ADVANCING WHOLE BUILDING LIFE CYCLE ASSESSMENT

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Growing awareness about building related resource consumption and vulnerability to natural hazards has resulted in the interest of designing more sustainable and resilient buildings. The building industry has seen an increased uptake of sustainable design practices, development of rating systems addressing building performance, and the use of life cycle assessment (LCA) and performance-based assessment tools; however, there is still a disconnect between these efforts which results in limited understanding of the tradeoffs between various design decisions. The primary goal of this research is to improve understanding of building sustainability and resilience from a life cycle perspective by combining the knowledge from rating systems and performance-based tools within an expanded whole building LCA. The first step of this research is studying water related performance normally addressed by green building rating systems using life cycle assessment (LCA), specifically comparing environmental impacts of using centralized and decentralized water systems. The second step is understanding how natural hazards can impact the environmental performance of buildings over their lifetime by combining environmental LCA with performance-based earthquake engineering. The final step consists of synthesizing work done in the first two steps with the rest of the typical building LCA knowledge on operational and embodied impacts of buildings. The synthesis is used for a sensitivity analysis on design decisions typically considered during the conceptual phase, which can improve the understanding of the relative importance of the various building performance aspects.

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NOMENCLATURE

AEC	Architecture, Engineering and Construction
ASCE	American Society of Civil Engineers
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CBECS	Commercial Buildings Energy Consumption Survey
CEE	Civil and Environmental Engineering
EERI	Earthquake Engineering Research Institute
eGRID	Emissions & Generation Resource Integrated Database
EUI	Energy use intensity
HVAC	Heating, Ventilation, and Air Conditioning
IEA	International Energy Agency
kWh	Thousand-watt hour
LEED	Leadership in Energy and Environmental Design
LCA	Life Cycle Assessment
LCC	Life cycle costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
NCDC	National Climatic Data Center
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
NSF	National Science Foundation
PNNL	Pacific Northwest National Laboratory

SOM EA Tool	Skidmore, Owings, and Merril Environmental Analysis Tool
TRACI	The Tool for the Reduction and Assessment of Chemical and other environmental Impacts
US DOE	United States Department of Energy
US EIA	United States Energy Information Administration
US EPA	United States Environmental Protection Agency
VAV	Variable Air Volume
W	Watt
Wh	Watt hour
AP	Acidification potential
EP	Eutrophication potential
GWP	Global warming potential
ODP	Ozone depletion potential
SFP	Smog formation potential
FFD	Fossil fuel depletion
RED	Renewable energy demand
NED	Non-renewable energy demand
PED	Primary energy demand

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1.0 INTRODUCTION

1.1 QUANTIFYING SUSTAINABILITY AND RESILIENCE OF BUILDINGS

Environmental issues related to the built environment have triggered discussions about sustainability and resilience of infrastructure over the past couple of decades. Buildings in particular are a major consumer of energy and material resources (Ruuska & Häkkinen, 2014). Operation of buildings in the U.S. is responsible for consuming 39% of energy, 72% of electricity, 38% of carbon (U.S. Energy Information Administration, 2015) and 12% of water (Maupin et al., 2014). Buildings and infrastructure can also be vulnerable to natural hazards such as earthquakes, hurricanes, flooding, and storms, especially with the built environment aging and often not being designed to accommodate the additional stresses from such events. In the U.S., two major earthquakes since 1994 resulted in approximately $54 billion in damages, and eight major hurricanes since 2005 resulted in over $500 billion in damages (EERI, 2011; NCDC, 2012; Wile, 2017). A nationwide assessment of the hazard vulnerability of U.S. homes revealed that 43% of all U.S. homes with an estimated market value of $6.6 trillion are in areas of high disaster risk (RealtyTrac, 2015).

The industry has seen an increased uptake of sustainable design practices as a response to these issues over the past couple of decades (Yudelson, 2010). Some regions have seen the establishment of more stringent building codes and there has been an increased pursuit of building performance certifications around the world. Although the methods used to evaluate building performance in the areas of sustainability and resilience are improving, there are still gaps and disconnections between the various efforts. Life cycle assessment (LCA) and performance-based design approaches are becoming more commonly used during the design process but they are often limited in scope and are used in isolation, preventing the study off tradeoffs between design decisions and hindering a holistic understating of building performance (AIA, 2012).

