (3) uncertainty in calculating the damage given the response, considering the details of construction, and damageability of the components; and (4) uncertainties in the assumptions for repair methods, materials, and procedures. Within the FEMA P-58 methodology, uncertainty in estimating consequences is explicitly considered in the assessment process. Uncertainty in estimating the associated environmental impacts should be treated in a similar way.

Chapter 4

Overview of the FEMA P-58 Methodology

4.1 Seismic Performance Assessment Methodology

The FEMA P-58 series of reports describe a general methodology and recommended procedures for assessing the probable earthquake performance of individual buildings based on their unique site, structural, nonstructural, and occupancy characteristics. Performance measures include potential causalities, direct economic losses (building repair or replacement costs), and potential loss of use (due to repair time or unsafe placarding). This section provides a brief overview of the FEMA P-58 methodology, with an emphasis on information that is most relevant to the context of assessing environmental impact consequences. The basic steps of the seismic performance assessment methodology are shown in Figure 4-1. Chapter references in the figure refer to chapters in FEMA P-58-1, *Seismic Performance Assessment of Buildings, Volume 1 – Methodology* (FEMA 2012a).

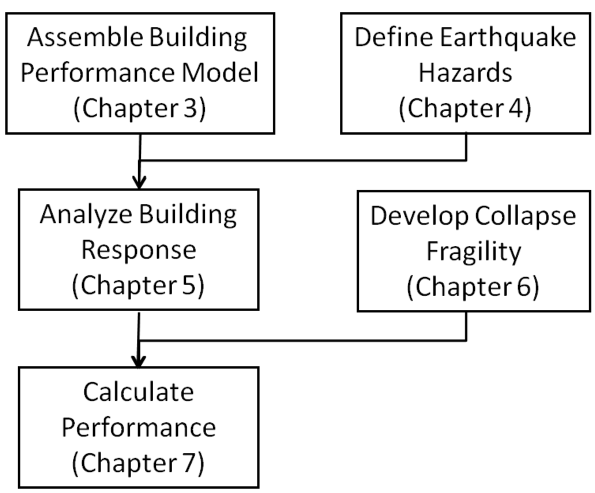


Figure 4-1 Flowchart of the FEMA P-58 methodology for seismic performance assessment of buildings (FEMA, 2012a).

Two steps that are particularly important for integration of environmental impact assessments are: (1) assembly of the building performance model; and (2) calculation of performance. The remaining steps are important, but do not require modification for integration of environmental impacts. All steps are briefly described below.

Assemble Building Performance Model. The building performance model is an organized collection of data necessary to define building assets that are vulnerable to the effects of earthquake shaking. The building performance model is assembled by defining the damageable structural and nonstructural components in the building, the types of damage that they can sustain, and the consequences of that damage (in terms of repair costs, repair time, and casualty potential).

The inventory of components is quantified, and each component is assigned to a performance group. Performance groups are defined as collections of components that have similar vulnerability to damage and will experience similar demands imposed by the earthquake response of the building. Performance groups are typically organized by story level and direction, as shown in Figure 4-2. The relationships between possible component damage states and reference demand parameters (e.g., story drift, floor velocity, or floor acceleration) are defined as fragility functions, which indicate the probability of incurring damage as a function of demand. The consequences associated with each damage state are also defined in a probabilistic manner considering uncertainty in repair methods, repair costs, and other factors.

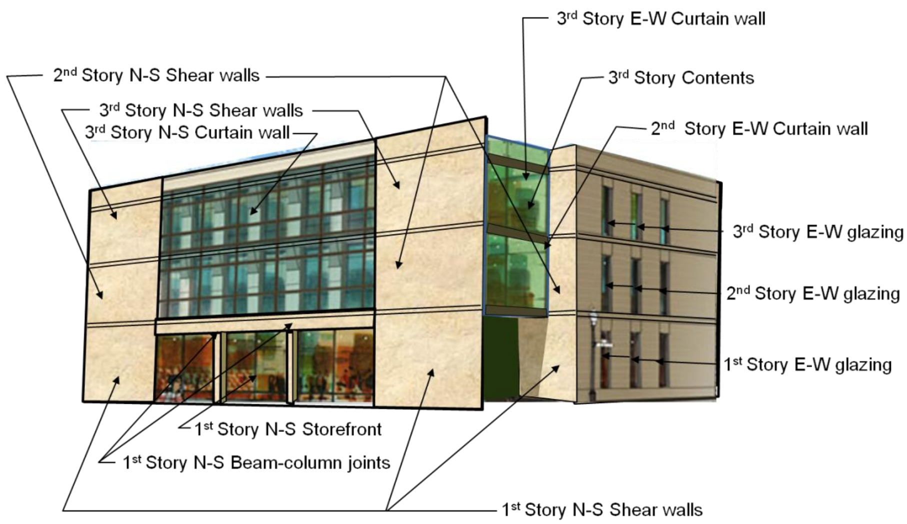


Figure 4-2 Example performance groups in a three-story office building (FEMA, 2012a).

Define Earthquake Hazards. Earthquake hazards are defined by quantifying the magnitude and distance to the site for earthquakes of interest (scenario-based assessments), the intensity of anticipated earthquake ground shaking (intensity-based assessments), and the site-specific probability that earthquakes of a given intensity will occur (time-based assessments).

Analyze Building Response. Structural analysis, based on nonlinear response-history or simplified equivalent lateral force procedures, is used to predict structural response in terms of peak values of various demand parameters, at different intensities, and at different points throughout the structure.

Develop Collapse Fragility. The probability of incurring partial or total structural collapse is a function of ground motion intensity, and is represented as a collapse fragility function. The collapse response mode is most relevant to estimation of casualties, but is also relevant to environmental impacts associated with the building being deemed a total loss.

Calculate Performance. Performance calculations are conducted with the assistance of the *Performance Assessment Calculation Tool* (PACT). PACT utilizes data drawn from component fragilities and damage repair estimates to translate building response into damage, and ultimately into consequences. The methodology uses a Monte Carlo process to generate hundreds to thousands of realizations, each with a unique combination of demand parameters, damage states, and consequences. These realizations each represent one possible building performance outcome in response to earthquake shaking, given the uncertainties in the defined ground motion, structural response, building model, fragility relationships, and the resulting consequences. Because consequences are accumulated into a full-building performance outcome, material quantities and labor associated with the repair actions for each component are not immediately known. This has an important effect on the ability to assess environmental impacts, particularly if a bill-of-materials (BOM) unit process based approach will be used. Results are displayed in a probabilistic distribution that shows the likelihood that consequences will not exceed specific values. A hypothetical FEMA P-58 building performance function is shown in Figure 4-3.

4.2 Building Performance Model

The building performance model will be essential to the integration of environmental impacts in the seismic performance assessment process. The performance model defines the building assets considered to be at risk in earthquakes, including structural components, nonstructural components, contents, and occupants. For the purpose of assessing environmental impacts associated with earthquakes, only the structural and nonstructural components will be considered. The building contents and occupants need not be considered.

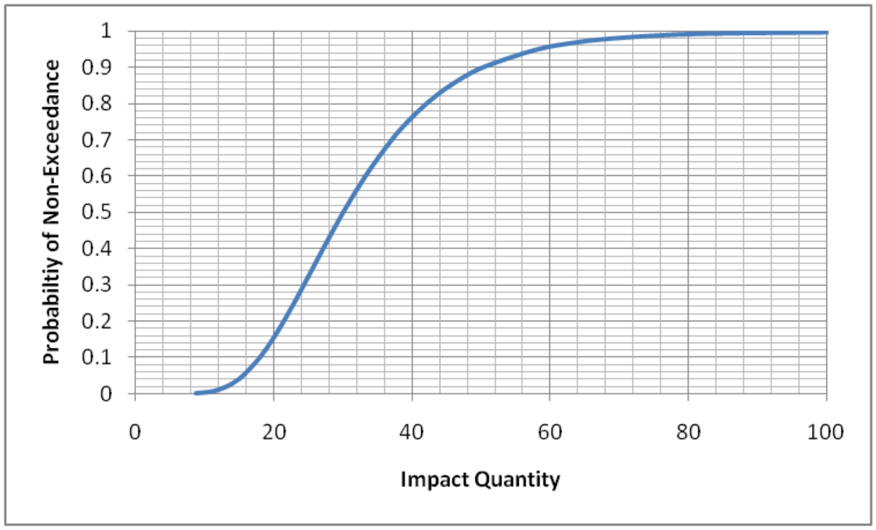


Figure 4-3 Hypothetical building performance function (FEMA, 2012a).

The FEMA P-58 methodology and associated products currently include more than 700 types of damageable components. For each damageable component, it defines a series of one to five damage states with unique damage characteristics and associated consequences. Accordingly, there are approximately 2000 different component damage states, each with unique repair cost, repair time, and casualty consequences. Damage state descriptions, fragility functions, and consequence functions are defined in fragility specifications for each damageable component.

As currently defined in the FEMA P-58 methodology, the building performance model includes only the damageable components of a building, and not the inherently rugged, relatively non-damageable components such as foundations, gravity floor framing and certain roof systems. As such, the building performance model will not capture the environmental impacts associated with the construction, maintenance, and demolition of non-damageable components. Environmental impacts associated with rugged components can be assessed outside of PACT, and considered in the assessment process accordingly, but they are not currently calculated within the existing framework.

4.3 Component Repair Estimates and Fragility Specifications

Consequences are based on component repair estimates that were developed based on expert opinion regarding the scope of structural and non-structural work required to repair each damage state to its pre-earthquake condition. Component repair estimates are provided in separate Excel workbooks independent of PACT and its fragility database. Each component repair estimate includes an associated repair scope of work, with a summary that lists the total costs, including median and dispersion, for each damage state, and a breakdown of the labor and material costs for each. Component repair estimates do not currently display comprehensive bills-of-materials as a basis for each repair cost estimate, but they could potentially be expanded to provide that information for use in environmental impact assessment.

All of the damage states, fragility, and consequence data associated with each component are recorded in a fragility specification. The fragility specification reports summary costs (median and dispersion) from the component damage state repair estimates described above. It does not include a bill-of-materials or other cost breakdown for individual damage states.

Fragility specification data are imported into PACT and referenced by the Building Manager and Fragility Manager modules of the program. Fragility specifications can be updated and re-imported into PACT, or can be modified within PACT using the Fragility Manager.

4.4 PACT Input

PACT is structured to receive input from several sources. The Building Manager component of PACT takes input from the user to define the building size and number of stories, occupant loads, and the inventory of components, fragility groups, and performance groups. It references fragility characteristics from the imported fragility specifications contained in the Fragility Manager component of PACT. It accepts building response data (e.g., accelerations, velocities, and story drifts from throughout the structure) that are imported by the user based on results from an external structural analysis.

4.5 PACT Output

PACT uses a Monte Carlo process to simulate hundreds to thousands of earthquake realizations. PACT tracks the number of occurrences of each damage state in each realization and translates damage states into dollar losses (or other consequences), on a realization basis, and on a performance group per realization basis.

Primary PACT output consists of probabilistic distributions of consequences (i.e., performance functions) in terms of total repair costs, repair time, casualties, and unsafe placarding. Sample PACT results for repair cost are shown in Figure 4-4. The lower portion of the figure shows the realization

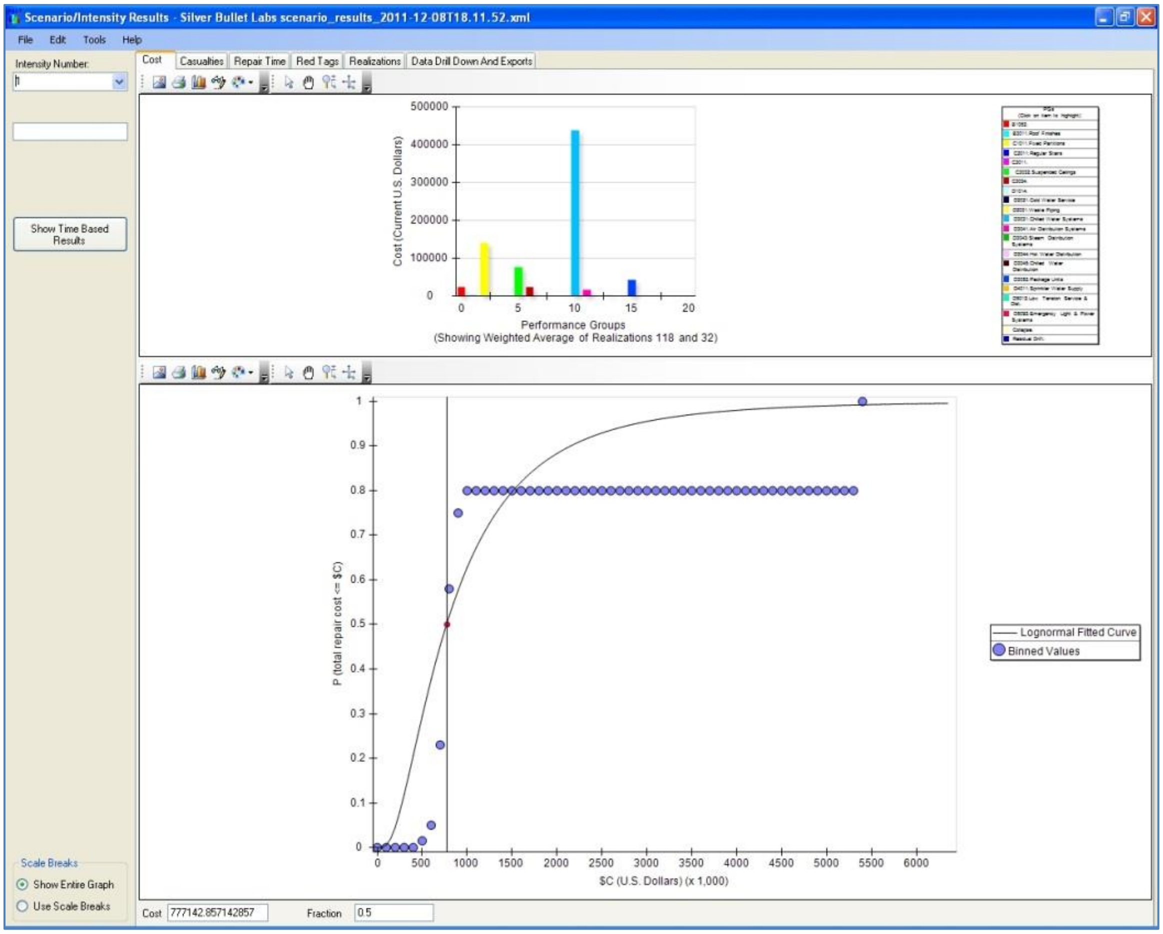


Figure 4-4 Sample PACT output for replacement costs associated with a scenario- or intensity-based assessment (FEMA, 2012b).

data generating the performance function for repair costs. The horizontal axis is the dollar value of repair cost, and the vertical axis is the probability of non-exceedance (probability that total repair costs will be less than or equal to the dollar value).

The upper portion of the figure shows the contribution to repair cost attributable to each performance group. An expanded view of this information is shown in Figure 4-5. Detailed information regarding repair costs for each component group, and the number of occurrences of each damage state per realization is available through "drill down" menus in PACT. An example of this information is shown in Figure 4-6. This detailed data enables users to analyze the major and minor contributing factors to the calculated losses, and can be adapted to similarly report environmental impacts. Tracking of component damage states in PACT can be useful in deriving bills-of-materials for use in generating environmental impacts per realization.

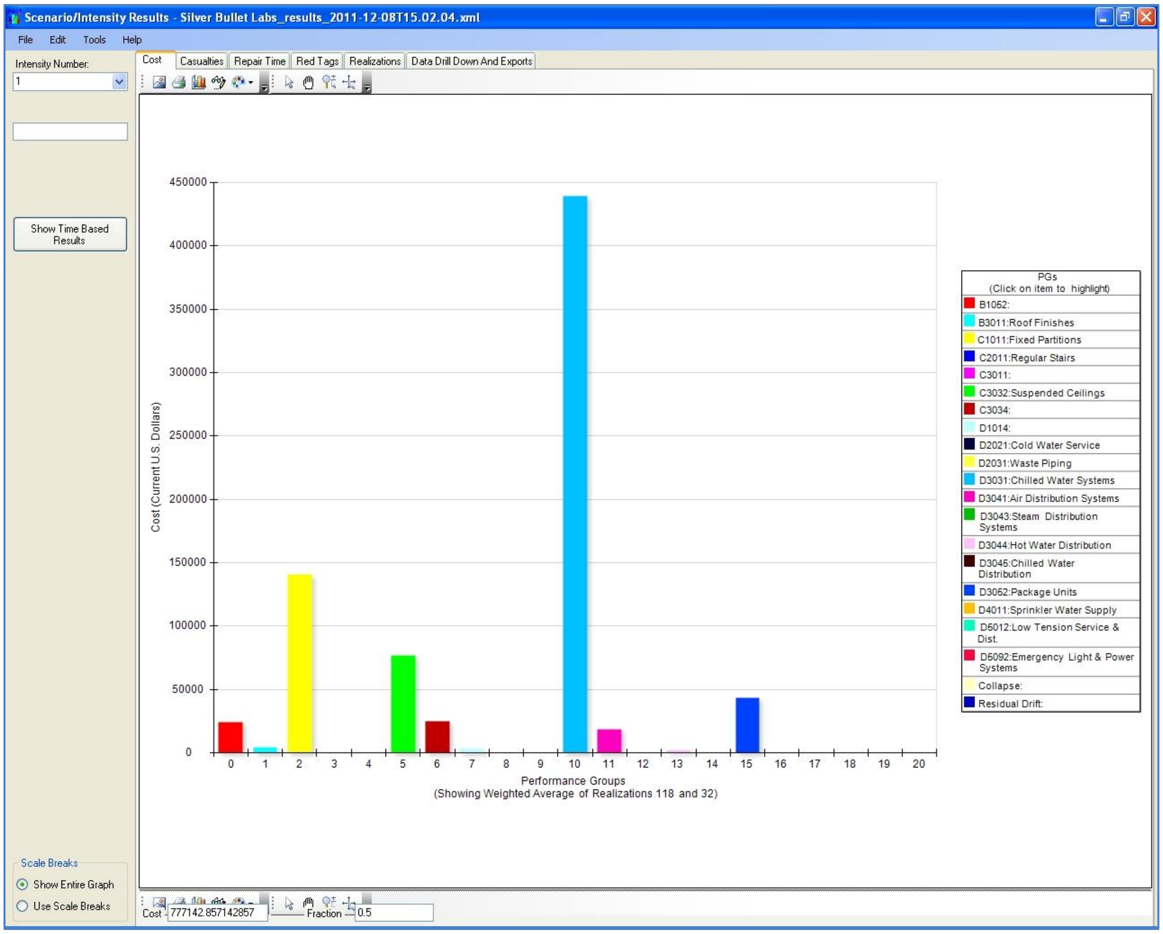


Figure 4-5 Sample PACT output showing repair cost by performance group (FEMA, 2012b).

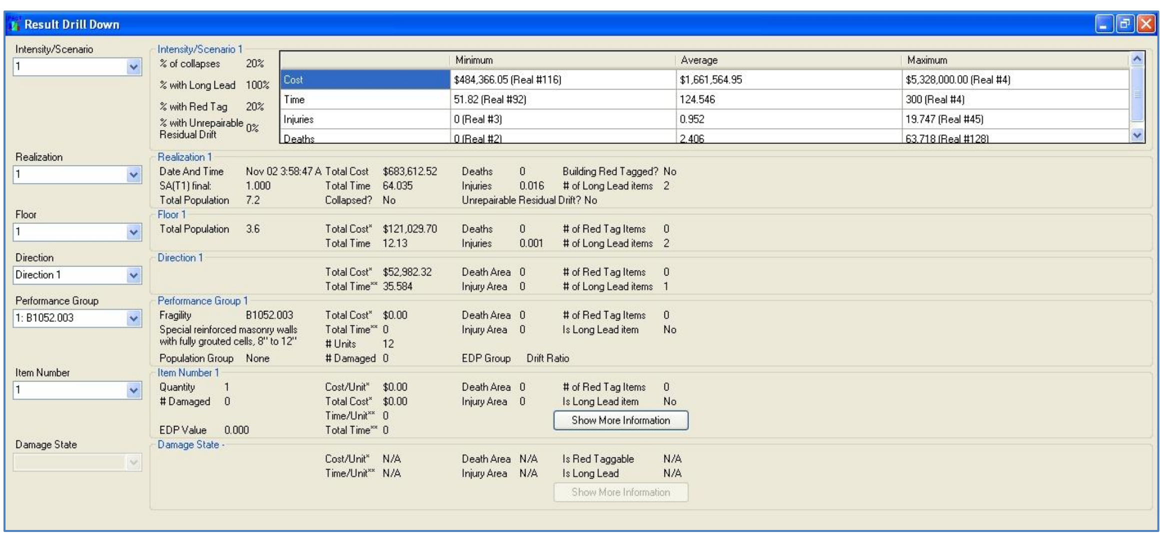


Figure 4-6 Sample PACT drill down window for a specific performance group in a specific realization (FEMA, 2012b).

Figure 4-7 shows sample PACT output for annualized repair costs from a time-based assessment. Annualized environmental impacts can be used to compare environmental performance of different seismic designs in different seismic hazard exposures.

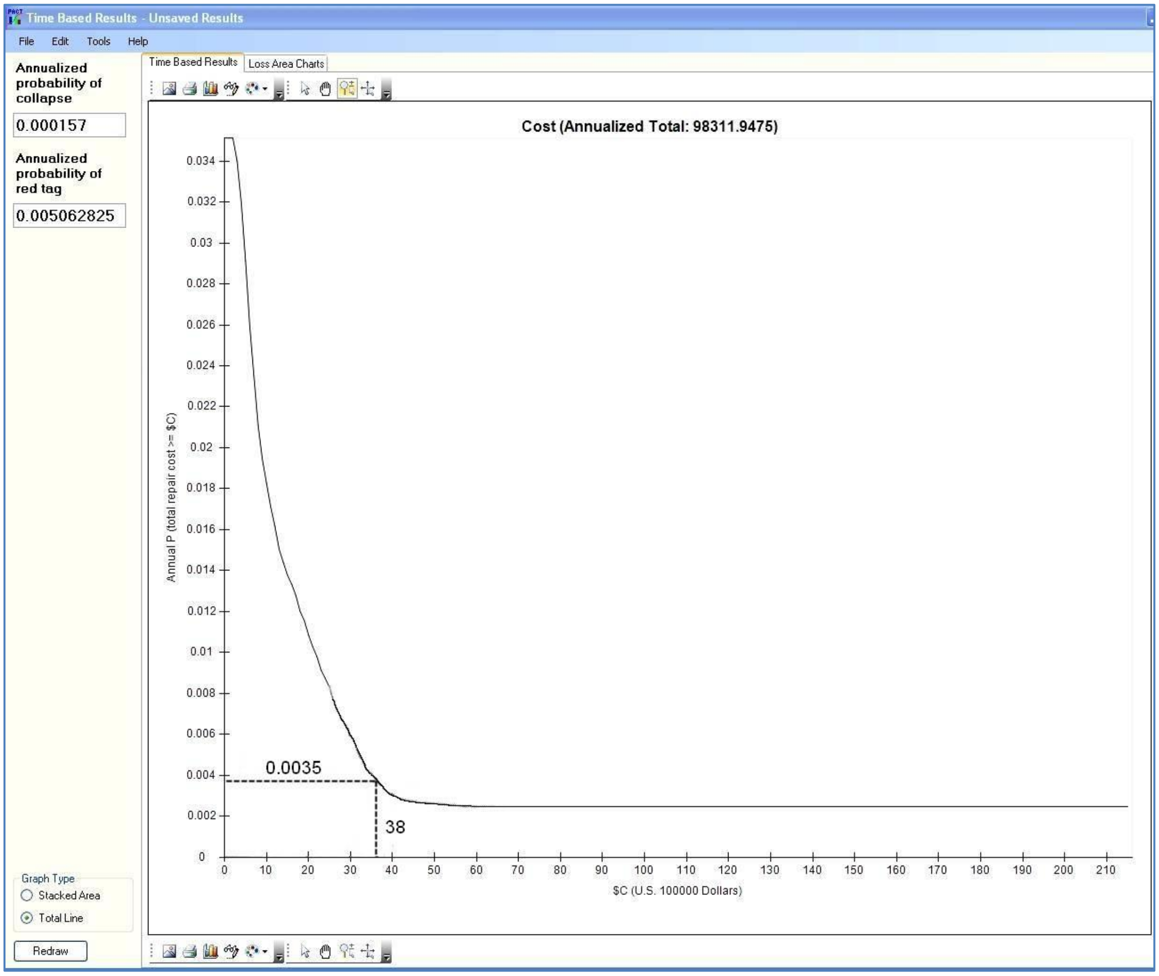


Figure 4-7 Sample PACT output showing annualized repair costs for a time-based assessment (FEMA, 2012b).

Chapter 5

Adding Environmental Impact Assessments to the FEMA P-58 Methodology

5.1 Introduction

This chapter presents a general methodology for integration of environmental impacts into seismic performance assessment. It discusses key considerations, including items considered or excluded from the assessment, environmental data sources and assessment tools, uncertainties, and transparency in the assessment process.

5.2 General Methodology

The recommended strategy is to integrate life cycle assessment procedures into the FEMA P-58 computational framework. The challenge then involves identifying and selecting relevant environmental metrics and quantifying the environmental impacts of the predicted earthquake damage. Probable environmental impacts from seismic performance assessment should be quantified in such a way that they are easily combined with other environmental impacts measured by traditional non-seismic life cycle assessment in a rigorous and consistent manner.

The general level of precision and detail, and the methods of accumulation of consequences, should ideally parallel what is included in the FEMA P-58 methodology. Currently, the FEMA P-58 computational framework applies greater precision in estimating and accumulating repair costs, and comparatively less precision (greater uncertainty) for repair time, casualties, and unsafe placarding consequences.

The general methodology for adding environmental impacts into seismic performance assessment includes:

- **Selecting environmental impact metrics.** Recommended metrics are discussed in Section 5.2.1.

- **Quantifying earthquake damage and repair actions.** Quantification of repair actions as they relate to environmental impacts is discussed in Section 5.2.2.
- **Quantifying environmental impacts of earthquake damage and repair actions.** Methods for quantifying environmental impacts associated with repair actions are discussed in Section 5.2.3.
- **Integrating impact measures into the computational framework.** Alternative approaches for integrating environmental impacts into the FEMA P-58 computational framework are discussed in Section 5.2.4.
- **Reporting environmental impacts.** Methods of reporting environmental impacts are discussed in Section 5.2.5.

5.2.1 Selecting Environmental Impact Metrics

Standard environmental impact metrics were introduced in Chapter 2. Current ISO standards, emerging European standards, and current practice for life cycle assessment provide a suite of impact and resource use measures that can be used. The most common metrics include climate change potential (measured in CO_2 equivalents) and primary energy consumption. Other significant factors include several polluting emissions and effluents. As a minimum, the following two measures are recommended as the highest priority environmental impacts:

- Climate Change Potential
- Primary Energy Use

If feasible, in terms of availability of inventory data and funding resources, the following additional measures specified in ISO 21930 (ISO, 2007), are recommended for consideration:

- Ozone Depletion Potential
- Acidification Potential
- Eutrophication Potential
- Photochemical Smog Potential

An additional measure of interest is waste generation, which can be calculated with relative ease when using a bill-of-materials approach. Other additional environmental measures associated with life cycle assessment are not recommended due to lack of available data, added complexity in calculating impacts, and potential difficulty in interpreting results. The list of recommended environmental measures may evolve as future science, technology, and environmental policies develop.

5.2.2 Quantifying Earthquake Damage and Repair Actions

The FEMA P-58 methodology quantifies probable damage resulting from earthquake shaking. It does so by defining a set of discrete damage states for each structural and nonstructural component type, and by predicting the number of times each damage state occurs in a specific seismic response realization. It also quantifies the estimated repair costs for each component damage state, and sums the total repair costs for each realization. It does not, however, quantify a bill-of-materials for repairs at the individual component level, or the realization level.

For environmental impacts to be assessed, earthquake damage and repair actions must be quantified in terms of material costs or a bill-of-materials. If material costs are known, then an economic input-output based assessment can be performed to obtain a rough estimate of environmental impacts. If a bill-of-materials is known, then a more detailed (and more precise) unit process based assessment of environmental impacts can be performed. Labor is typically not counted in life cycle assessment.

Material Costs. Quantification of repair material costs is needed for economic input-output (EIO) assessments. The FEMA P-58 computational framework currently quantifies repair costs for each pre-defined component damage state, and then calculates total repair costs per component group and realization. Approximate ratios between material costs and labor costs can be obtained from the repair estimates that were used to generate the FEMA P-58 consequence functions, but material costs are not explicitly itemized. To implement EIO assessments, material costs would need to be derived from the approximate material cost versus labor cost ratios, or by re-examining the nearly 2000 component damage state repair estimates to develop detailed material versus labor cost breakdowns.

Bill-of-Materials. Quantification of repair actions in terms of a bill-of-materials (BOM) is needed for a unit process based assessment. FEMA P-58 consequence functions are based on a general scope of repairs defined for each component damage state in the damage repair estimates. These estimates were intended to capture the expected range of costs for repairing each damage state, with an understanding that there will be significant uncertainty in defining the actual work, materials, and processes needed to repair damage in an actual building. A BOM could be developed for each component damage state by separating the material costs from the labor costs and reconstructing the basic material assumptions implicit in the estimates. The feasibility of this approach was investigated in the repair estimate studies described in Appendix A. The resulting BOMs should represent the range of probable material quantities needed to repair the defined damage state.

A sample BOM adapted from a component repair estimate is presented in Figure 5-1 (variability is not yet included in this example). Once a BOM is generated and recorded for each pre-defined component damage state, a total BOM can be developed for each realization by multiplying the component damage state BOM quantities by the predicted number of damage state occurrences. Inherent variability of material quantity data could be characterized by mean, upper bound, and lower bound quantities, or by median and dispersion parameters, in the manner that variability is captured for repair costs in the FEMA P-58 methodology.

					BOM		
		Quantity	Units		material	quantity	units
Concrete Moment Frame -Damage State DS2							
Estimate Basis - damage extends (each direction)		4	LF				
Estimate Basis - Column/beam width avg		2	LF				
Estimate Basis - crack length		50	LF				
Demolition							
Floor finishes		324	SF		waste-flr finishes -carpet	324	lbs
Partitions obstructing works (full height)		270	SF		waste-studs&drywall	1620	lbs
Remove, store and reinstall							
Ceilings							
Mechanical and electrical systems		120	SF				
Office furniture and equipment		1	LS				
Temporary							
Floor protection (access)		1	LS		plywood - 3/4"	250	sqft
					polyethylene - 10 mil	30	lbs
Dust curtains		600	SF		Wood stud framing	300	bf
					polyethylene - 6 mil	60	lbs
Scaffolding or work platforms (underside access)		1	LS				
Shoring		1	LS		Wood Shoring	500	bf
Column/beam repairs							
Prepare work area		64	SF				
Remove loose concrete, clean rebar		1	LS		Power tools - heavy hand	40	hrs
Epoxy injection		50	LF		epoxy	25	lbs
Formwork (including removal)		64	SF		plywood - 3/4"	64	sf
Concrete	1	5	CY		concrete-3000psi, 0%flyash	5	CY
	2				concrete-4000psi 20%flyash	5	CY
					Power tools - concrete pump	2	hrs
Replace							
Partitions removed - patch in		270	SF		stl studs-20ga x 4"	540	lbs
					gypsum drywall - 2 layers, 1/2"	1080	lbs
					Paint	1.8	gal
Floor finishes	1	324	SF		flr finishes - 80% carpet, 20% tile	324	sf
	2				flrg - carpet	324	sf
	3				flrg - tile & grout	324	sf
	4				flrg - sheet vinyl	324	sf
Mechanical and electrical modifications or relocations							
as required for repair work		1	LS		sheet metal - 24 ga	100	lbs
					copper wire	20	lbs
					plastic coating	2	lbs

Figure 5-1 Sample FEMA P-58 component repair estimate (costs not shown for clarity) adapted to include basic material assumptions (shaded in grey) for a bill-of-materials (BOM).

5.2.3 *Quantifying Environmental Impacts of Earthquake Damage and Repair Actions*

Given a prediction of earthquake damage and repair quantities, environmental impacts can be quantified through unit process, economic input-output, or hybrid approaches. Each of these approaches requires a different level of effort to implement, and will potentially deliver a different level of precision and accuracy. If repair actions are quantified in terms of material costs, then an economic input-output procedure can be used. If they are quantified in terms of a bill-of-materials, then a unit process procedure can be used. If they are estimated using a combination of material cost and quantity data, then a hybrid procedure can potentially be used.

Bill-of-Materials Unit Process Approach. The bill-of-materials (BOM) unit process approach is a detailed (bottom-up) approach that begins with the quantification of environmental impacts for each of the materials and processes contributing to each component repair action. It likely requires the greatest level of effort to implement, but provides the highest level of precision and accuracy in impact assessment. The BOM unit process approach includes the following steps:

- **Step 1.** Generate and record a BOM for each defined damage repair on a component level. A BOM itemizes the material and equipment usage for each component damage state.
- **Step 2.** Generate and record environmental impacts for each defined component repair. This would be accomplished by using life cycle impact assessment resources (tools and databases) to generate impacts for each item in the BOM.
- **Step 3.** Quantify the environmental impacts of each earthquake damage realization. This would be accomplished by multiplying the number of component damage state occurrences in a realization by the impacts per damage state determined in Step 2.

This is a classic unit process life cycle assessment approach in which the environmental impact of each BOM line item and the total impact per component and realization are predicted to the greatest precision feasible. Tools and resources for generating the life cycle impacts for each line item include:

- **Publically available data sources.** Some life cycle inventory data are publically available free of charge, but available data are not sufficient to generate impacts associated with earthquake damage without additional data sources and LCA expertise. Public data sources include the *Building for Environmental and Economics Sustainability* (BEES) tool

(NIST, 2011) and the U.S. Life Cycle Inventory (LCI) database (NREL, 2011). The BEES data are currently limited, and is not in the form of a relational LCI database. BEES simply reports environmental impacts for select materials. The U.S. LCI database provides U.S.-specific unit process inventory data for use in commercially available tools, but additional work would be required to develop environmental impacts for a specific product (e.g., a glue-laminated beam). Currently, there is no LCI database in the public domain that is readily available for use in seismic performance assessment.

- **Commercially available tools.** Several commercially available tools include fairly comprehensive LCI databases. Leading tools include the Athena Impact Estimator (Athena, 2012b), SimaPro (Pré Sustainability, 2011), and GaBi (PE International, 2012). Data from these tools can be used to generate customized environmental impact datasets (impacts per unit of material or process) that could be embedded into the FEMA P-58 calculation process to address anticipated repair actions. Use of these tools would require licensing agreements, and would require experienced individuals to draw linkages between repair action BOMs and the LCI data as cataloged by the tools. Additional information on commercially available tools is provided in Appendix B.
- **Life cycle assessment expert consultant.** An experienced LCA consultant, with access to both public and proprietary tools and datasets, could be retained to provide impact-per-unit measures for each item in a component-based BOM. This consultant could be an independent LCA professional, or could be affiliated with a commercial tool or dataset provider.