1.2 RESEARCH GOALS AND OBJECTIVES

The goal of this research is to investigate the significance of currently missing phases (e.g., water management and repair) in whole building LCAs, and therefore improve the evaluation and understanding of building sustainability and resilience. Additionally, since building design includes multitude of variables, performance metrics, decision makers, and design tools, this research also aims to advance the use of interdisciplinary methods within whole building LCA. The following are the specific research questions for this project:

1. How should designers and policy makers consider water treatment in the context of high-performance buildings (i.e., net zero water) in a developed country?
2. How can we consider structural and non-structural integrity simultaneously with building life cycle environmental performance? What are the environmental impacts of repair from natural hazard events?
3. Is there a way of integrating multitude of building performance assessment methods and tools into a whole building life cycle assessment? How does life cycle performance (e.g. costs, environmental impacts) change across large set of building designs?

The following research objectives will guide the process of answering the research questions:

A. Conduct a comparative life cycle assessment of water-related impacts of living building with a decentralized, net-zero water system to a centralized, water efficient building.

B. Using hazard loss assessment and life cycle assessment, develop an approach and a life cycle inventory to determine the environmental impact of repairs during a building life cycle.

C. Integrate life cycle assessment, energy modeling, seismic loss assessment, and water modeling into a whole building LCA study considering building design decisions related to building shape, material selection, energy sources, and water management. Conduct a sensitivity analysis for select decision metrics and life cycle phases and develop recommendations for building designers and rating systems.

The overall connection between these objectives is shown in Figure 1. Energy and material impact of buildings has been widely studied using LCA, thus this research focuses on expanding the scope of whole building LCA (Objectives A and B) and understanding the holistic performance of buildings in a variety of environments and using a range of technologies (Objective C).

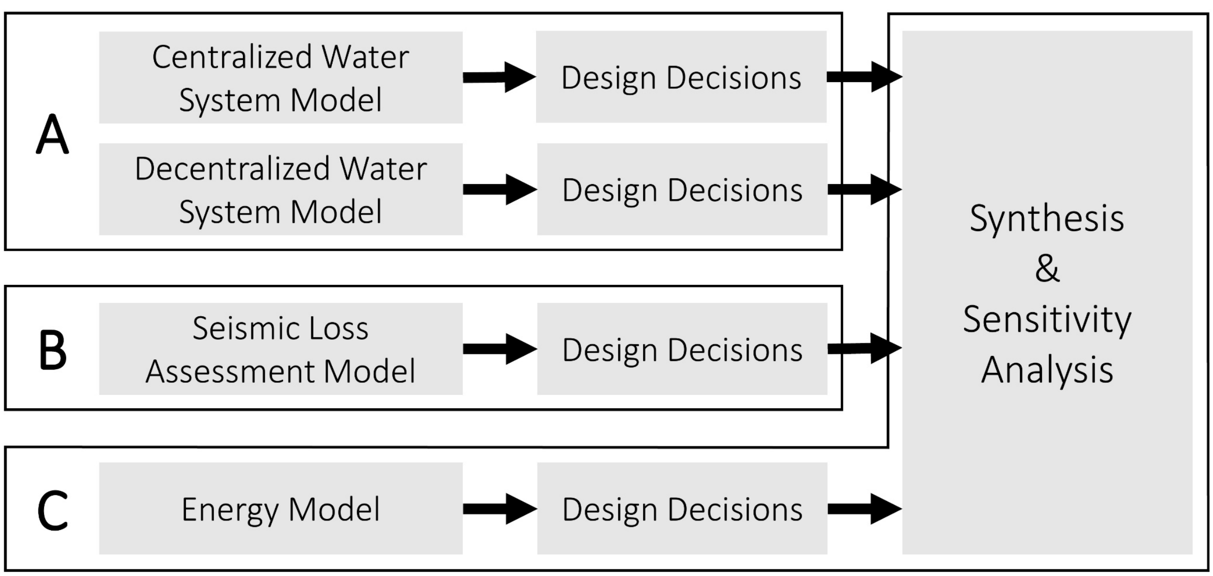

Figure 1. Overview of dissertation objectives.

1.3 BROADER IMPACTS

Part of this research explored the barriers preventing the adoption of LCA within the building industry. We worked closely with building managers and maintenance personnel in the case study buildings during the development of the life cycle inventories. Results were shared, missing aspects of typical LCA were discussed, and frameworks were expanded based on suggestions from industry representatives. Identified shortcomings of LCA use in the building industry were addressed by developing impact data for new building components and expanding the traditional whole building LCA scope via additional analyses and metrics. The main portion of this research stems from the NSF funded Resilient and Sustainable Buildings (RSB) project, which aims to develop a sequential decision framework that would allow for tradeoff exploration of multi-hazard resilient and sustainable building designs. This research directly addresses some of the needs of this project by exploring the connections between sustainability and resilience of buildings, expanding current LCA methods to include metrics of resilience, and focusing on the applicability of the developed methods to building design. The outcomes of this research have been shared with the academic, architectural, and engineering community via journal publications, conference presentations, and direct cooperation with architectural and engineering professionals. The direct cooperation included a 5-month internship with a leading architecture firm, KieranTimberlake, focused on the improvement of LCA use in practice.

1.4 INTELLECTUAL MERIT

This proposed work addresses needs of the building industry by exploring the connections between sustainability and resilience of buildings, expanding current LCA methods to include metrics of resilience, and focusing on the applicability of the developed methods to building design. The field of building LCA specifically will benefit from the addition of models and life cycle inventories for evaluating water and structural performance of buildings. This addresses the need for a more holistic approach to building performance analysis and closes the gap between rating systems and performance assessment tools. The synthesis of the expanded work in a whole building sensitivity analysis may be used to inform building designers and stakeholders as well as rating system developers of the relative importance of select design decisions.

1.5 DISSERTATION ORGANIZATION

This document begins with an overarching background related to the typical and broader aspects of life cycle assessment of buildings. The following four sections then focus on individual objectives of this dissertation: chapter 3 consists of the assessment of water-related life cycle environmental impacts from a building perspective, chapters 4 and 5 discuss the use of hazard loss assessment for addressing life cycle impacts due to damage repair, and chapter 6 investigates the relative influence and sensitivity of the water and repair aspects in relation to other building life cycle stages. Finally, chapter 7 discusses overarching conclusions, limitations, and recommendations for future work.

2.0 BACKGROUND AND LITERATURE REVIEW

This section discusses the characteristics of sustainable and resilient buildings, the use of life cycle assessment for the evaluation of building performance, and the consideration of water management and damage repair within building LCA.

2.1 SUSTAINABILITY AND RESILIENCE OF BUILDINGS

2.1.1 Definitions and motivation

Sustainability has first been defined in connection to sustainable development as the "development that meets the needs and aspirations of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987). In regard to buildings, sustainability has been closely linked with the way building design decisions affect resource use and emissions release over the entire life of a building (i.e. how design decisions affect use-phase performance, and end-of-life disposal).

Resilience has first been defined in the context of ecological systems as the ability of a system to absorb changes and still retain its original structure and function (Holling, 1973). Joseph Fiksel (2003) described resilience in terms of laws of thermodynamics as an ability of a system to resist disorder and the ability to maintain or return to a stable state after a perturbation. In terms of buildings, resilience has most often been approached as a way of anticipating and coping with natural hazard events in the most effective and efficient manner in terms of recovery effort and duration. Concerns over changes to our climate such as the changing dynamics of storm events, global warming, and rising sea levels have also led to the discussion of making buildings and infrastructure not just resistant, but adaptable to the changing environment (Leichenko, 2011; Stewart & Deng, 2014; The World Bank, 2012).

2.1.2 Methods of evaluation

Building codes were introduced as a way of ensuring all buildings provide at least some level of performance and life safety guarantees and included some of the motivations behind sustainability and resilience as well (Kneer & Maclise, 2008); however, they only focus on setting minimum requirements and may not be perceived as rigorous enough from a sustainability and resilience perspective. For this reason, independent building and infrastructure rating systems, such as Leadership in Energy and Environmental Design (LEED) (USGBC, 2014) and Envision (Shivakumar et al., 2014) have been created with the goal of providing improved guidance for and evaluation of the performance of buildings and infrastructure, respectively. Building rating systems are typically prescriptive in nature and focus on improving the design and operation of buildings. They are developed by using information from case studies and consensus amongst industry experts and stakeholders, who also decide on the relative importance of different performance aspects for general groups of building types and regions (USGBC, 2014). The issue with using qualitatively predefined weighing is that it may not adequately address localized and temporally sensitive issues and may not provide the best means of optimizing the performance of diverse buildings. Using quantitative methods that can capture the specific environment a building is located in and analyzing results using metrics most useful for decision making (e.g. cost, global warming potential, etc.) provide better means of design optimization (Attia et al., 2013).