Economic Input-Output Approach. The economic input-output (EIO) approach is a global (top-down) approach for quickly estimating impacts based on material costs and EIO environmental impact factors. It is less detailed and less precise than a BOM unit process approach. Options for implementing an EIO approach include:

- **Single sector (commercial construction) economic input-output.** Single sector EIO starts with total repair costs generated on a realization level. From this, the material costs are estimated and multiplied by appropriate EIO factors for commercial construction to obtain impacts per realization. This approach is simple, but considered to be of limited accuracy because environmental impacts would track linearly with total material costs, not accounting for the relative significance of different contributing components or their environmental effects.

- **Multi-sector economic input-output.** Multi-sector EIO starts by reviewing the component repair estimates and grouping components based on similar repair characteristics (i.e., similar materials and similar labor to material cost ratios). The costs per repair estimate can be proportioned based on relevant EIO sectors (e.g., 30% glazing, 60% aluminum, and 10% gypsum wallboard) that can then be multiplied by the EIO sector emissions per dollar, and totaled to get the emissions per unit of repair item. These factors could be multiplied by material costs to obtain impacts using either the component or realization-based approaches described in Section 5.2.4. Additional work would be required to estimate the impacts of waste generated by debris disposal. Multiple components could be tested individually to check the accuracy of this approach compared to a BOM unit process approach. The level of accuracy could be refined by further dividing components into appropriate smaller sub-groupings (the groupings can be subdivided, but the EIO categories cannot). Groupings could proceed from broad categories to subcategories following the fragility classification system used in FEMA P-58 and illustrated in Figure 5-2.

Of these EIO options, a multi-sector EIO approach is recommended. More information on available EIO datasets is provided in Appendix B.

Hybrid Approach. A hybrid approach combines both bill-of-materials (BOM) unit process and economic input-output (EIO) approaches. Options for implementing a hybrid approach include:

- **Begin with an EIO based approach.** Start with a top-down multi-sector EIO approach. Develop environmental impacts per dollar for each component group. Use this data to perform sensitivity studies to determine the significance of different components and materials. For significant items, fill in more precise impacts with unit process analyses, then complete an assessment of the impacts per realization.
- **Begin with a BOM unit process based approach.** Utilize unit process procedures to assess impacts for each item in the BOM. For items lacking sufficient unit process data, use EIO procedures to develop approximate impacts, then complete an assessment of the impacts per realization.

A potential benefit of beginning with an EIO approach is that the initial economic input-output analysis can function as a sensitivity test to identify which component repairs are the most significant contributors, and warrant more detailed impact studies. Either hybrid approach, however, allows for the use of EIO procedures to fill in where sufficient unit process information is not available.

General System Description	Fragility Classification Number	Component Description	Number of Sub-Categories
Miscellaneous Structural Steel Components/ Connections	B1031.001	Bolted shear tab gravity connections	1
	B1031.011	Steel column base plates	3
	B1031.021	Welded column splices	3
Structural Steel Special Concentrically Braced Frames	B1033.001	Special Concentrically Braced Frame with wide flange (WF) braces, balanced design criteria, chevron brace	3
	B1033.002	Special Concentrically Braced Frame with WF braces, balanced design criteria, single diagonal	3
	B1033.003	Special Concentrically Braced Frame with WF braces, balanced design criteria, X Brace	3
	B1033.011	Special Concentrically Braced Frame with hollow structural section (HSS) braces, balanced design criteria, chevron brace	3
	B1033.012	Special Concentrically Braced Frame with HSS braces, balanced design criteria, single diagonal	3
	B1033.013	Special Concentrically Braced Frame with HSS braces, balanced design criteria, X Brace	3
	B1033.021	Special Concentrically Braced Frame with HSS braces, tapered gusset plates, design to AISC minimum standard, chevron brace	3
	B1033.022	Special Concentrically Braced Frame with HSS braces, tapered gusset plates, design to AISC minimum standard, single diagonal	3
	B1033.023	Special Concentrically Braced Frame with HSS braces, tapered gusset plates, design to AISC minimum standard, X Brace	3

Figure 5-2 Excerpt from FEMA P-58 list of provided fragility specifications (FEMA, 2012a).

A challenge with the hybrid approach is to ensure that the EIO and unit process assessments are of comparable scope and scale. Economic input-output assessments are often based on a more comprehensive set of upstream factors, so care must be taken to harmonize EIO and unit process results.

Decisions on which approach to use (unit process, EIO, or hybrid) should be based on balancing the precision needed (or desired) with the available developmental budget. Unit process and hybrid approaches are most consistent with the level of precision inherent in the FEMA P-58 methodology for assessment of repair costs. The EIO approach is more consistent with the level of precision inherent in the FEMA P-58 methodology for assessment of repair time.

5.2.4 Integrating Impact Measures into the Computational Framework

Environmental impacts generated using the approaches outlined above can be integrated into the FEMA P-58 computational framework at the component level or the realization level. Integration approaches are described below:

Integration at the component level. At the component level, environmental impacts would be estimated for each of the approximately 2000 damage states in the component repair estimates. Environmental impacts would then be added to the component fragility specifications as an additional consequence function, similar to repair costs, and environmental impacts accumulated along with other FEMA P-58 consequences through the performance assessment process.

Integration at the realization level. At the realization level, using an EIO procedure, the ratio of environmental impacts per repair dollar would be established for each performance group. That ratio would then be multiplied by component group repair costs to calculate environmental impacts at the realization level. At the realization level, using a BOM unit process or hybrid procedure, a bill-of-materials for each component damage state would be developed and aggregated for each realization by multiplying the number of damage state occurrences (predicted through the performance assessment process) by the quantities in the associated BOM. The aggregated BOM would then be linked directly to a customized environmental impact dataset to calculate impacts per realization.

Because the FEMA P-58 computational framework involves running several hundred to several thousand realizations, it would not be practical to export BOMs (at the component or realization level) into a life cycle assessment tool, and then re-import environmental impact results back into the FEMA P-58 computational framework to display probability distributions for each measure. Instead, a dataset of environmental impacts per dollar (in an EIO procedure) or per unit of material (in a BOM procedure) would need to be built into, or directly linked to, the *Performance Assessment Calculation Tool* (PACT), or its successor programs.

5.2.5 Reporting Environmental Impacts

Environmental impacts can be reported as performance functions (i.e., probabilistic distributions) in the same way that other consequences (e.g., repair costs) are reported as output from the FEMA P-58 methodology. Alternatively, impacts could be reported as mean or median values with dispersions for each metric. This method of reporting is likely more useful for comparing to, or combining with, impacts calculated using standard life cycle assessment tools for non-seismic related environmental impacts. Both capabilities are recommended for reporting environmental impacts as part of a seismic performance assessment.

5.3 Recommended Strategy for Implementation

The recommended strategy for implementing environmental impact assessments within the FEMA P-58 methodology is to consider a two-phased approach. The first phase (near term) consists of implementing a simplified economic input-output (EIO) procedure for preliminary or interim use. The second phase (long term) consists of implementing a unit process based approach in which bills-of-materials (BOM) for repair are generated and linked to a customized impact per unit dataset that is developed specifically for use in FEMA P-58 seismic performance assessment calculations. This approach has the benefit of allowing the impact dataset to be updated and regionalized, independent of the component fragility data and repair material quantity estimates embedded within the computational framework.

Chapter 6 provides further discussion related to the implementation of these methods within the FEMA P-58 *Performance Assessment Calculation Tool* (PACT).

5.3.1 Economic Input-Output Methodology (Phase 1 – Near Term)

A simplified environmental impact assessment methodology could be developed using the customized economic input-output (EIO) procedure described in Section 5.2.3. EIO procedures provide simple relationships between material costs and environmental impacts, and could be developed with less effort than a bill-of-materials (BOM) unit process procedure. It could be refined as needed with selected unit process studies on components that are identified as important contributors to environmental impacts.

Although results are not specific to building construction or location details, this method could capture the relative magnitude of impacts, and could serve as a practical interim solution. It could also be used for sensitivity studies to inform and prioritize subsequent unit process development under Phase 2.

5.3.2 *Bill-of-Materials Methodology (Phase 2 – Long Term)*

A more detailed environmental impact methodology involves developing a bill-of-materials (BOM) for each repair action and using unit process procedures, or hybrid procedures, to estimate environmental impacts. This methodology could be implemented on a component level or a realization level as described in Section 5.2.4. It would require substantially more work effort than the Phase 1 simplified EIO methodology, but would provide greater precision and detail in generating environmental impacts. Despite the greater precision, care must be taken to ensure that the uncertainty in prediction of impacts is transparent in the analysis.

5.4 Other Considerations: Labor, Laborer Travel, Construction Processes, and Equipment

The labor component of construction is typically excluded from life cycle assessments. Therefore, labor must be separated from material quantities and construction processes in assessing impacts. Travel of labor to the jobsite, however, is considered, and can contribute measurably to construction impacts, particularly in a post-earthquake scenario in which damage is widespread over an entire region, and longer travel distances might be required for the labor force. Travel can be estimated, for example, based on the number of labor hours divided by eight to estimate the number of trips, and then multiplied by an assumed travel distance. Allowance should be made to account for longer travel distance assumptions.

Construction processes and equipment can also have measurable environmental impacts. Related power usage, which can be accounted for based on estimated hours of equipment use, and material consequences such as concrete form use and disposal, should be tracked. Accounting for these items requires various assumptions. The assumptions should be transparent and documented, and allowance should be made to account for different assumptions.

5.5 Environmental Data Sources and Characteristics

In order to add environmental assessments to the FEMA P-58 methodology, developers will need to utilize external data sources and tools to develop environmental impact measures. The BOM and EIO procedures have different data requirements and will utilize different resources.

For BOM methods, the ideal data source is an LCA tool with a comprehensive, up-to-date, region-specific LCI database. It would be applicable for both earthquake damage repair and new construction so that repair options could be compared with new construction options using the same data sources and assumptions. Such a data source would also account for full life cycle material impacts, including transportation, maintenance, and end-of-life.

Data sources should be comprehensive enough to cover significant impact contributors ranging from the primary structural system to the secondary finish and mechanical systems. Preliminary sensitivity studies can help identify these significant contributors. Developing new LCI data where none exists is difficult and time-consuming.

Ideally, referenced data sources should be consistently maintained and up-to-date with regard to evolving manufacturing and construction technologies and energy sources. Implementation should allow for updated datasets to be easily imported as new versions of the tools are released.

Data sources should be region-specific to reflect local material and energy sources, and local technologies. Regional specificity is particularly important for detailed unit process based assessments. It is less relevant for EIO based assessments, which are currently generated based on national economic and environmental statistics.

Available data sources will likely need to be customized or supplemented to specifically address earthquake damage repair actions. Items such as mechanical equipment, special architectural finishes, and concrete or steel component repairs may not be fully (or properly) addressed in available life cycle inventories.

U.S. life cycle inventory data (emissions per a unit process) is available for a limited number of construction products. Limited availability, and the growing interest in life cycle assessment for buildings, suggests that a more comprehensive public database, similar to those already developed in the Netherlands, Switzerland, and France, is needed in the United States.

For economic input-output procedures, available external data sources are compiled on an economic sector level, and are typically dated to the latest national economic data. Underlying EIO data for the United States were developed using national economic statistics showing the inter-relationship of 400 to 500 sectors of the economy. These data were last updated in 2002.

These EIO data are theoretically comprehensive, capturing inter-relationships and impacts within an economy, though in practice, they do not capture international sources and effects. Data are also very general, tracking categories of items on an economic sector level, rather than tracking specific items on a product or material level. General EIO data can only be utilized by effectively mapping specific building materials and systems to appropriate sectors in appropriate proportions. Datasets of impacts per dollar of material will need to be developed based on engineering judgment and appropriate mapping of material damages to material categories or economic sectors.

Data sources should be reputable and well documented to ensure user credibility. Quality assurance and maintenance plans should be put into place to ensure that data taken from available datasets are kept up to date. Several available potential data sources, and their characteristics, are summarized in Appendix B.

5.6 Data Uncertainty and Variability

5.6.1 Uncertainties considered in the FEMA P-58 Methodology and PACT

The FEMA P-58 methodology explicitly considers uncertainty in the seismic performance assessment process and calculation of consequences. Specifically, repair cost estimates include "most likely," "highest," and "lowest" probable costs for each repair action. Each component repair estimate considers these costs with an approximate statistical range. This range considers many potential sources of uncertainty (e.g., material quantities, market conditions, site complexities) and was developed using estimating expertise and professional judgment. For each realization, the magnitude of repair cost for each component is randomly selected from the estimated range using statistical relationships and then used in calculating total losses.

5.6.2 Data Quality and Variability in Environmental Assessments

For environmental impact assessments, sources of uncertainty include: (1) variable LCI data quality (e.g., "good" data may not be available for certain items); (2) age of data in industries that are rapidly changing; (3) expected variability in quantities of materials needed for repair; and (4) variability in environmental impacts based on variable manufacturing processes and materials used.

Ideally, existing data sources would contain an evaluation of the data quality (i.e., how representative, consistent, or comprehensive the data are) and variability (i.e., standard deviation and statistical distribution). Unfortunately, most do not include this information. Data quality is addressed qualitatively (if at all). Average values are presented with unknown variability. Life cycle impact datasets should be developed with data of the "best available quality," and an evaluation of the data quality should be included in the documentation.

Ideally, integrating environmental data variability should be addressed in a manner similar to the way cost variability is modeled in the FEMA P-58 methodology. Data variability could include variability of both material and environmental impact quantities:

- **Material Quantity Variability.** Variability in material quantities is most easily captured by considering a range of estimated material quantities, provided that life cycle impact assessment results are generated using a BOM approach. This would require added time in evaluating each of the estimates.
- **Environmental Impact Variability.** Environmental impacts per unit of material or process vary due to many factors including manufacturing processes, material sources, energy sources, and transportation distances. Options to account for environmental impact variability include:
    - **Acknowledge variability.** Given that limited actual data exist, acknowledge variability but do not explicitly include it. This avoids the risk of inaccurately characterizing variability, but provides little or no guidance on how to address it.
    - **Estimate variability based on professional judgment.** Quality ratings for specific materials or processes could be assigned based on expert opinion and judgment, similar to the process used in the FEMA P-58 methodology, and illustrated in Figure 5-3. Variability ratings (e.g., superior, average, and limited) could then be defined for different materials and processes. For example, materials manufactured in controlled processes could be assigned low values of dispersion, and materials manufactured with multiple processes and ingredients could be assigned high values of dispersion. Expertise on evaluating environmental data variability is limited, as most life cycle assessment research has focused on establishing average values rather than statistical ranges. However, recognizing that there is uncertainty in the estimates of variability can help avoid inaccurately characterizing the precision of the data.
    - **Determine precise statistical variation.** Determining the statistical variation in environmental data would involve the development of a detailed understanding and knowledge of the sources and magnitude of environmental impacts. While most precise, this exercise would require a significant research effort (perhaps requiring the collection of primary LCI data).

Building Definition and Construction Quality Assurance	β_c
Superior Quality, New Buildings: The building is completely designed and will be constructed with rigorous construction quality assurance, including special inspection, materials testing, and structural observation. *Superior Quality, Existing Buildings*: Drawings and specifications are available and field investigation confirms they are representative of the actual construction, or if not, the actual construction is understood. Material properties are confirmed by extensive materials testing.	0.10
Average Quality, New Buildings: The building design is completed to a level typical of design development; construction quality assurance and inspection are anticipated to be of limited quality. *Average Quality, Existing Buildings:* Documents defining the building design are available and are confirmed by visual observation. Material properties are confirmed by limited materials testing.	0.25
Limited Quality, New Buildings: The building design is completed to a level typical of schematic design, or other similar level of detail. *Limited Quality, Existing Buildings*: Construction documents are not available and knowledge of the structure is based on limited field investigation. Material properties are based on default values typical for buildings of the type, location, and age of construction.	0.40

Figure 5-3 Example of quality rating descriptions and associated values of dispersion, β_c (FEMA, 2012a).

5.6.3 Additional Sources of Uncertainty

Additional sources of environmental impact uncertainty include:

- **Labor transportation.** Labor transportation is discussed in Section 5.4. Quantities and impacts associated with labor transportation will be highly variable.
- **Material transportation.** Some life cycle impact databases are cradle-to-gate. Data used for material transport should be clearly defined as cradle-to-site, and the transportation impacts approximately included. Note that in a regional disaster, there might be added transportation from secondary distribution locations if local suppliers are adversely affected.
- **Site energy use.** Site energy use can be estimated based on hours of equipment use, as discussed in Section 5.4, but this quantity can be highly variable.
- **Economies of scale and enabling work.** Repairs can range from very minor, isolated repairs to major repairs throughout the building. As a result the extent and contribution of enabling work (e.g., staging, removal of finishes, and temporary protection) can vary widely.

5.7 Transparency

Environmental impact assessment procedures should be transparent so that the processes, assumptions, data sources, and results are clearly understandable and independently verifiable. Transparency is particularly important for environmental assessments, because users are less likely to be familiar with the procedures or to have a "feel" for the results. This section provides general guidance for maintaining transparency.

Technical users will be cautious about accepting results from analytical tools without verification. The computational procedures underlying any future development of environmental assessments should be clearly explained in accompanying documentation. This transparency will:

- allow users to independently verify procedures and results,
- help users evaluate unexpected results,
- increase user confidence, and
- help future developers understand the workings of the assessment tool.

Environmental assessments depend upon many factors and assumptions including repair techniques, material quantities, material and laborer transportation distances, energy sources, and life cycle inventory flows. Users should be able to verify or modify quantities and assumptions, and should be able to confidently rely on the tools and resources used to generate impacts. The tools and processes used in the assessments should conform to ISO standards and should come with third party verification to assure acceptable credibility.