For centuries, building resilience and/or risk has partly been addressed through building codes in terms of response to various loads (e.g. seismic, wind, snow, etc.) on the structural and envelope systems. In the past decades resilience has also been pursued from the system management perspective, but mostly in regards to communities (The World Bank, 2012). While this perspective is important, it is difficult to quantify and has often been approached via qualitative assessments. Bruneau et al. (Bruneau et al., 2003) were the first to define a general quantitative description of system resilience, while other scientists have started to implement computational models linking the structural and other performance characteristics of buildings to potential behavior of the buildings under stresses (Cutter et al., 2008; Menna et al., 2013). Rating systems typically focused on sustainability have also started to look into including resilience within their assessments by implementing credit categories for durability and passive survivability (e.g. maintaining safe range of indoor temperatures during energy outages via passive design strategies) (Larsen, 2011).

2.2 WHOLE BUILDING LIFE CYCLE ASSESSMENT

2.2.1 Life cycle assessment

One way of quantitatively assessing the sustainability of products and processes, including buildings, is through LCA. LCA is a quantitative approach to assessing the impact on the environment and human health via the study of resource and emission exchanges between the technical and natural environment, and consists of four steps: goal and scope definition, life cycle inventory, impact assessment, and interpretation and analysis (ISO, 2006). The definition of the study boundary and scope is a required step in the international standard for LCA. According to the ISO standard for LCA and as applied to buildings, there can be the following scopes of building LCA studies:

Cradle to gate – including material extraction, processing, and construction

Cradle to grave – including all phases from pre-use to end-of-life without any feedback loops

Cradle to cradle – including all phases and feedback loops, such as material reuse, recycling, or waste-to-energy

Life cycle assessment framework is based on the environmental exchanges of matter between processes. A complete LCA accounts for the emissions of elements to soil, water, and air, as well as consumption of raw materials. A life cycle inventory (LCI) is comprised of individual chemical releases (such as CO_2, CH_4, N_2O, etc.) and material use. A life cycle impact assessment method translates the LCI into midpoint impact categories (such as global warming potential, acidification, eutrophication, etc.) with some impact assessment methods further aggregating the midpoint categories into endpoint categories (such as climate change, human health, etc.).

Whole building LCA can help quantify environmental impacts in both conventional and high-performance buildings given the availability of data for individual building systems and components. The life cycle phases included in whole building LCA studies should include raw material extraction, material processing, construction, use phase, end-of-life, and transportation along the way, as stated in the EN 15978 and ISO 21931 standards for environmental performance evaluation of buildings (CEN, 2011; ISO, 2010). The use phase is further divided into operational water and energy use, maintenance, repair, replacement, and refurbishment. Figure 2 shows the life cycle phases and sustainability focused performance aspects covered in the ISO 21931 standard (ISO, 2010) and LEED v4 rating system (USGBC, 2014). It can be seen in the figure that

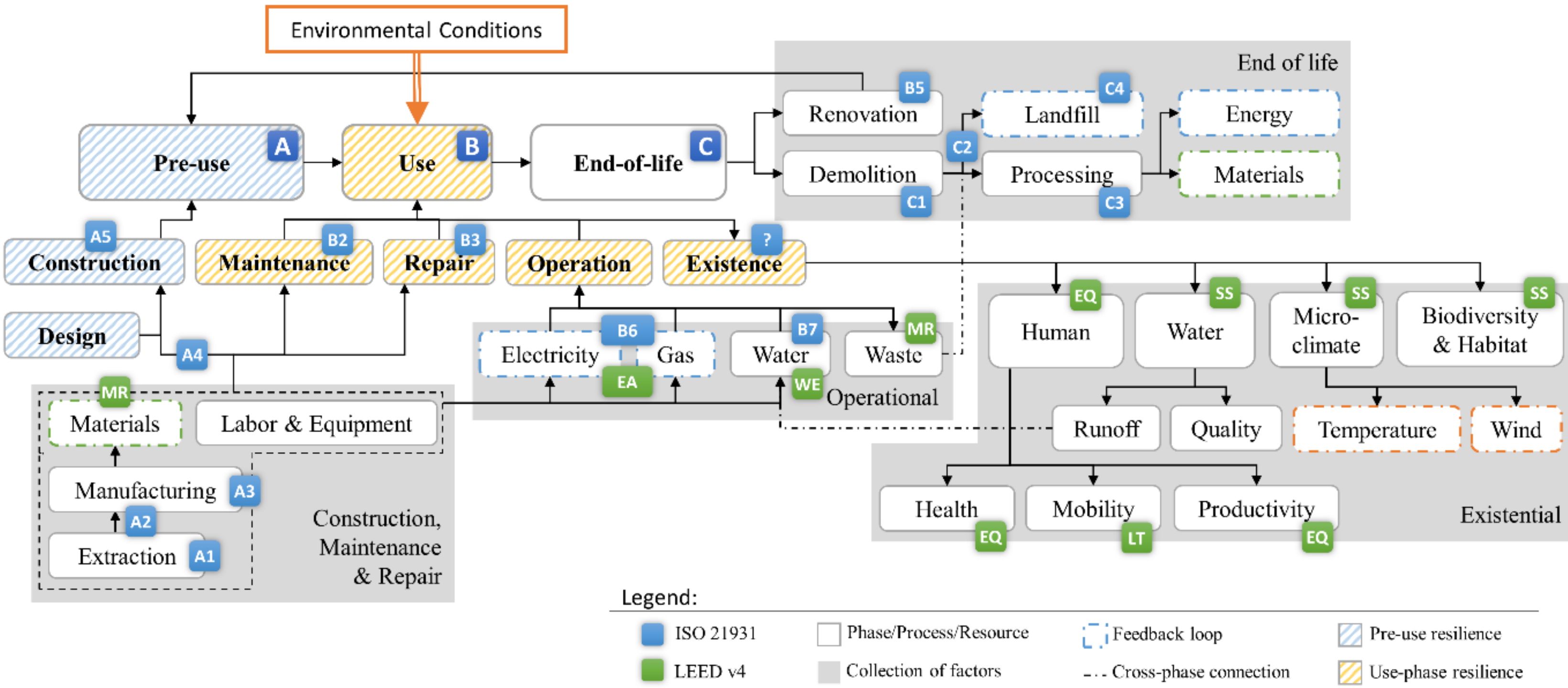

Figure 2. Building life cycle phases and performance aspects.

The figure is based on ISO standard 21931 (ISO, 2010) and LEED v4 rating system (USGBC, 2014) with additional graphical connection to resilience.

LCA focuses on clearly quantifiable aspects of building performance (e.g. material and energy use), while the LEED v4 rating system attempts to address a broader set of sustainability issues (e.g. occupant comfort and mobility, biodiversity and habitat protection, etc.).

2.2.2 Building LCA literature

Sustainability of different aspects of buildings has been often studied retroactively using life cycle assessment (LCA) (Bilec et al., 2010; Bilec et al., 2006; Guggemos & Horvath, 2006; Junnila & Horvath, 2003; Junnila et al., 2006; Scheuer et al., 2003; Sharrard et al., 2008), with some organizations and researchers developing design focused LCA for buildings (Basbagill et al., 2013; Bribián et al., 2009; SMI, 2012). Most building LCA studies to date have focused on life cycle impacts from material use, construction, operational energy use, and end-of-life disposal or reuse (Junnila & Horvath, 2003; Leckner & Zmeureanu, 2011; Scheuer et al., 2003; Thiel et al., 2013). Operational energy consumption has been found to account for majority of building related impacts, for example Scheuer et al. (2003) found operational energy of a case study building to account for 60-95% of impacts in five different impact categories, and Ramesh et al. (2010) found that most conventional buildings' operational energy accounts for 79-92% of total life cycle energy demand.; however, that is likely to change with the design of net-zero buildings (Blengini & Di Carlo, 2010). Energy consumption can be related to the design and orientation of windows and openings, shading strategies, envelope systems performance, and heating, ventilation, and air-conditioning (HVAC) systems, to name a few variables. The impacts of operation can be significantly reduced with an advanced design and preconstruction analysis, which may result in marginal upfront costs but reduced life cycle costs (Ochoa et al., 2002). The tradeoff in the design of high-performance buildings is their tendency to have higher embodied impacts due to the installation of additional on-site systems (e.g. on-site solar array, on-site wastewater treatment system, additional insulation materials, etc.) (Berggren et al., 2013; Blengini & Di Carlo, 2010; Crawford & Stephan, 2013; Sartori & Hestnes, 2007). Performance-based tools and LCA can help in assessing the cost-benefit of implementing these systems.