5.7.1 Repair Assumptions

Assumptions regarding repair materials, quantities, and processes should be clearly documented. Assumptions regarding quantities and types of finishes to be removed for repairs, structural and nonstructural component and system details, concrete mix designs, and other similar material details should be clearly explained. Documentation should also clarify assumptions regarding:

- material transportation distances and modes;
- worker transportation distances and modes;
- energy sources and site energy generation;
- construction impacts, such as crane and other equipment usage; and
- treatment of uncertainties regarding the scope of repairs and other factors.

5.7.2 Underlying Environmental Metrics

The tools or resources used to generate environmental impact datasets should be documented and, if non-confidential, the summary impact measures per unit of material should be tabulated for user review. The methodology should allow users to customize environmental impact datasets as needed for regional specificity, special conditions, or for custom damage states. In addition, documentation should provide:

- credentials of the impact dataset developer or provider;
- methodologies, standards, and quality assurance procedures used to develop the datasets; and
- age of data and assumptions regarding production technologies.

5.7.3 Dataset Update Procedures

Many factors will change with time, including:

- repair technologies;
- building construction materials and methods;
- material manufacturing processes;
- availability of environmental data; and
- relative importance of environmental impacts.

Documentation should explain the intended maintenance plans for updating environmental impact datasets and calculations.

Chapter 6

Adding Environmental Impact Assessments to PACT

6.1 Introduction

For the foreseeable future, application of the FEMA P-58 methodology will rely on the *Performance Assessment Calculation Tool* (PACT), or a successor program, to facilitate the statistical computations and manage building information and fragility specification data. This chapter presents detailed recommendations for implementing environmental impact assessments into PACT. The recommended procedures involve manipulations of the component repair estimates and fragility specifications created as data sources for PACT.

The recommended strategy for implementing environmental impact assessments within the FEMA P-58 methodology is to consider a two-phased approach. Phase 1 (near term) consists of implementing a simplified economic input-output (EIO) procedure for preliminary or interim use. Phase 2 (long term) consists of implementing a bill-of-materials (BOM) unit process based approach that is linked to a customized impact per unit dataset developed specifically for use in FEMA P-58 seismic performance assessment calculations.

BOM procedures provide a rigorous, engineering-like method for environmental impact assessment with a level of detail and accuracy that is similar to the levels currently provided for repair costs in PACT. EIO procedures provide a more generalized estimate of impacts, similar to the level of accuracy provided for causality and downtime estimates in PACT. The following sections describe methods and procedures for adding environmental assessment capabilities to PACT, following the general methodology outlined in Chapter 5.

6.2 Economic Input-Output Methodology (Phase 1 – Near Term)

Two economic input-output (EIO) methods are presented, one based on a component-level approach and one based on a realization-level approach.

6.2.1 EIO Procedure 1A: Component-Based Approach

This approach involves adding factors for environmental impacts per unit to the component repair estimates on the input side of PACT, as illustrated in Figure 6-1.

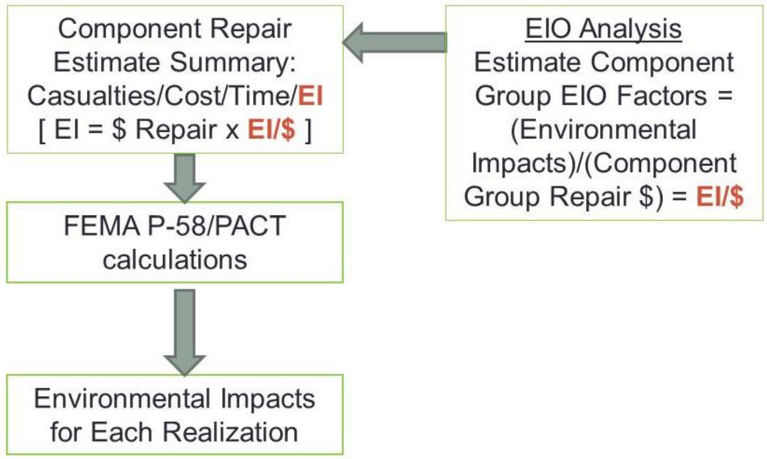


Figure 6-1 Flowchart of EIO Procedure 1A, Component-Based Approach.

Per-unit impacts can be added to the component repair estimates using an EIO procedure or a hybrid procedure. Implementation of this procedure would include the following steps:

1. **Quantify environmental impacts per component.** Expand the master summary of FEMA P-58 component repair estimates to include environmental impacts for each component damage state based on component groupings as described below, or based on analysis of each of the 2000 individual component damage states. The component repair estimates already provide an estimate of the percentage of repair costs attributable to labor versus materials. Environmental impacts per dollar could be estimated using the total repair costs with the breakdown of labor versus materials together with impact per dollar ratios derived from an EIO analysis. This would require expertise in both the estimation of repair actions and use of EIO impact data.

   To simplify this process, the approximately 2000 component repair estimates could be grouped by fragility classification numbers into categories representing different material groups (e.g., steel, concrete, or wood), different structural systems (e.g., moment frames, or shear walls), or different component types (e.g., structural members, mechanical equipment, or architectural finishes). Each category would be assigned to a single EIO sector, or proportioned to multiple sectors based on their constituent repair materials to calculate environmental impacts per dollar using standard EIO databases. The refinement of this approach is limited to the level of refinement inherent in the EIO sectors.

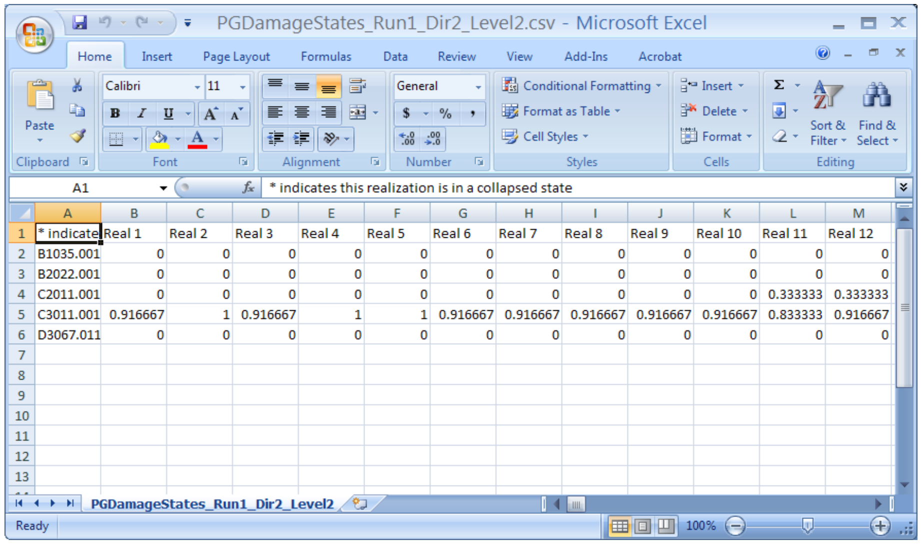
It is envisioned that a component-based EIO procedure could be developed relatively economically by a team including EIO expertise and cost expertise. Such a team could review component repair estimates to identify appropriate “average” ratios of material quantities for each component group and determine appropriate EIO sectors and factors for calculating environmental impacts in each group. The team would need access (i.e., license) an existing EIO tool or database, and use judgment to develop the dataset of factors for impacts per dollar of repair cost. These factors would then be multiplied by the material costs in each component repair estimate to determine the impacts per component damage state repair action.

2. **Quantify environmental impacts per realization.** The impacts per component damage state repair action estimated in Step 1 could then be imported to the fragility specification database and into PACT. PACT could then process environmental impacts in the same way that it calculates repair costs. Once the number of damage state occurrences is calculated for each realization, the impacts could then be tallied for the realization by multiplying and summing the impacts per damage state imported from the fragility specification.

3. **Reporting environmental impacts.** Environmental impact measures could then be reported and displayed in the same way that repair costs are currently displayed, either in probability curves or in tables through the drill down menus. Mean or median values can be tabulated to facilitate combining with non-seismic environmental impacts.

6.2.2 EIO Procedure 1A: Alternative Implementation External to PACT

PACT output includes a partial compilation of the number of occurrences of each component damage state in each realization, as shown in Figure 6-2. PACT could be modified to output a complete count. The environmental impacts for each realization could then be estimated by multiplying the number of occurrences times the impacts per damage state determined in Step 1 above. The database of impacts per damage state could be maintained outside of PACT, the number of damage state occurrences could be exported, and the environmental impacts could be calculated in post-processing outside of PACT.



A	B	C	D	E	F	G	H	I	J	K	L	M
* indicates this realization is in a collapsed state	Real 1	Real 2	Real 3	Real 4	Real 5	Real 6	Real 7	Real 8	Real 9	Real 10	Real 11	Real 12
B1035.001	0	0	0	0	0	0	0	0	0	0	0	0
B2022.001	0	0	0	0	0	0	0	0	0	0	0	0
C2011.001	0	0	0	0	0	0	0	0	0	0	0.333333	0.333333
C3011.001	0.916667	1	0.916667	1	1	0.916667	0.916667	0.916667	0.916667	0.916667	0.833333	0.916667
D3067.011	0	0	0	0	0	0	0	0	0	0	0	0

Figure 6-2 Sample PACT output, exported into Microsoft Excel, showing coded number of damage state occurrences.

6.2.3 EIO Procedure 1B: Realization-Based Approach

PACT output includes repair cost estimates for each performance group for each realization. This approach, illustrated in Figure 6-3, involves selecting a set of component groupings from the approximately 700 component types identified in the FEMA P-58 methodology and developing a dataset of representative environmental impacts per dollar of repair cost for these component groups. The procedure could yield results that are similar to EIO Procedure 1A, but would involve a different integration into the PACT computational structure, and would require a different level of programming effort. Also, it would not necessarily allow for continuous refinement toward a hybrid solution in the way that EIO Procedure 1A would. Implementation of this procedure would include the following steps:

1. **Quantify impacts per dollar factors per component group.** Select appropriate component groupings based on fragility classification numbers, material groups, structural systems, or component types. Develop environmental impact factors by expert opinion, using the component repair estimates, apportioning repair costs between labor and materials, apportioning material costs between appropriate EIO sectors, and developing environmental impacts based on EIO databases. This approach is very similar to the method of working with component repair estimates in EIO Procedure 1A, but results in a simplified dataset of selected component groups and associated factors of impacts per dollar of repair cost. The dataset is simplified because the development of environmental impacts is not required for every component in the fragility database. The environmental portion of the dataset could be

updated as needed without updating the component repair estimates or the fragility specification database.

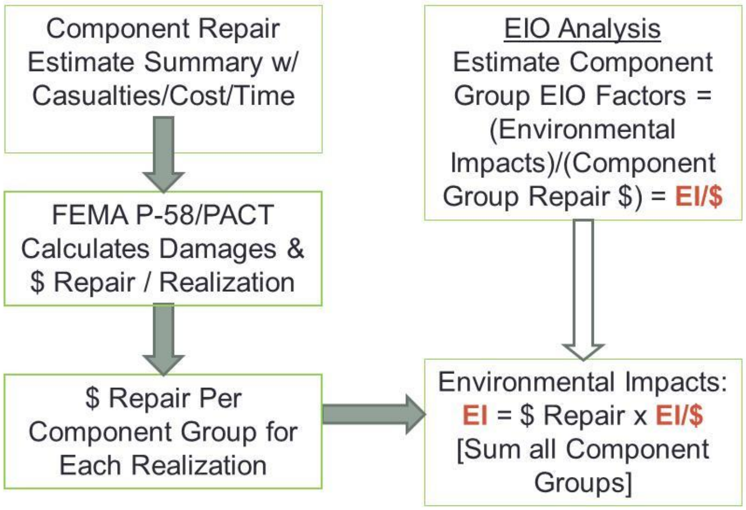


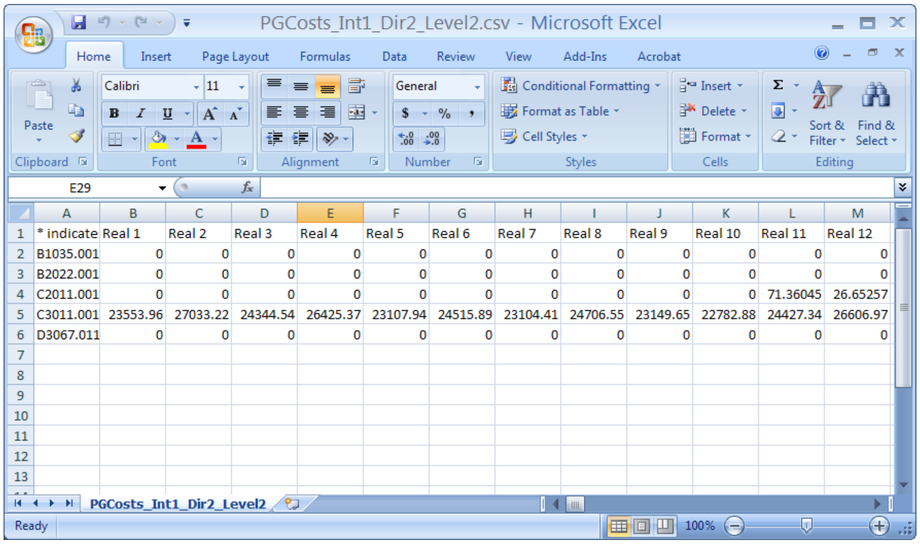
Figure 6-3 Flowchart of EIO Procedure 1B, Realization-Based Approach.

2. **Quantify environmental impacts per realization.** The dataset factors for impacts per dollar per component group developed under Step 1 would be imported into PACT. These factors would then be multiplied by the repair costs per component group to estimate impacts per realization. This calculation must account for the ratio of material costs to total costs versus labor attributed to the total repair costs. PACT would need to be revised to accumulate impacts per component group and per realization. This approach would likely require more extensive reprogramming of PACT than EIO Procedure 1A.

3. **Reporting environmental impacts.** Environmental impact measures could then be reported and displayed in the same way that repair costs are currently displayed, either in probability curves or in tables through the drill down menus. Mean or median values could be tabulated to facilitate combining with non-seismic environmental impacts.

6.2.4 EIO Procedure 1B: Alternative Implementation External to PACT

The dataset of impacts per dollar per component group could be maintained outside of PACT, the component group repair costs could be exported from PACT, and the impacts per realization could be calculated in post processing outside of PACT. This is shown in Figure 6-4.



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	* indicate	Real 1	Real 2	Real 3	Real 4	Real 5	Real 6	Real 7	Real 8	Real 9	Real 10	Real 11	Real 12
2	B1035.001	0	0	0	0	0	0	0	0	0	0	0	0
3	B2022.001	0	0	0	0	0	0	0	0	0	0	0	0
4	C2011.001	0	0	0	0	0	0	0	0	0	0	71.36045	26.65257
5	C3011.001	23553.96	27033.22	24344.54	26425.37	23107.94	24515.89	23104.41	24706.55	23149.65	22782.88	24427.34	26606.97
6	D3067.011	0	0	0	0	0	0	0	0	0	0	0	0

Figure 6-4 Sample PACT output showing dollar loss per performance group.

6.3 Bill-of-Materials Methodology (Phase 2 – Long Term)

A more detailed approach for integrating environmental assessments into the FEMA P-58 methodology involves a BOM approach to quantifying repairs and generating environmental impacts by linking to a dataset of impacts per unit of material or process. Such a dataset would need to be customized to address the specific earthquake repair actions identified in the BOM, and could be maintained separately from PACT, or within PACT, to facilitate updates and regionalization of environmental data.

The BOM would be multiplied by the environmental impact dataset to quantify environmental impacts. This process could be implemented within the PACT computational structure using component-based BOMs and internal datasets, or using realization-based BOMs linked to external datasets. The realization-based approach with external datasets has the advantages of being more readily updateable, flexible, adaptable to different assessment tools, and transparent, however, it would require more radical transformation and reprogramming of the PACT computational structure. Either approach would require considerable work effort to: (1) generate BOMs; and (2) adapt standard life cycle assessment tools to generate customized environmental impact per unit datasets tailored to earthquake damage repair scenarios.

Considering the work effort to generate BOMs and related environmental impact per unit datasets, sensitivity testing should be performed to identify which components and materials are significant contributors, and which are negligible contributors to environmental impacts. With this information, full

BOMs could be developed more efficiently by focusing on the major contributors to the environmental impacts, and either omitting inconsequential contributors or using simplified estimates for minor contributors. Preliminary sensitivity tests could be conducted using EIO procedures as outlined in Section 6.2, or through sample component testing as described in Appendix A.

Two BOM procedures, one based on a component-level approach, and one based on a realization-level approach, along with one hybrid method, are presented below.

6.3.1 BOM Procedure 2A: Component-Based Approach

In this approach, BOMs are considered at the component damage state level, and associated environmental impacts are calculated using an internal dataset that is entered into the fragility specification database and imported into PACT. A flowchart of this approach is illustrated in Figure 6-5.

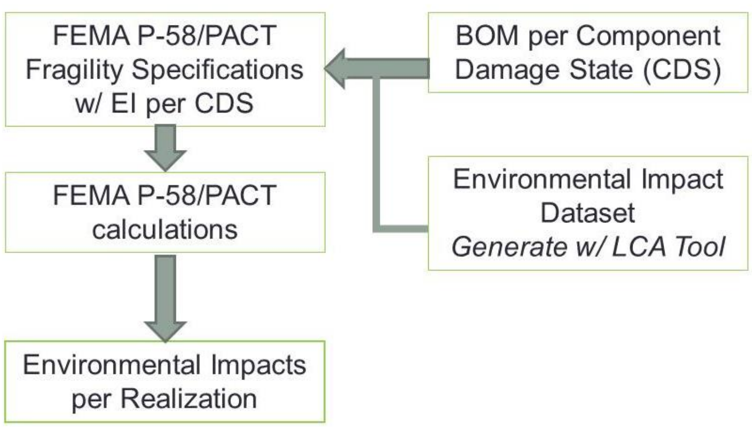


Figure 6-5 Flowchart of BOM Procedure 2A, Component-Based Approach.

PACT would then utilize total impacts per damage state from the imported data, and then calculate environmental impacts for each realization in the same way that it currently calculates repair costs. Implementation of this procedure would include the following steps:

1. **Quantify BOMs per component damage state.** Expand the component repair estimates to include a breakdown of labor versus materials and a bill-of-materials and processes for each repair action.
2. **Quantify environmental impacts per damage state.** Identify each unique line item from the BOMs in Step 1 to create a comprehensive list of unique material types or construction processes covering all repair actions. Using a life cycle assessment tool, compile a dataset of environmental impact per unit of material or process for each unique

line item. This dataset would then be multiplied by the material quantities in each estimate to determine the environmental impacts per component damage state. The environmental impacts would then be imported into the fragility specification database and from there into PACT. The key task in this step is the compilation of a dataset of environmental impacts per unit of material or process. Available data sources and tools for performing this task are described in Appendix B.

3. **Quantify environmental impacts per realization.** PACT currently accumulates the number of damage state occurrences per realization, and then assigns associated consequences (i.e., repair costs) from the imported fragility specification database (and ultimately from the component repair estimates). It then totals and records repair costs per realization and repair costs per performance group per realization. PACT can be revised to process environmental impacts in the same manner.

4. **Report environmental impacts.** Environmental impact measures could then be reported and displayed in the same way that repair costs are currently displayed. Mean or median values can be tabulated to facilitate combining with non-seismic environmental impacts.

6.3.2 BOM Procedure 2B: Realization-Based Approach

In this approach, BOMs are considered at the realization level, and associated environmental impacts are calculated by linking to an updateable regional dataset for environmental impacts per unit of material. A flowchart of this approach is illustrated in Figure 6-6. Implementation of this procedure would include the following steps:

1. **Quantify BOMs per component damage state.** Expand the component repair estimates to include a breakdown of labor versus material and a bill-of-materials and processes for each repair action.

2. **Quantify BOMs per realization.** PACT currently calculates the number of occurrences of each damage state in each realization. It then multiplies the number of occurrences by the associated consequences (i.e., repair costs) imported from the fragility specification database (and ultimately from the component repair estimates). PACT can be revised to use the number of damage state occurrences per realization to accumulate a BOM per realization by summing the BOMs for each of the occurring damage states.

3. **Quantify environmental impacts per realization.** Using a life cycle assessment tool, complete a dataset of environmental impacts per unit of

material or process. This dataset can be maintained, updated, and regionalized outside of PACT. At the realization level, PACT can link to this dataset to calculate environmental impacts per realization. Available data sources and tools for performing this task are described in Appendix B.

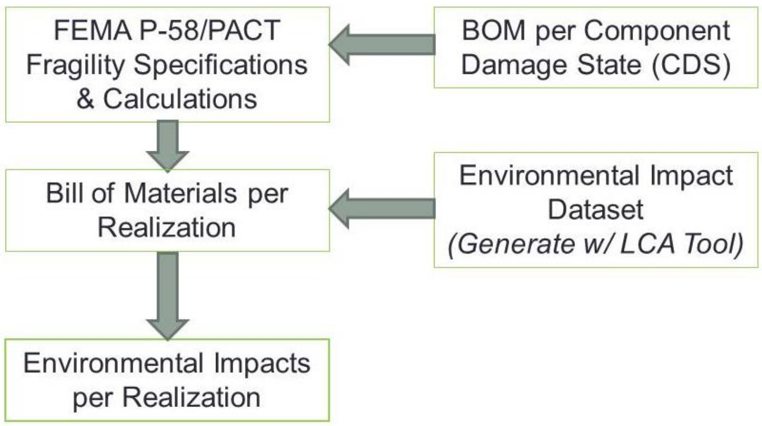


Figure 6-6 Flowchart of BOM Procedure 2B, Realization-Based Approach.

4. **Report environmental impacts.** Environmental impact measures could then be reported and displayed in the same way that repair costs are currently displayed. Mean or median values can be tabulated to facilitate combining with non-seismic environmental impacts.

6.3.3 Hybrid Procedure 2C: Component-Based Approach

This component-based hybrid approach is a combination of BOM Procedure 2A and EIO Procedure 1A. In this approach component repair estimates would be expanded using an EIO based procedure to assign EIO sector categories and calculate a set of environmental impacts for each of the approximately 2000 component damage states. The fragility specifications would be revised and PACT modified to calculate environmental impacts in the same way that repair costs are calculated. Sensitivity testing should be performed using the EIO based impact estimates to identify components that are major contributors to the environmental impacts. With information from sensitivity testing, the work effort associated with developing BOMs would be focused on critical components, and EIO based data would be used on non-critical components.

The result is a hybrid EIO and unit process based procedure for assessing environmental impacts. Depending upon available resources, the work effort can be scaled by adjusting the number of components for which BOM unit process data are generated to calculate environmental impacts.

6.4 Implementation Issues

6.4.1 EIO Implementation Issues

Judgment. EIO procedures will rely heavily on expert judgment to develop environmental impacts. EIO procedures begin with a review of component repair estimates to develop appropriate component groupings, material ratios, EIO sectors, and impact factors. Implementation will depend upon expert opinion and will need to subdivide the components into small enough subgroups to meaningfully represent the range of components and their environmental impacts.

Transparency. Because these procedures rely heavily on judgment, assumptions regarding component groupings, labor versus material breakdowns, material ratios within the groupings, economic sector mapping, and impact data per sector should be clearly documented.

Data Control and Flexibility. Users should have a degree of access to adapt environmental impact data to suit a particular building or assessment need. A balance will need to be maintained between control of the data versus giving users the flexibility to make modifications, recognizing that users may have limited expertise in this area.

Updating and Regionalizing Data. Most EIO data are currently based on national averages from 2002 economic data. Implementation will need to consider how EIO data providers update the impacts per dollar data to account for price escalations and technology changes, whether they regionalize the data, and whether it is appropriate and feasible for PACT users to have flexibility in updating and regionalizing data.

6.4.2 BOM Implementation Issues

Implementing BOM procedures will require development of detailed BOMs, which is a labor-intensive undertaking that requires familiarity with the logic used in generating component repair estimates. It will require assumptions regarding the quantification of the finish removal and replacement, and finish types and quantities. Finishes can be significant contributors to environmental impacts associated with repairs.

When internal datasets of impacts per unit of material are used, the calculated repair impacts are imported into the fragility specification database and into PACT where they will remain static until the next PACT update cycle. When external datasets of impacts per unit of material are used, the datasets can be maintained outside of PACT, making the procedure more flexible in terms of updating and regionalizing.

Data coordination. BOM inventory information will need to be coordinated with available assessment tool providers (e.g., Athena, GaBi or SimaPro), to render the BOM inventory in an appropriate form with agreed upon nomenclature and units so that the providers can readily complete the impacts per unit based on the material list provided.

Data specificity. The costs versus benefits of generating specific impact data (e.g., for different types and strengths of concrete, glass, or steel, and quantities of fly ash in concrete mix designs) will need to be considered, and then appropriate levels of specificity will need to be built into the implementation.

Chapter 7

Environmental Impact Assessment and Design Decision Making

7.1 Introduction

The procedures discussed in Chapters 5 and 6 will enable users to assess the environmental impacts associated with earthquake effects on buildings. Seismic impacts must then be integrated with the results of non-seismic life cycle assessments to be useful in the sustainable design decision-making process. This chapter discusses the integration of environmental impacts into the decision-making process for new building seismic design, seismic retrofit design, and repair-versus-demolition decisions on earthquake-damaged buildings.

Sustainable design decisions are made assuming that basic code and seismic life safety requirements have already been met. Economic considerations are often important criteria, but sustainable design considerations can take precedence as a result of stakeholder preferences or jurisdictional mandates. Sustainable design strategies and environmental cost-benefit considerations are also discussed.

7.2 Sustainable Seismic Design of New Buildings

The sustainable design process for new buildings that will be subjected to earthquakes can account for life cycle environmental impacts including seismic impacts. This process includes assessment of the initial construction, operation and maintenance, earthquake damage and repair, and end-of-life phases of the building life cycle. The procedures recommended in Chapters 5 and 6 can account for seismic-related environmental impacts. Non-seismic impacts need to be accounted for separately, outside the FEMA P-58 assessment process, and combined with probable seismic impacts. A flowchart of the sustainable seismic design process for new buildings is depicted in Figure 7-1.

Seismic impacts can be treated as additive to non-seismic life cycle assessment impacts if earthquake damage does not result in collapse or demolition, and the damage is repaired in-kind, without changing the expected service life of the building. Original material and operational life cycle impacts are unchanged by the earthquake, and additional impacts can be directly added to the original non-seismic impacts. The life cycle impacts associated with the repair of earthquake damage comprise the total environmental impact that is added to the life cycle assessment.

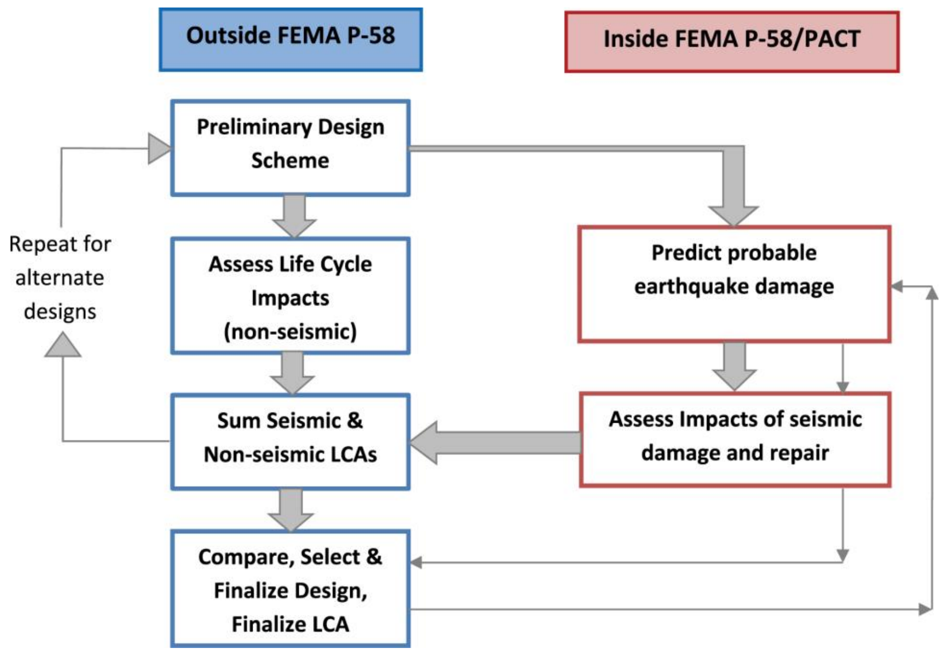


Figure 7-1 Flowchart of the sustainable seismic design process for new buildings.

If the expected service life of the building is changed by earthquake damage, or the associated repairs, then that change needs to be accounted for in the overall life cycle assessment. If the service life is shortened, then the material impacts are spread over fewer years, and the annual impact is increased (i.e., the impact is more intense). If the service life is extended by the repairs, then the material impact is spread over more years, and the annual impact is potentially decreased (i.e., the impact may be less intense). Additional guidance on how to integrate changes in expected building service life in life cycle assessments will need to be provided in the final implementation of the methodology.

Overall life cycle impacts for alternative seismic designs can be compared to determine the more environmentally effective design. Ideally, this process will lead to a balance between seismic resistance, environmental performance, and seismic risk. The nature of the seismic force-resisting system can also have an effect on non-seismic impacts. For example, concrete shear walls might contribute to the thermal mass of a building and reduce the HVAC demands and operational impacts over the building service life. Hence the entire life cycle impacts of different designs will need to be compared to optimize environmental performance.

7.3 Sustainable Seismic Retrofit Design

The sustainable design process for seismic retrofit of existing buildings can also account for life cycle environmental impacts. This process includes assessment of the existing building to compare the un-retrofitted performance to the retrofitted performance in potential future earthquakes. Assessments should include the retrofit construction, future operations and maintenance, earthquake damage and repair, and end-of-life phases of the building life cycle. Retrofits will typically be expected to extend the useful life of a building, and this extended service life should be accounted for in the life cycle assessment. A flowchart for the sustainable design process for seismic retrofit is depicted in Figure 7-2.

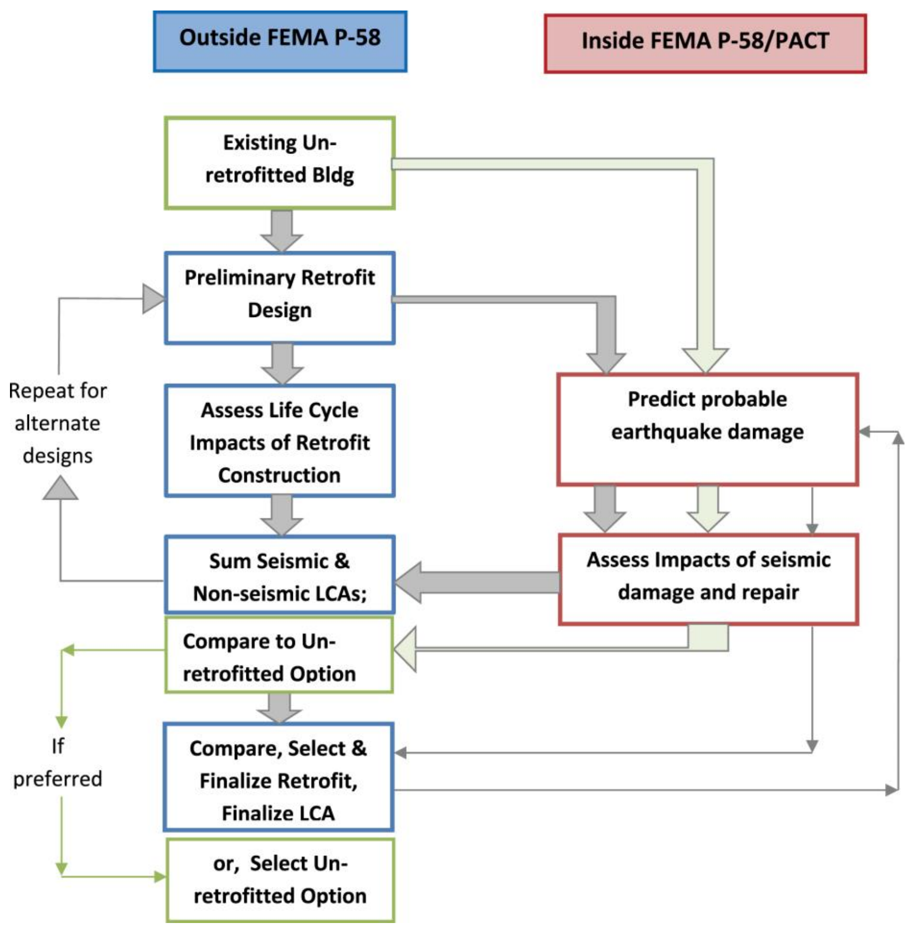


Figure 7-2 Flowchart of the sustainable design process for seismic retrofit.

The procedures recommended in Chapters 5 and 6 can account for seismic-related environmental impacts. Non-seismic impacts of retrofit designs will need to be accounted for separately, outside of the FEMA P-58 assessment process, and combined with the probable seismic impacts.

The overall life cycle impacts for alternative retrofitted versus un-retrofitted seismic designs can be compared to determine the more environmentally effective design.

7.4 Repair versus Replacement of Damaged Buildings

In a post-earthquake scenario, a damaged building can be assessed to compare options for repair versus replacement. A flowchart for the sustainable design decision making process for repair versus demolition and replacement is depicted in Figure 7-3.

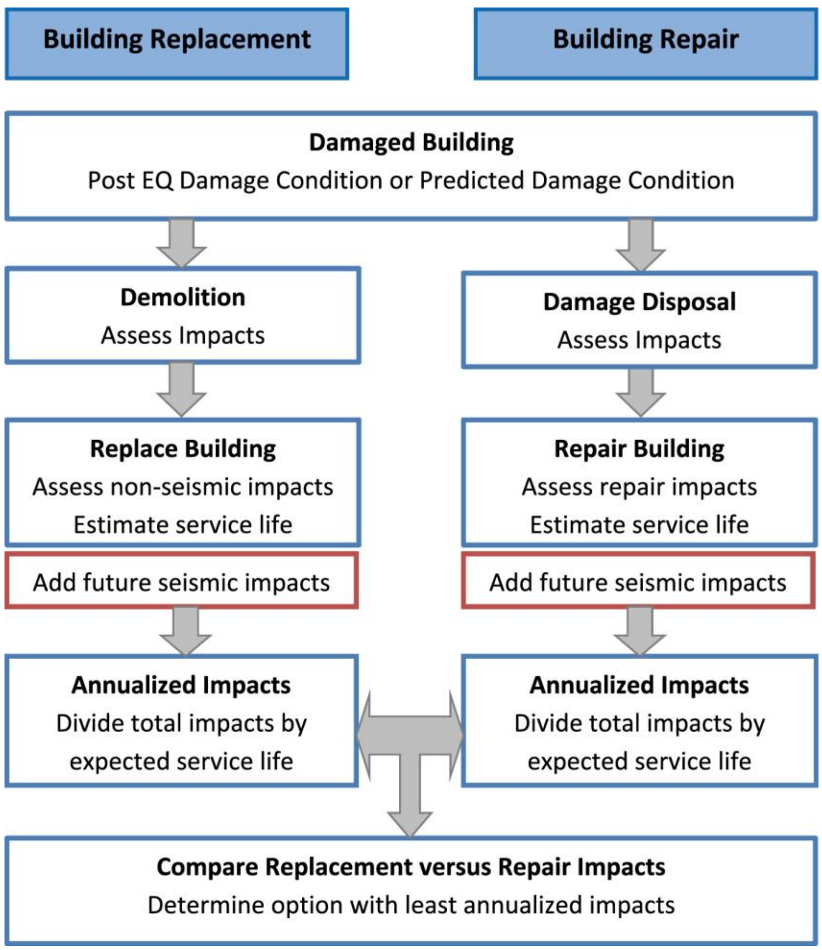


Figure 7-3 Flowchart for repair versus replacement decision making.