2.2.3 Current building LCA limitations

While sustainability generally demands that the objects of interest be assessed over a broad range of factors and functional capacities, LCA studies may inherently suffer from a truncation of the studied boundary based on the practitioner's decision and availability of data (Suh et al., 2004). For example, many building LCA studies conduct cradle to grave assessments but omit certain phases of the building's life cycle, such as construction and demolition, due to the relatively low importance referenced in other studies (Adalberth, 1997b; Junnila et al., 2006; Scheuer et al., 2003). It is important to note that this argument has often been based on the results of a limited number of conducted studies representing small sample size of buildings. Some phases mentioned in the ISO 21931 standard have also not been included in most existing building LCA studies. The most notable one is the use-phase repair of damage to the building. Researchers started addressing this phase around 2010, but it has not been adequately included within existing whole building LCA tools. Operational water use is rarely included in building LCA as well, even though it is listed in the ISO 21931 standard (ISO, 2010). Another issue is boundary setting of building systems. Many building LCA studies and currently available building LCA tools focus only on specific systems, such as structural and certain envelope systems, excluding any plumbing, electrical, finishing, specialty, and other building systems, further truncating the overall study boundary. Lastly, existential impacts of buildings beyond the flow of resources and energy (e.g.

human productivity and health, or direct stresses on the environment due to stormwater runoff and heat island effect) typically covered in building codes and certification systems are generally not included in building LCA studies, as shown in Figure 2.

This work addresses some of the limitations by developing models and data for new systems, new applications (specifically in water and repair LCA related to buildings) and investigating the potential influence of broader design decisions on the overall sustainability and resilience of buildings.

3.0 LCA OF BUILDING-SCALE WATER SYSTEMS

This chapter is focused on addressing Objective A, i.e., understanding of life cycle environmental impacts of building scale water systems. The content of this chapter is based on an article titled *Evaluating the Life Cycle Environmental Benefits and Trade-Offs of Water Reuse Systems for Net-Zero Buildings* published in the journal *Environmental Science & Technology* (Hasik, Anderson, et al., 2017). An adapted version of the article is being used with permission from Hasik, V., Anderson, N. E., Collinge, W. O., Thiel, C. L., Khanna, V., Wirick, J., Piacentini, R., Landis, A. E., Bilec, M. M. (2017). Evaluating the Life Cycle Environmental Benefits and Trade-Offs of Water Reuse Systems for Net-Zero Buildings. *Environmental Science & Technology, 51*(3), 1110-1119. doi:10.1021/acs.est.6b03879. Copyright 2017 American Chemical Society. Appendix A provides supporting information for this chapter.

3.1 INTRODUCTION

Engineered water infrastructure provides around 91% of the world's population (over 6.5 billion people) with access to fresh, potable water (The World Bank, 2015a, 2015b). In developed countries like the United States this infrastructure often consists of a centralized water treatment plant (WTP), a network of piping and pumps for potable water distribution, a network for wastewater collection, and a wastewater treatment plant (WWTP) that treats sewage and discharges it into nearby surface water. This infrastructure system has been in place in many US cities for the last 200 years and has vastly improved public and environmental health since its advent (Burian et al., 2000). Additionally, centralized water systems can transport large volumes of water from remote sources; they can be built, maintained, and monitored according to effective standards; and they provide relatively predictable treatment performance, justifying the large capital investment (Burian et al., 2000; Hering et al., 2013; Hophmayer-Tokich, 2006). Although there are numerous advantages of centralized water systems, there are inefficiencies as well. Water treatment is energy and resource intensive, with some municipalities in the United States spending about 35% of their energy budget on water and wastewater treatment facilities (Pirnie, 2008). Additionally, on both residential and commercial scales, 80 to 85% of WTP's outputs are used for demand that could be met by non-potable water such as rainwater or greywater (Sisolak & Spataro, 2011). Water infrastructure is aging and its maintenance is costly, resulting in leaks and increased pumping demands (Hendrickson & Horvath, 2014). In 2014, water infrastructure costs in the United States were estimated at $137 billion, and the total cost over the next 20 years is estimated to exceed $1 trillion (American Society of Civil Engineers, 2013; U.S. Congressional Budget Office, 2015). Since existing water infrastructure across the US is nearing the end of its useful lifetime, planners have a unique opportunity to transition into a new water-management paradigm (Hering et al., 2013).