Assessments can be made to compare the annualized impacts of a building repair through its expected post-repair service life, versus demolition of the building and replacement with a new building of equivalent function through its expected service life. Depending on the level of repair and extent of retrofit, the repaired building would likely have a shorter expected service life than a replacement building. In each scenario, the embodied impacts of the existing building and the end-of-life impacts can be omitted from the assessment. In such cases, only the repair construction, operations and maintenance, and potential future seismic damage and repair actions need to be assessed and compared between the retrofit and replacement alternatives. If the service life of the repaired building and the replacement building differ, these can be accounted for by comparing the annualized impacts for the two options (i.e., the total impacts divided by the expected service lives). The methods to estimate expected service life should be further developed as part of the implementation of the methodology.

Comparative assessments can be used to determine the environmental reparability threshold for buildings. If it is considered environmentally beneficial to repair a building rather than replace it, then the damage level has not crossed the environmental reparability threshold. It is expected that buildings will be deemed economically unrepairable at a lower damage threshold than they will be deemed environmentally unrepairable. This relationship is due, in large part, to the fact that repair work is significantly more labor intensive and, hence, more costly than new construction.

7.5 Sustainable Design Strategies

Many factors contribute to the overall design solution for better environmental performance. Some of these factors are integral to seismic design, while others are unrelated to seismic design, but are affected by the seismic performance of the building.

Environmental design decisions can be made most effectively within the context of a full life cycle assessment. A minimal seismic design in a high seismic region may save in materials and environmental initial costs, but may be ineffective at avoiding earthquake damage and repair consequences when subjected to an earthquake. A conservatively designed building with higher initial costs may be capable of performing well in earthquakes, but may never be subjected to a design-level seismic event, and, therefore, may not realize the potential environmental benefits over the building life cycle.

An effective and efficient seismic design can protect structural and nonstructural systems, and sustainable design features and components. Buildings and systems that survive earthquakes have smaller annualized environmental impacts, and can continue in use or can be adaptively reused.

Effective strategies for improved environmental performance can also include a range of non-seismic design considerations. Integrated design, in which the structure can serve multiple purposes (e.g., serving as architectural finish, or as a heat sink to reduce the operational HVAC demands), can be an effective design strategy for better life cycle environmental performance. Elimination of nonstructural finishes reduces the initial material demands as well as the post-earthquake repair demands and can dramatically reduce environmental impacts. Design for efficient use of materials, for reduced operational energy demands, for durability and extended service life, for future adaptive re-use, and for eventual deconstruction and recycling all contribute significantly to the improved environmental performance and reduced environmental impacts. These concepts are discussed in greater detail in *Sustainability Guidelines for the Structural Engineer* (ASCE, 2010).

Seismic design should complement and safeguard other sustainable design features and strategies to be effective in improving the life cycle environmental performance. To the extent that the seismic design compromises these other features, it will be detrimental to environmental performance.

7.6 Balancing Costs and Benefits

In current practice, design decisions are usually driven by functional, safety, and economic considerations rather than by environmental considerations, but that landscape is changing. Governments and corporations are placing higher emphasis on sustainable design objectives. Green building rating systems, including LEED, *Leadership in Energy and Environmental Design* (USGBC, 2012) and Green Globes (Green Building Initiative, 2012) are increasingly recognizing life cycle assessment as an effective tool for achieving green building ratings. Furthermore, life cycle economic and environmental impact design decisions frequently point in similar directions. These factors combine to provide momentum in the building industry toward environmentally based design decisions.

A seismic performance assessment tool, such as the FEMA P-58 methodology, which can be enhanced to measure environmental impacts, will be useful in sustainable design decision making. It can be used to evaluate the extent to which improved seismic performance can reduce the environmental impacts of buildings subjected to earthquakes.

Within the sustainable seismic design context, design decisions should weigh the incremental environmental costs and benefits between alternative seismic designs in a life cycle assessment framework. If the incremental life cycle environmental benefit of designing for improved seismic performance outweighs the incremental life cycle environmental impact, then the design decision should favor the design for improved seismic performance.

Sustainable design "costs" and "benefits" can also be viewed in a broader context of design decision trade-offs between various design objectives and criteria. These concepts are illustrated in Figure 7-4, in which comparative design solutions are rated by each of eight criteria. A particular green design solution is highlighted where "costs" in some criteria are offset by "benefits" in other criteria.

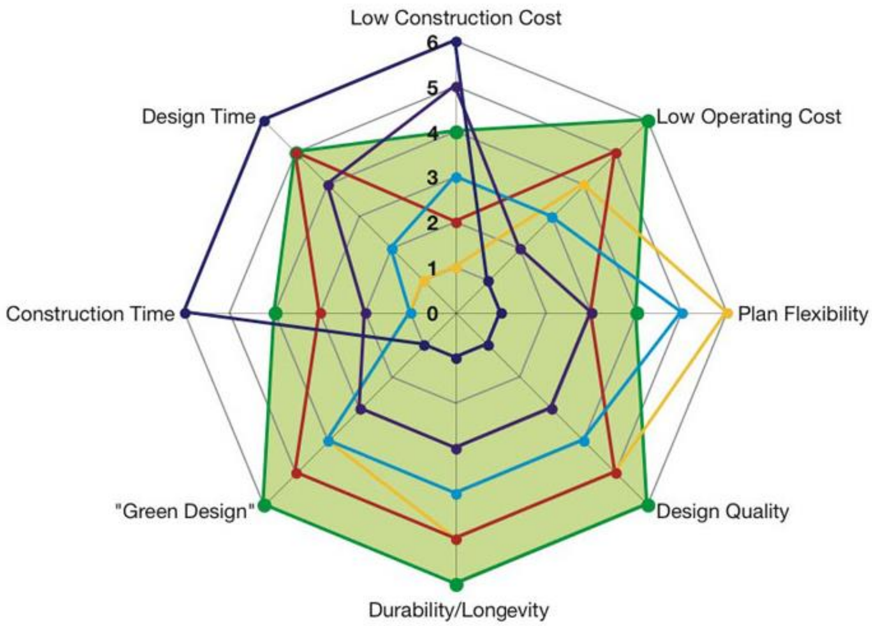


Figure 7-4 Cost versus benefit trade-offs between competing design objectives.

Chapter 8

Conclusions and Recommendations

8.1 Introduction

Sustainable design has gained a high national and international prominence as concerns over climate change potential and pressures on energy reserves, natural resources, and environmental quality have grown. Green building rating systems and green building standards have been widely embraced by Federal, State, and local governments, and have been increasingly embraced by private industry as means to reduce environmental impacts. While rating systems and standards have succeeded in raising public awareness about green building design, and have qualitatively improved sustainable design practice, they remain largely prescriptive. The need for rational and effective sustainable design tools to measure and reduce environmental impacts of buildings is manifest.

The FEMA P-58 methodology represents a major advancement in seismic performance assessment, but it does not yet include assessment of environmental impacts. Full building life cycle assessment is a comprehensive methodology for assessing environmental impacts, but it has not traditionally considered seismic impacts. The development of the FEMA P-58 methodology affords a unique opportunity to combine environmental life cycle and seismic assessment to create an effective tool to improve the sustainable seismic design.

8.2 Recommended Methodologies and Implementation Procedures

The recommended strategy for implementing environmental impact assessments within the FEMA P-58 methodology is to consider a two-phased approach. Phase 1 (near term) consists of implementing a simplified economic input-output (EIO) procedure for preliminary or interim use. Phase 2 (long term) consists of implementing a bill-of-materials (BOM) unit process based approach that is linked to a customized impact per unit dataset developed specifically for use in FEMA P-58 seismic performance assessment calculations.

8.3 Economic Input-Output Methodology (Phase 1 – Near Term)

The economic input-output (EIO) approach is a global (top-down) approach for more quickly estimating impacts based on material costs and EIO environmental impact factors. It is less detailed and less precise than a unit process based approach. It relies on broad sector based data rather than process specific data, making it suitable for preliminary assessments and generalized recommendations.

8.3.1 Advantages of an EIO Approach

Advantages of an EIO approach include the following:

- Requires comparatively less work to implement.
- Yields potentially useful results for comparing design concepts and big picture decision making.
- Enables preliminary testing and research to guide and prioritize the long term development of a more detailed bill-of-materials approach.
- Serves as an initial phase in a long term effort to develop a top-down hybrid procedure.

EIO procedures can provide approximate assessments suitable for preliminary decision making and planning purposes. They cannot provide detailed assessments for refined comparisons and detailed decision making.

EIO procedures can be used in preliminary testing and research into earthquake impact assessments. They can be used on an interim basis to help identify what users will need from environmental assessments, particularly for earthquake damage.

They can be used to identify high-impact items in seismic design and repair scenarios. Based on this information, subsequent work can focus on integrating unit process procedures for high-impact items among the component and material repairs.

8.3.2 Disadvantages of an EIO Approach

Disadvantages of an EIO approach include the following:

- Less detailed.
- Likely to be less accurate.
- Less credible.
- More dependent upon expert opinion.

EIO procedures are more general and not detailed in their analysis of specific repairs and specific impacts. They are based on national economic data, generally dating back to 2002. Impact data are based on a few broad sectors of the economy related to building materials, and are not specific to materials or products.

Due to their generality, their lack of material or product specificity, the age of their underlying economic data, and their national rather than regional basis, they are expected to be less accurate than unit process based procedures. As a result, they are potentially less credible to many users and other stakeholders.

The derivation of impact factors is heavily reliant on expert opinion to select component groupings, to identify material subcategories and costs for repair estimates, to assign appropriate EIO sectors, and to apportion material costs and EIO sector impacts for each material subcategory.

8.4 Bill-of-Materials Methodology (Phase 2 – Long Term)

The bill-of-materials (BOM) unit process based approach is a detailed (bottom-up) impact analysis procedure that begins with life cycle inventory analysis and quantification of environmental impacts for each of the materials and processes contributing to each component repair action. It likely requires the greatest level of effort to implement, but provides the greatest level of precision and accuracy in environmental impact assessments.

8.4.1 Advantages of a BOM Approach

Advantages of a BOM approach include the following:

- More transparent.
- More credible.
- More detailed and engineering based, similar to FEMA P-58 assessments of repair cost.
- Typically more accurate.

BOM procedures are more transparent in that the basis of the assessments are clear, readily documented, and well established. They are more widely used and understood. They are more transparent and more verifiable. As a result, they are potentially more credible to many users and other stakeholders.

BOM procedures are more rigorously detailed in their derivation and development, more “engineering-like,” and similar to FEMA P-58 calculations of repair costs.

Due to their detailed engineering basis, and their material, product, and regional specificity, they are potentially more accurate than EIO procedures. However, they can only be as accurate as the BOM, and those quantities are estimated based on probable building response to probable earthquakes, resulting in probable damages and probable repairs, all of which have a corresponding level of uncertainty.

8.4.2 Disadvantages of a BOM Approach

Disadvantages of a BOM approach include the following:

- More work effort to develop.
- More cost to develop.
- More hurdles for using and integrating commercial tools and resources for assessing repair impacts.

BOM procedures require a greater work effort to develop an accurate BOM, to estimate impacts per unit of material, and to integrate into the FEMA P-58 methodology. Additional work effort will result in greater developmental costs.

Procedures will depend on access to proprietary assessment tools and data sources because sufficient data are not currently available in the public domain. This will require coordination with commercial life cycle assessment tool developers, and will require licensing or other use agreements with proprietary providers.

8.5 Uncertainty and Transparency

Seismic performance assessment in general, and environmental impact assessment in particular, involve significant uncertainty. This uncertainty will need to be addressed and appropriately quantified as part of the implementation of an environmental assessment methodology. The FEMA P-58 methodology for assessing repair costs, repair time, and casualties, includes explicit consideration of uncertainty based on the expert judgment of the FEMA P-58 project team. Similar judgment will be required to consider the potential variability in environmental data, material quantities, transportation distances, and manufacturing methods, among other sources of uncertainty in assessing environmental impacts. This variability will need to be considered in tandem with the development of either the BOM unit process or EIO methods of implementation.

In addition, the environmental assessment procedures will need to maintain sufficient transparency in the assumptions used in their development, including damage quantification, life cycle inventory assessment methods, and data sources, in order to be verifiable and credible to the users.

Appendix A
Repair Estimate Studies

A preliminary analysis of selected damage state repair estimates from the FEMA P-58 component repair estimate database was conducted to test procedures for developing unit process based environmental impact assessments. The purpose of this analysis was to investigate the steps that would be required to develop a bill-of-materials and set of impact measures, and to analyze the results as a preliminary sensitivity test for identifying high-impact contributors to environmental impacts. An additional review of the data was conducted to investigate the implications for potential economic input-output assessments.

Thirteen repair types (i.e., component damage state repair estimates) were selected from the approximately 2000 repair estimates developed as part of the FEMA P-58 methodology. The Athena Sustainable Materials Institute and PE International contributed sample global warming potential and primary energy data that were used to calculate preliminary impacts for these repair types. Results are for demonstration and preliminary evaluation purposes only, since the material quantities, material types, and environmental metrics would require additional review and validation to be incorporated into a future environmental assessment tool.

Figure A-1 is a sample repair estimate for a concrete moment frame in damage state DS2. As developed in FEMA P-58, the original estimate included only the quantity and unit data shown in the first column (e.g., lump sum for floor protection; 50 lineal feet of epoxy injection), along with associated cost estimates. Original FEMA P-58 repair estimates do not include a bill-of-materials.

A bill-of-materials was generated from the repair estimate as shown in the second column. Materials and unit types were coordinated with a database of environmental impacts. For example, temporary floor protection was estimated to require 250 square feet of 3/4-inch plywood. The sample environmental impact database includes a global warming potential (GWP) value of 0.21 kg of CO_2e, and primary energy use of 3.4 MJ per square foot of 3/4-inch plywood, resulting in impacts of 52 kg and 852 MJ, respectively, for these two measures.

Only climate change potential and primary energy use were calculated in this analysis. Figure A-1 includes columns for other environmental metrics that could be considered.

For a unit process based approach, a bill-of-materials for each of the repair types would need to be developed, and a life cycle assessment tool (e.g., Athena, GaBi, or SimaPro) would need to be used to generate a dataset of impacts per unit of material. A parametric study could be used to demonstrate that some material types and quantities have a negligible contribution to environmental impacts and could therefore be omitted from the environmental assessment.

Results of this study were used to:

- determine whether certain materials could potentially be neglected when quantifying environmental impacts; and
- evaluate the relationship between cost and environmental impact of these repairs.

The study confirmed that it might be acceptable to simplify bills-of-materials by omitting certain materials and processes. For example, referring to Figure A-1, floor protection, use of power tools, and paint contributed relatively little to the selected environmental impacts. A prioritized list of materials and processes that are found to be major and minor contributors to environmental impacts could be developed. The full range of environmental impacts will need to be considered, because some materials and processes might contribute significantly to some environmental metrics, but might be relatively minor contributors to other metrics.

Figure A-2 summarizes the estimated costs and environmental impacts for the thirteen example repair types. For each repair type, the table includes the labor cost and total cost, the GWP and primary energy use, and ratios of GWP to total cost and material cost. As noted above, these results are for demonstration and preliminary evaluation purposes only.

Damage states DS1, DS2, and DS3 represent increasing levels of damage. In this limited data set, the percentage of repair costs due to labor decreases slightly with increasing levels of damage within the same repair category (e.g., concrete moment frame). In other words, more extensive repairs are more material-intensive, while less extensive repairs are more labor-intensive. In all cases (except for chiller replacement), however, labor costs accounted for well over 50% of the repair costs.

To assess the feasibility of using repair costs as the basis for an economic input-output (EIO) model to generate environmental impact measures, the ratios of GWP/ total cost and GWP/ material cost were calculated. Across all categories, the ratio of GWP/ material cost ranged from a low of 53 g/$ for ceiling damage state DS1, to a high of 1057 g/$ for concrete moment frame damage state DS1, a factor of nearly 20:1. Within a single repair category, the range was smaller, though still significant. In the case of gypsum wall repairs, for example, the ratio of GWP/material cost varied from 147 g/$ to 762 g/$, a factor of 5:1, increasing with greater damage.

These results suggest that an EIO approach should only be considered for preliminary assessment of environmental impacts, because the correlation between material costs and environmental impacts varies widely (even within individual repair categories). It is possible that the effort needed to refine an EIO based assessment for improved accuracy and reliability could be comparable to the effort required to generate bills-of-materials for use in a more accurate unit process based approach. Further study is needed to confirm these findings.

				Bill of Materials			Life Cycle Inventory Analysis Impact Categories						Resource Use Indicators	
		Quantity	Units	material	quantity	units	Global Warming Potential (CO2e)	Acidification of land and water	Eutrophication	Photochemical ozone creation	Depletion on abiotic resources (elements)	Depletion of abiotic resources (fossil)	Primary Energy Use	Use of Fresh Water
							kg						MJ	
Concrete Moment Frame -Damage State DS2														
Estimate Basis - damage extends (each direction)		4	LF											
Estimate Basis - Column/beam width avg		2	LF											
Estimate Basis - crack length		50	LF											
Demolition														
Floor finishes		324	SF	waste-flr finishes -carpet	324	lbs	111						-2273 (1)	
Partitions obstructing works (full height)		270	SF	waste-studs&drywall	1620	lbs	1069						869	
Remove, store and reinstall														
Ceilings				none										
Mechanical and electrical systems		120	SF	none										
Office furniture and equipment		1	LS	none										
Temporary														
Floor protection (access)		1	LS	plywood - 3/4"	250	sqft	52						852	
				polyethylene - 10 mil	30	lbs	27						1005	
Dust curtains		600	SF	Wood stud framing	300	bf	147						2158	
				polyethylene - 6 mil	60	lbs	55						2009	
Scaffolding or work platforms (underside access)		1	LS	none										
Shoring		1	LS	Wood Shoring	500	bf	245						3596	
Column/beam repairs														
Prepare work area		64	SF	none										
Remove loose concrete, clean rebar		1	LS	Power tools - heavy hand	40	hrs	13						0	
Epoxy injection		50	LF	epoxy	25	lbs	99						1695	
Formwork (including removal)		64	SF	plywood - 3/4"	64	sf	13						218	
Concrete	1	5	CY	average concrete	5	CY	1073						7008	
				Power tools - concrete pump	2	hrs	229						3374	
Replace														
Partitions removed - patch in		270	SF	stl studs-20ga x 4"	540	lbs	610						6757	
				gypsum drywall - 2 layers, 1/2"	1080	lbs	128						2071	
				Paint	1.8	gal	0						0	
Floor finishes	1	324	SF	flr finishes - 80% carpet, 20% til	324	sf	606						8873	
Mechanical and electrical modifications or relocations														
as required for repair work		1	LS	sheet metal - 24 ga	100	lbs	46						649	
				copper wire	20	lbs	52						575	
				plastic coating	2	lbs	2						66	
Construction energy & equipment				assume 5%			229						1975	
Labor travel = labor cost/($60x8) x 20mi				estimated labor travel	1,106	mi	375						5274	
Total Environmental Impact							**5183**						**46749**	

Footnotes:

(1) *The negative Primary Energy Use assumes that the waste carpeting is sent to a waste-to-energy facility to produce electricity.*

Figure A-1 Sample repair estimate and environmental metrics.

Summary of Calculations for Selected Repairs

Type of Repair	labor cost	total cost	percent labor cost	Global Warming Potential (kg CO2e)	Primary Energy Use (MJ)	ratio of GWP/total cost (gm/$)	ratio of GWP/ material cost (gm/$)
Concrete Moment Frame -Damage State DS1	$ 18,706	$ 21,420	87%	2870	21479	134	1057
Concrete Moment Frame -Damage State DS2	$ 26,546	$ 32,482	82%	4579	39500	141	771
Concrete Moment Frame -Damage State DS3	$ 33,146	$ 39,982	83%	5478	48138	137	801
Welded Column Splices Damage State DS1	$ 8,435	$ 9,340	90%	665	7479	71	734
Welded Column Splices Damage State DS2	$ 9,935	$ 11,340	88%	816	9745	72	581
Welded Column Splices Damage State DS3	$ 31,652	$ 38,110	83%	2683	22321	70	415
Standard Lay-In Ceiling Damage State DS1: 5% of tiles fall, no grid damage	$ 268	$ 363	74%	5	72	14	53
Standard Lay-In Ceiling Damage State DS2: 30% of tiles fall, some grid damage	$ 1,849	$ 2,838	65%	63	1122	22	63
Standard Lay-In Ceiling Damage State DS3: Total loss	$ 3,559	$ 5,638	63%	161	2588	29	77
Chiller Replacement	$ 6,100	$ 46,800	13%	11736	141281	251	288
Gypsum Wall Damage State DS1	$ 4,760	$ 5,900	81%	167	2546	28	147
Gypsum Wall Damage State DS2	$ 15,140	$ 18,800	81%	1652	25121	88	451
Gypsum Wall Damage State DS3	$ 23,540	$ 29,300	80%	4388	52854	150	762

Figure A-2 Summary of environmental impact calculations for selected repairs.

Appendix B

Data Sources and Tools for Environmental Impacts

This appendix describes available public domain and proprietary tools and data sources for assessing environmental impacts. Descriptions are provided for reference and information. Identification in this report is not intended to imply recommendation or endorsement by FEMA, nor is it intended to imply that such software or data are necessarily the best available for the purpose.

For unit process assessments, environmental impact data are available as part of assessment tools. There are no stand-alone, public domain or proprietary environmental impact databases that are readily available for use in developing a unit process approach for seismic performance assessment.

For economic input-output (EIO) assessments, the National Institute of Standards and Technology (NIST) is developing a hybrid LCA tool to establish baseline EIO impact measures for different building types. There are also several proprietary EIO databases that are commercially available.

B.1 Unit Process Assessment Tools and Data Sources: Public Domain

B.1.1 NIST – Building for Environment and Economic Sustainability (BEES)

Limited environmental data are currently available in the public domain. A source of public, U.S.-based data for building materials is the *Building for Environment and Economic Sustainability* (BEES), a tool developed by NIST (2011). BEES is a web application that was last updated in 2011. The tool incorporates environmental impact measures from TRACI, *Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts* (EPA, 2011). Impact measures in TRACI have been updated in TRACI v4, but BEES has not yet adopted these new measures. BEES includes only a portion of the materials that would be needed to generate environmental impact results in a seismic performance assessment. Missing materials include structural steel, concrete masonry, and steel deck. Although the update schedule is not known, NIST is still adding products to the BEES database.

B.1.2 U.S. Life Cycle Inventory Database

The U.S. Life Cycle Inventory (U.S. LCI) database (NREL, 2011) includes inventory data for a number of materials, but is not readily available for environmental impact assessments. The U.S. LCI database does not include environmental measures, so the inventory data would need to be converted to environmental impacts, which would require developers to apply impact characterization factors such as those found in TRACI (EPA, 2011). Two environmental measures that would require the least effort to generate from U.S. LCI data are: energy consumption and global warming potential. Given access to comprehensive LCI data, generating other environmental impacts is not complex, but would take time and effort. Developers would need to create models for transportation and end-of-life impacts to fully capture life cycle environmental impacts for each material.

B.2 Unit Process Assessment Tools and Data Sources: Proprietary

B.2.1 Athena

The *Athena Impact Estimator for Buildings* (Athena, 2012b) was originally developed by the Athena Sustainable Materials Institute during the 1990s. The Athena Institute is based in Canada, making the Impact Estimator the only building-related LCA tool with roots in North America. Over the years, Athena has added region-specific environmental data for various U.S. and Canadian regions, including the seismically active Los Angeles region. Users do not have direct access to the underlying database. Results are given at the whole building level and the assembly group level (e.g., walls), although it is possible to get impact measures for specific materials using the "Extra Basic Materials" menu. An assembly group typically includes numerous products. The *Athena Impact Estimator for Buildings* only addresses structural systems, building envelope systems, and interior partitions, so it does not include mechanical, electrical, and plumbing systems, and other finish and repair materials that would be required in a seismic performance assessment. Athena is currently testing and releasing a version that can read a bill-of-materials (BOM) and provide related impact measures.

B.2.2 EarthSmart

EarthSmart (EarthShift, 2012a) is a web-based life cycle assessment tool that is targeted at reducing the complexity associated with completing a life cycle assessment. *EarthSmart* allows users to quickly assemble products and associated life cycles, and then examine specific environmental impacts of interest. Users can easily perform comparative studies by copying the original design and modifying it with alternative materials, providing a "what if" tool for product engineers and designers. Leveraging U.S. LCI (NREL, 2011), US-EI (EarthShift, 2012b), Swiss Ecoinvent (2012), and other datasets, EarthSmart presents users with a list of materials that can be customized to reduce the learning curve for non-experts in LCA. Built-in reporting tools enable rapid creation and dissemination of LCA information.

B.2.3 GaBi

The *GaBi* software (PE International, 2012) is produced by PE International, an LCA company with an international presence based in Germany. The LCI database behind *GaBi* includes data from both European and North American sources. In addition to self-generated data, PE International has access to the U.S. LCI (NREL, 2011) and the Swiss Ecoinvent (2012) datasets, and other datasets provided by trade organizations. The *GaBi* software is not building-specific, so it can be used to evaluate a wide range of products. PE International also offers a building-specific software product called *GaBi Build-It*, currently only available in German, and using data specific to European construction. U.S. data in *GaBi* are based on national averages, but PE International has the capability to create regional datasets using region-specific electricity mixes and materials sourcing for select construction products. PE International reviews its database annually and updates it as necessary.

B.2.4 SimaPro

SimaPro, *System for Integrated Environmental Assessment of Products* (Pré Sustainability, 2011), was introduced in 1990 by Pré Sustainability, a Dutch company. LCI data are drawn from a number of sources, including the U.S. LCI (NREL, 2011) and Swiss EcoInvent (2012) datasets. SimaPro is not building specific, so it includes a wide range of materials and processes, and is intended for use by LCA professionals. In addition to unit process based LCI data, SimaPro includes U.S. and other region-specific input-output databases to enable hybrid life cycle assessments. EarthShift is the North American distributor for SimaPro. They provide sales, marketing, and technical support for SimaPro users in the United States and Canada. EarthShift also developed (and maintains) the US-EI database (EarthShift, 2012b), which bridges the current gap in the U.S. LCI dataset and applies U.S. electrical conditions to the Swiss Ecoinvent dataset.

B.3 Economic Input-Output Data Sources: Public Domain

B.3.1 NIST – Building Industry Reporting and Design for Sustainability (BIRDS)

NIST is presently focusing its efforts on a whole building sustainability measurement tool called *Building Industry Reporting and Design for Sustainability* (BIRDS), which uses a hybrid LCA approach (NIST, 2013). BIRDS can be used to determine TRACI environmental impact measures (EPA, 2011) as well as energy, land, and water use measures. BIRDS uses an integrated design approach to assess whole building life cycle environmental impacts and costs, covering building materials, construction, and operating energy use for twelve building prototypes keyed to 228 U.S. cities and five levels of operating energy efficiency.

BIRDS is being developed in collaboration with the lead researcher for the development of CEDA (Climate Earth, 2010) described below, and is scheduled for release in 2013. At this time, it is not clear if BIRDS will address the full range of building materials necessary for seismic performance assessment. From the NIST website (http://www.nist.gov /el/economics/metrics_for_sustainable_bldg.cfm):

> *"Baseline databases enabling sustainability performance assessment for a range of new and existing commercial and residential buildings, energy technologies and systems will be compiled. These databases will include energy, environment, and economic performance measurements. EL will also work with academic experts to begin developing more detailed "top-down" I/O data for the building industry, permitting development of environmental I/O data customized to the same new and existing commercial and residential buildings for which energy and cost data are being compiled."*

B.4 Economic Input-Output Data Sources: Proprietary

B.4.1 Carnegie Mellon Green Design Institute: EIO-LCA

Economic Input-Output Life Cycle Assessment (EIO-LCA) is provided by the Green Design Institute (Carnegie Mellon Green Design Institute, 2008), which is an interdisciplinary research effort at Carnegie Mellon University that includes divisions focused on life cycle assessment and carbon footprinting. EIO-LCA is available free for academic use, and can be used for commercial applications (including sponsored research), or integrated into a derivative work (e.g., PACT), for an annual licensing fee. With a paid license, users obtain access to comprehensive LCI data that can be used to assess environmental impact measures as defined in TRACI (EPA, 2011). From the EIO-LCA website (http://www.eiolca.net/):

> *"Results from using the EIO-LCA on-line tool provide guidance on the relative impacts of different types of products, materials, services, or industries with respect to resource use and emissions throughout the supply chain."*

EIO-LCA utilizes several different economic models, the most relevant of which is based on U.S. data from 2002. Data have been developed over multiple years, and have been used in multiple research projects, but have not typically been peer reviewed.

B.4.2 Climate Earth: CEDA

The *Comprehensive Environmental Data Archive* (CEDA) is available from the authorized United States distributor, Climate Earth (2010) for a licensing fee. CEDA is a suite of economic input-output databases intended to assist in life cycle assessments. From the CEDA information website (http://cedainformation.net/index.html):

> *"CEDA covers a comprehensive list of environmental interventions including natural resource types (fossil fuels, water, metals ores and minerals), and various emissions to air, water and soil. CEDA quantifies the amount of natural resources use and environmental emissions of products throughout their life-cycles by connecting input-output tables, which represent the entire supply-chain network of an economy, with a comprehensive list of environmental interventions."*

The current version of CEDA is based on data from 2002, covering the United States, United Kingdom, and China.

B.4.3 The Sustainability Consortium: Open IO

The *Open IO Computational Tool and Database* is available from The Sustainability Consortium (2011), which is an organization sponsored by large-scale U.S. industry leaders and jointly administered by Arizona State University and the University of Arkansas. With a commitment to open source and transparency, *Open IO* is made available to end users at no cost. From the website (http://www.sustainabilityconsortium.org/open-io/):

> *"Open IO is a comprehensive research project of The Sustainability Consortium that provides users with a fully accessible, transparent, economic input-output life cycle assessment database. Economic input-output models detail the interactions between industries and describe*

how each industry buys from and sells to other industries. By associating economic inputs and outputs with environmental impacts, Open IO provides environmental impacts that result from economic activities."

Data are based on 2002 U.S. government information. More analysis of the format of the data would be required to fully understand the opportunities and challenges associated with using *Open IO* data for development of seismic a performance assessment methodology for environmental impacts.

Glossary

Definitions

Acidification potential. A measure in terms of sulfur dioxide equivalent chemical pollutants released into the environment with the potential to cause acid rain and acidification of the land and water.

Bill-of-materials. An itemization of the materials and processes used or expended in the fabrication of a product or construction of a building.

Bill-of-materials procedure. See "unit process procedure."

Carbon footprint. A measure of the CO_2 equivalent emissions generated over the life cycle of a building or product.

Characterization factor. The factor derived from a characterization model, such as the Tool for Reduction and Assessment of Chemical and other environmental Impacts (TRACI), which is applied to convert a life cycle inventory analysis result to common unit of a category indicator.

Climate change potential (Global warming potential). A measure of the greenhouse gas emissions, converted to units of kilograms of CO_2 equivalents, including contributions from carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perflourocarbons, and sulfur hexafluoride, among others.

Construction stage. The construction phase of a building life cycle, including transportation of materials to the building site, construction processes and equipment usage, power usage, fuel usage, construction waste disposal, runoff, and dust particle generation.

Cradle-to-cradle. A product or building lifespan, extending from the material extraction and production stages, through the construction stage, the building operation stage, the building demolition and disposal stage, and the recycle or return to the environment stages, for use in future generations.

Cradle-to-gate. A product lifespan, extending from material extraction, through the manufacturing process, to the exit gate of the manufacturing facility (or farm, or mill). This lifespan does not include transportation or other activities beyond the manufacturing facility.

Cradle-to-grave. A product or building lifespan from the material extraction and production stages, through the construction stage, the building operation stage, and end-of-life building demolition and disposal stage.

Cradle-to-site. A product lifespan from material harvest, through the manufacturing process, through the exit gate of the manufacturing facility (or farm, or mill), including transportation to the site where the use will occur.

Data. Facts and statistics collected for reference or analysis.

Database. A structured set of data, especially one that is accessible using a computer.

Dataset. A collection of related sets of information, such as life cycle inventory data, that is composed of separate elements but can be manipulated as a unit in a computer. Also a set of impact data customized for use in the FEMA P-58 methodology.

Data source. Life cycle inventory databases, life cycle impact assessment tools, economic input-output databases, and economic input-output assessment tools from which environmental data can be drawn.

Economic input-output procedure (method). A life cycle assessment method that estimates materials and energy resources use, and the associated environmental impacts, based on economic activity between national economic sectors (current total of 430 sectors tracked in the United States). The method estimates the environmental impact per dollar of production or service for each sector.

End-of-life stage. Building life cycle stage that includes de-construction or demolition, transport of waste or salvaged materials, and processing and disposal (including stockpiling for re-use) of these materials. Also includes demolition equipment usage and power usage, dust and runoff abatement, and other related activities.

Environmental data. Facts and statistics related to life cycle inventories, life cycle impacts or economic input-output based inventory or impact quantities.

Environmental footprint. The total environmental impact of a building, product, or process, as measured by each environmental factor that is positively or negatively affected.

Environmental impact. An environmental consequence of a building or product, including consequences related to manufacture, construction, operation, demolition, seismic retrofit, or earthquake damage repair.

Eutrophication potential. The potential to release excess nutrients (e.g., nitrogen, phosphorous, and carbon) into bodies of water causing excessive algae growth, which results in a reduction in dissolved oxygen and inability to support aquatic plant or animal life.

Hybrid procedure. A life cycle assessment method that combines aspects of unit process and economic input-output based methods, capturing the strengths of each, in assessing environmental impacts.

Impact category. A class representing environmental issues of concern, to which life cycle inventory analysis results may be assigned, including climate change potential, acidification potential, eutrophication potential, photochemical ozone creation potential, ozone depletion potential, and primary energy use, among others.

Leadership in Energy and Environmental Design (LEED). A green building rating system, administered by the United States Green Building Council, Washington, D.C., which is widely recognized and used in the United States and internationally.

Life cycle. The cradle-to-grave lifespan of a product or building, from the material acquisition and production (or construction) stages, through the operational and end-of-life stages.