Centralized WTPs and WWTPs were implemented in the US as a substitute for ineffective early decentralized systems (Burian et al., 2000). Since their implementation, however, decentralized systems' efficacy has vastly improved and is now comparable to that of centralized systems (Burian et al., 2000; Hering et al., 2013). Organizations such as the United States Green Building Council (USGBC) and the International Living Future Institute (ILFI) support decentralized water infrastructure in their building rating systems as a way to foster positive environmental and public health benefits (Sisolak & Spataro, 2011). The building analyzed in this study received four different certifications and employs state-of-the-art water and energy systems, serving as a model for other green and high-performance buildings. Decentralized water systems are often regarded as more sustainable than centralized systems because they increase the potential for water conservation and reuse, increase the resiliency of the water infrastructure network, and reduce the cost of infrastructure replacement (Makropoulos & Butler, 2010). A decentralized water system sources its water and/or treats its wastewater at points disconnected from the centralized grid, and typically involves technologies such as rainwater harvesting, bioswales, constructed wetlands, septic tanks, and other small-scale technologies (Makropoulos & Butler, 2010; Massoud et al., 2009; Sisolak & Spataro, 2011). With advancements in small-scale treatment technologies, these systems can produce potable water, though municipal and state codes often restrict usage to non-potable purposes (McLennan & Brukman, 2012).

With the inextricable linking of the water-energy nexus, sustainable development, and public health, an understanding of the life cycle environmental impacts of water infrastructure is critical to offering solutions to decision makers. This can be accomplished by using Life Cycle Assessment (LCA), a tool for quantifying the environmental impacts of a product or process. LCA scientifically analyzes the relative environmental impacts of products, processes, and systems through the entirety of their life cycles (i.e. from material extraction, through processing, transportation, use, and to the end of life) (ISO, 2006).

LCA has previously been used to compare centralized and decentralized water supply and treatment systems in different contexts and with different system boundaries, often resulting in conflicting conclusions. A study comparing centralized and decentralized wastewater treatment in urban areas found a centralized anaerobic digestion plant to have lower material, energy, and greenhouse gas (GHG) impacts due to higher treatment efficiency per unit volume of wastewater treated (Shehabi et al., 2012), while another study comparing systems in rural areas found passive decentralized treatment (i.e. constructed wetlands and slow rate infiltration) to have lower impacts than a centralized plant with aeration (Machado et al., 2007). Other studies have compared the environmental impacts of different aspects and types of wastewater technologies (Foley et al., 2010; Kalbar et al., 2013; Lopsik, 2013; Tillman et al., 1998; Wu et al., 2010), as well as alternative/decentralized water supply, distribution, and reuse systems—these studies also had varying conclusions (Filion et al., 2004; Lemos et al., 2013; Mo et al., 2010; J. Stokes & Horvath, 2006). A recent analysis of a living machine (LM) concluded that the centralized WWTP emitted less GHGs but required more energy than the LM on a per unit volume basis (Hendrickson et al., 2015). Another recent study investigating the sustainability of wastewater treatment at different scales concluded that centralized city-scale treatment is more efficient in terms of resource use and GHG emissions. The study also concluded that decentralized community-scale systems with nutrient removal can have lower eutrophication impacts than city or household-scale systems (Cornejo et al., 2016). The diversity of these findings illustrates the impact of technological and regional differences on the relative sustainability of water systems, and the difficulty for designers, planners, and policy-makers to make the best decisions when trying to reduce impacts of building-related water use.