Life cycle assessment (LCA). A standardized methodology for assessing potential environmental impacts of a product or building throughout its life cycle, performed by compiling an inventory of material, energy and emission flows to and from nature, evaluating the impacts associated with these inputs and outputs, and interpreting their significance.

Life cycle impact assessment (LCIA). A phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product or building.

Life cycle inventory (LCI) analysis. A phase of life cycle assessment involving the compilation and quantification of inputs and outputs to and from the environment for a product or building.

Material extraction and production stages. Product or building life cycle stages that include raw material extraction or harvesting and component manufacturing.

Non-renewable resource use. Depletion of rare or limited resources that, once expended, will no longer be available for use by future generations, or will be extractable only at a higher cost or environmental impact.

Ozone depletion. A measure in terms of nitrous oxide (N_2O) equivalent emissions released into the atmosphere with the potential to reduce stratospheric ozone.

Performance Assessment Calculation Tool (PACT). One of the FEMA P-58 series of products, PACT is an electronic application that utilizes data on component fragilities and damage repair estimates to estimate damage, accumulate consequences, and report losses in terms of potential causalities, direct economic losses (building repair or replacement costs), and loss of use (due to repair time or unsafe placarding).

Photochemical smog potential (photochemical ozone creation potential). An air pollutant measured in terms of nitrogen oxide (NO) equivalent emissions, caused when many chemicals react with atmospheric sunlight to cause visible haze, air pollution, and detrimental human health effects.

Pollutants. Carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen oxides (NOx), mercury (Hg), small particulates ($PM_{2.5}$), and large particulates (PM_{10}), and other potentially detrimental substances emitted into the air, in water, or on land.

Primary energy. Fossil fuels, nuclear, and renewable sourced energies consumed in the material production, construction, operation, and end-of-life stages of a building life cycle.

Recycling. Collection, reprocessing, marketing, and use of materials that are diverted or recovered from the solid waste stream.

Resource depletion. A measure of renewable or non-renewable resource use, particularly at a non-sustainable rate.

Sustainability. A measure of the environmental footprint of a building and its impact on the ability of society and natural systems to endure and flourish. The Brundtland Commission (United Nations, 1987) defined sustainable development as “development to meet the needs of the present without compromising the ability of future generations to meet their own needs.”

Unit process procedure (method). A life cycle assessment method using systematic and methodical procedures to research and quantify the complete inventory of all the energy and material flows. It includes the input flows from nature and the output flows back to nature throughout the stages of a product or building life, and then calculates the environmental impacts of those inventory flows.

Use stage (operational stage). A life cycle stage that results in environmental impacts related to energy usage, building component maintenance, resource inflow, and waste outflow as part of the use and operation of a product or building.

Waste. Debris, refuse or discarded materials generated in material extraction, production, construction, operation, or end-of-life stages of a product or building life cycle.

References and Bibliography

ANSI/ASHRAE/USGBC/IES (ASHRAE), 2011, *Standard for the Design of High-Performance Green Buildings Except Low-Rise Residential Buildings*, ASHRAE 189.1, American Society of Heating, Refrigeration and Air-Conditioning Engineers, Atlanta, Georgia, last accessed on November 12, 2012, http://www.ashrae.org/resources publications /bookstore/standard-189-1.

Architecture 2030, 2011a, *The 2030 Challenge for Products*, Architecture 2030, Santa Fee, New Mexico, last accessed on November 12, 2012, http://www.architecture2030.org/2030_challenge/products.

Architecture 2030, 2011b, *Problem: The Building Sector,* Architecture 2030, last accessed on December 2, 2012, http://www.architecture2030.org /the_problem/buildings_problem_why.

ASCE, 2010, *Sustainability Guidelines for the Structural Engineer*, American Society of Civil Engineers, Reston, Virginia.

Athena, 2012a, *Athena Eco Calculator for Commercial Assemblies*, Athena Sustainable Materials Institute, Ottawa, Ontario, last accessed on November 12, 2012, http://www.athenasmi.org/our-software -data/ecocalculator.

Athena, 2012b, *Athena Impact Estimator for Buildings,* Athena Sustainable Materials Institute, Ottawa, Ontario, last accessed on November 12, 2012, http://www.athenasmi.org/our-software-data/impact-estimator.

BEA, 2002, *Benchmark Input-Output Accounts*, Bureau of Economic Analysis, U.S. Department of Commerce, Washington, D.C., last accessed on December 2, 2012, http://www.bea.gov/industry /iedguide.htm.

Carnegie Mellon Green Design Institute, 2008, *Economic Input-Output Life Cycle Assessment* (EIO-LCA), *US 1997 Industry Benchmark model*, Carnegie Mellon University Green Design Institute, Pittsburg, Pennsylvania, last accessed on November 12, 2012, http://www.eiolca.net.

CBSC, 2012, *Supplement to the 2010 Title 24, Part 11, California Green Building Standards Code*, California Building Standards Commission, Sacramento, California, last accessed on September 1, 2012, http://www.iccsafe.org/cs/codes/Errata/State/CA/5570S1002.pdf.

CEN, 2005, *Sustainability of Construction Works – Assessment of Buildings – Part 2: Framework for the Assessment of Environmental Performance*, FprEN 15643-2:2001, European Committee for Standardization, Brussels, Belgium.

CEN, 2012, *Sustainability of Construction Works – Environmental Product Declarations – Core Rules for the Product Category of Construction Products*, BS EN 15804:2012, European Committee for Standardization, Brussels, Belgium.

Chiu, C.K., Chen. M.R., and Chiu, C.H., 2012, "Financial and Environmental Payback Periods of Seismic Retrofit Investments for Reinforced Concrete Buildings Estimated using a Novel Method," *Journal of Architectural Engineering*, American Society of Civil Engineers, Reston, Virginia, last accessed on November 12, 2012, http://ascelibrary.org /doi/abs/10.1061/(ASCE)AE.1943-5568.0000105.

Climate Earth, 2010, *CEDA V4: Comprehensive Environmental Data Archive*, Climate Earth, Inc., Berkeley, California, last accessed on November 12, 2012, http://www.climateearth.com/subscriptions _to_data.shtml.

Comber, M., Poland, C., and Sinclair, M., 2012, "Environmental Impact Seismic Assessment: Application of Performance-Based Earthquake Engineering Methodologies to Optimize Environmental Performance," *Proceedings*, ASCE Structures Congress, Chicago, Illinois.

Court, A., Simonen, K., Webster, M., Trusty, W., and Morris, P., 2012, "Linking Next-Generation Performance-Based Seismic Design Criteria to Environmental Performance (ATC-86 and ATC-58)," *Proceedings*, ASCE Structures Congress, Chicago, Illinois.

EarthShift, 2012a, *EarthSmart LCA Tool,* EarthShift, Huntington, Vermont, last accessed on December 2, 2012, http://www.earthshift.com /earthsmart.

EarthShift, 2012b, *US-EI Database*, EarthShift, Huntington, Vermont, last accessed on December 2, 2012, http://www.earthshift.com/software /simapro/USEI-database.

Ecoinvent, 2012, *Ecoinvent Database V2.0*, Swiss Center for Life Cycle Inventories, Switzerland, last accessed on November 12, 2012, http://www.ecoinvent.org/database.

EIA, 2011, "Emissions of Greenhouse Gasses Report," *Environment*, U.S. Energy Information Administration, Washington, D.C., released February 2011, last accessed on November 12, 2012, http://www.eia.gov/oiaf/1605/ggrpt/carbon.html.

EIA, 2012a, "Annual Energy Review," *Total Energy*, U.S. Energy Information Administration, Washington, D.C., released September 27, 2012, last accessed on November 12, 2012, http://www.eia.gov /totalenergy/data/annual/showtext.cfm?t=ptb0201a.

EIA, 2012b, "How much energy is used in buildings in the United States?" *Frequently Asked Questions*, U.S. Energy Information Administration, Washington, D.C., last accessed on November 12, 2012, http://www.eia.gov/tools/faqs/faq.cfmid=86&t=1.

Environmental Protection Agency of South Australia, 2004, *Photo Chemical Smog – What it Means for Us*, Environmental Protection Agency of South Australia, Adelaide, South Australia, last accessed on December 2, 2012, http://www.epa.sa.gov.au/ xstd_files/Air/Information_sheet /info_photosmog.pdf.

EPA, 2006, *Life Cycle Assessment: Principles and Practice*, EPA/600/R-06/060, U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Cincinnati, Ohio, last accessed on November 12, 2012, http://www.epa.gov/nrmrl/std/lca/lca.html.

EPA, 2009, *Acid Rain Program 2009 Progress Reports*, U.S. Environmental Protection Agency, Washington, D.C., last accessed on December 2, 2012, http://www.epa.gov/airmarkets/progress/ARP09_1.html.

EPA, 2011, *Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI)*, TRACI 2.0 2001 11 8.xls, U.S. Environmental Protection Agency, Office of Research and Development, National Risk Management Research Laboratory, Sustainable Technology Division, Cincinnati, Ohio.

FEMA, 2012a, *Seismic Performance Assessment of Buildings, Volume 1 – Methodology*, FEMA P-58-1, prepared by the Applied Technology Council for the Federal Emergency Management Agency, Washington, D.C.

FEMA, 2012b, *Seismic Performance Assessment of Buildings, Volume 2 – Implementation Guide*, FEMA P-58-2, prepared by the Applied Technology Council for the Federal Emergency Management Agency, Washington, D.C.

FEMA, 2012c, *Seismic Performance Assessment of Buildings, Volume 3 – Supporting Electronic Materials and Background Documentation,* FEMA P-58-3, prepared by the Applied Technology Council for the Federal Emergency Management Agency, Washington, D.C.

Green Building Initiative, 2012, *Green Building Programs – Green Globes Overview*, Green Building Initiative, Portland, Oregon, last accessed on December 2, 2012, http://www.thegbi.org/green-globes.

Hamburger, R., 2011, "FEMA P-58 Next-Generation Performance Assessment of Buildings," *Proceedings,* ASCE Architectural Engineering Conference, Oakland, California.

Hammond, G., and Jones, C., 2008, *Bath Inventory of Carbon and Energy, Version 1.6a,* University of Bath, United Kingdom, last accessed on November 12, 2012, http://perigordvacance.typepad.com/files /inventoryofcarbonandenergy.pdf.

Hendrickson, C., Lave, B., and Matthews, H., 2006, *Environmental Life Cycle Assessment of Goods and Services: An Input-Output Approach*, Resources for the Future Press, Washington, D.C.

ICC, 2012, *International Green Construction Code,* International Code Council, Washington, D.C.

ISO, 2006a, *Life Cycle Assessment-Principles and Framework,* ISO 14040:2006, International Organization for Standardization, Geneva, Switzerland.

ISO, 2006b, *Environmental Management – Life Cycle Assessment – Requirements and Guidelines,* ISO 14044:2006, International Organization for Standardization, Geneva, Switzerland.

ISO, 2007, *Sustainability in Building Construction – Environmental Declaration of Building Products,* ISO 21930-2007(E), International Organization for Standardization, Geneva, Switzerland.

JRC IES, 2010, *ILCD Handbook: International Reference Life Cycle Data System, EUR24708 EN-2010*, Joint Research Center Institute for Environment and Sustainability, Ispra, Italy, last accessed on September 1, 2012, http://lct.jrc.ec.europa.eu/pdf-directory/ILCD-Handbook-General-guide-for-LCA-DETAIL-online-12March2010.pdf.

Konig, H., Kholer, N., Kreissig, J., and Lutzkendorf, T., 2010, *A Life Cycle Approach to Buildings: Principles, Calculations, Design Tools*, Institut für Internationale Architektur-Dokumentation, Munich, Germany.

Leontief, W., 1986, *Input-Output Economics*, Oxford University Press, New York, New York.

Liu, M., Wen, Y.K., and Burns, S.A., 2004, "Life cycle cost oriented seismic design optimization of steel moment frame structures with risk-taking preference," *Engineering Structures*, Elsevier Publishing, Netherlands, Vol. 26, No. 10, p. 1407.

Menna, C., Asprone, D., Jalayer, F., Protoa, A., and Manfredi, G., 2012, "Assessment of ecological sustainability of a building subjected to potential seismic events during its lifetime," *International Journal of Life Cycle Assessment*, Springer Publishing, Netherlands, last accessed on November 12, 2012, http://www.springerlink.com.offcampus .lib.washington.edu /content/922840lg80700887.

NIST, 2008, *Product Life Cycle.jpg*, Manufacturing Engineering Laboratory, National Institute of Standards and Technology, last accessed on December 2, 2012, http://en.m.wikipedia.org/wiki/File:Product %E2%80%99s_lifecycle.jpg.

NIST, 2011, *Building for Environmental and Economic Sustainability* (BEES), National Institute of Standards and Technology, Gaithersburg, Maryland, last accessed on November 12, 2012, http://www.nist.gov /el/economics/BEESSoftware.cfm.

NIST, 2013 (expected), *Building Industry Reporting and Design for Sustainability* (BIRDS), National Institute of Standards and Technology, Gaithersburg, Maryland, last accessed on December 2, 2012, http://www.nist.gov/el/economics/metrics_for_sustainable_bldg.cfm.

NOAA, 2009, *NOAA Study Shows Nitrous Oxide Now Top Ozone-Depleting Emission*, National Ocean and Atmospheric Administration, U.S. Department of Commerce, Washington, D.C., last accessed on December 2, 2012, http://www.noaanews.noaa.gov/stories2009/20090827 _ozone.html.

NREL, 2011, *U.S. Life Cycle Inventory Database*, National Renewable Energy Lab, Washington, D.C., last accessed on November 12, 2012, https://www.lcacommons.gov/nrel/search.

PE International, 2012, *GaBi 5 Software*, PE International, Leinfelden-Echterdingen, Germany, last accessed on November 12, 2012, http://www.gabi-software.com.

Pré Sustainability, 2011, *SimaPro 7.3 Software*, Pré Sustainability, Netherlands, last accessed on November 12, 2012, http://www.pre-sustainability.com/simapro-lca-software.

Sarkisian, M., Hu, L., Shook, D., 2012a, "Mapping a Structure's Impact on the Environment," *Proceedings*, ASCE Structures Congress, Chicago, Illinois.

Sarkisian, M., Long, E., Shook, D., Doo, C.S., 2012b, "Optimization Tools for the Design of Structures," *Proceedings*, ASCE Structures Congress, Chicago, Illinois.

Simonen, K., and Haselbach, L., 2012, *Life Cycle Assessment and Buildings Research for Washington State*, Life Cycle Assessment for Washington State, last accessed on September 10, 2012, http://courses.washington.edu/lcaforwa/wordpress.

Suh, S., ed., 2009, *Handbook of Input-Output Economics in Industrial Ecology*, Springer Publishing, Netherlands.

Suh, S., Lippiatt, B.C., 2012, "Framework for hybrid life cycle inventory databases: a case study on the Building for Environmental and Economic Sustainability (BEES) database," *International Journal of Life Cycle Assessment*, Springer Publishing, Netherlands, Vol. 17, No. 5, pp. 604-612.

The Sustainability Consortium, 2011, *Open IO Computational Tool and Database*, Arizona State University and the University of Arkansas, last accessed on November 12, 2012, http://www.sustainabilityconsortium.org/open-io/.

United Nations, 1987, "Report of the World Commission on Environment and Development: Our Common Future," *Development and International Co-operation: Environment*, Document A/42/427, United Nations, New York, New York.

USGBC, 2009, *LEED 2009 for Retail: New Construction and Major Renovations Rating System*, United States Green Building Council, Washington D.C.

USGBC, 2012, *Leadership in Energy and Environmental Design (LEED) Draft Version 4*, United States Green Building Council, Washington D.C.

Yang, F., 2011, "Integrating Life Cycle and Carbon Assessments: What Life Cycle Assessment can Teach Structural Engineers about Design and Specification," *Proceedings*, ASCE Structures Congress, Las Vegas, Nevada.

Project Participants

ATC Management and Oversight

Christopher Rojahn (Project Executive)
Applied Technology Council
201 Redwood Shores Parkway, Suite 240
Redwood City, California 94065

Jon A. Heintz (Project Manager)
Applied Technology Council
201 Redwood Shores Parkway, Suite 240
Redwood City, California 94065

William T. Holmes (Project Technical Monitor)
Rutherford & Chekene
55 Second Street, Suite 600
San Francisco, California 94105

FEMA Representatives

Erin Walsh (Task Monitor)
Federal Emergency Management Agency
500 C Street, SW, Room 416
Washington, D.C. 20472

Michael Mahoney (Project Officer)
Federal Emergency Management Agency
500 C Street, SW, Room 416
Washington, D.C. 20472

Robert D. Hanson (Technical Monitor)
Federal Emergency Management Agency
2926 Saklan Indian Drive
Walnut Creek, California 94595

Project Management Committee

Anthony B. Court (Project Technical Director)
A.B. Court & Associates
4340 Hawk Street
San Diego, California 92103

Peter Morris
Davis Langdon
1331 Garden Highway, Suite 310
Sacramento, California 95833

Kathrina Simonen
University of Washington
3925 2nd Ave NE
Seattle, Washington 98105

Wayne B. Trusty
Wayne B. Trusty & Associates Limited
P.O. Box 189
Merrickville, Ontario, Canada

Mark Webster
Simpson Gumpertz & Heger
41 Seyon Street, Building 1, Suite 500
Waltham, Massachusetts 02453

Jon A. Heintz (ex officio)

ATC-58 Project Representatives

Ronald O. Hamburger
(ATC-58 Project Technical Director)
Simpson Gumpertz & Heger
The Landmark @ One Market, Suite 600
San Francisco, California 94105

John D. Hooper
(ATC-58 Risk Mgmt. Products Team Leader)
Magnusson Klemencic Associates
1301 Fifth Avenue, Suite 3200
Seattle, Washington 98101