Whole-building LCA can help quantify impacts in both conventional and high-performance buildings. Most building LCA studies to date have focused on embodied impacts from material use, construction, operational energy use, and end-of-life disposal or reuse (Junnila & Horvath, 2003; Leckner & Zmeureanu, 2011; Scheuer et al., 2003; Thiel et al., 2013). No existing studies consider both water supply and wastewater treatment at a comprehensive building-based level, or in the context of a net-zero energy/water building. In the effort of creating better performing buildings, organizations like USGBC and ILFI often promote the use of on-site, decentralized, energy and water systems, with the goal of using local resources and increasing buildings' resilience through lower dependency on the centralized grid. The tradeoff in the design of high-performance buildings is their tendency to have higher embodied impacts due to the installation of additional on-site systems (Berggren et al., 2013; Blengini & Di Carlo, 2010; Crawford & Stephan, 2013; Sartori & Hestnes, 2007).

It is important to recognize the potential tradeoffs of decentralized and centralized water systems in the context of high-performance buildings, especially as green building rating systems evolve and increasingly impact markets. For this reason, and to fill a gap in the current literature, an LCA of the decentralized water system of a high-performance, net-zero energy, net-zero water building was conducted, and the results were compared with two modeled buildings (conventional and water efficient) that use a centralized water system. The case study building's reuse system is also unique in its use of septic tank aeration, on-site generated solar energy, and on-site reuse for non-irrigation purposes, avoiding emissions to soil and water. Typical building LCA studies also select fixed lifespan of buildings and report deterministic impact estimates, while this work examines the changes of impacts for varying building lifetimes and includes Monte Carlo uncertainty analysis. This work aims to help architects, engineers, planners, building owners, and policymakers understand the environmental implications related to water use in buildings. The framework presented in this chapter could be further refined and used to analyze systems in different settings, creating a platform for performance-based building design.

3.2 MATERIALS AND METHODS

3.2.1 Case study building

An innovative building was selected that has achieved some of the highest awards in the green building community. This building, the Center for Sustainable Landscapes (CSL), is the newest addition to the Phipps Conservatory and Botanical Gardens in Pittsburgh, Pennsylvania, and herein will be referred to as the *net-zero building (NZB).* With three stories and 24,350 square feet, the building now services 40 employees and is located on the lower grounds of the Phipps campus. The NZB is an administrative, educational, and research office building that was completed in the spring of 2013 and received certification from the Living Building Challenge (LBC) in March of 2015. The LBC is a building certification method developed by the International Living Future Institute in 2006 (McLennan & Brukman, 2012). Among other requirements, Living Building certified projects must be net-zero energy and net-zero water. "Net zero" criteria stipulate that the total annual energy used on-site cannot exceed the total annual energy generated on-site; and all of the building's water needs must be met using only captured rainwater, recycled wastewater or other closed loop systems, without the use of chemical treatment (McLennan & Brukman, 2012). Additionally, all stormwater and wastewater must be managed and treated on-site. In addition to the LBC certification, the NZB has also achieved LEED Platinum, a Four-Stars Sustainable Sites Initiative (SITES) certification for landscapes, and the Platinum ranking by WELL Building Standard (WELL) certification for health and wellbeing. It is the first building in the world to receive certification from all four of these sustainable building standards (Gray, 2015).

The net-zero energy requirement is mainly achieved by using electricity generated with on-site photovoltaic (PV) panels. The net-zero water requirement is achieved through the use of low-flow water fixtures and the building's complex decentralized water treatment and reuse system shown in Figure 3. Rainwater is harvested from the NZB and roofs of various buildings on the Phipps' upper campus, stored in a storage tank, disinfected with ultraviolet light (UV), and used as irrigation, service, or flush water in the NZB. Overflow rainwater is sent either to a lagoon, additional storage tanks, or rain gardens, while overflow wastewater is sent to a test-bed solar distillation system. Some of the overflow rainwater is then used for plant watering on Phipps's upper campus. The wastewater from the NZB is treated in an aerated septic tank, constructed wetlands, and sand filters before being disinfected and reused as flush water in the building. The NZB has two disinfection units, one dedicated to treating wastewater, and another for the treatment of rainwater. These units include UV lamps, additional filters, and pressure tanks, and herein will be referred to as *UV treatment*.

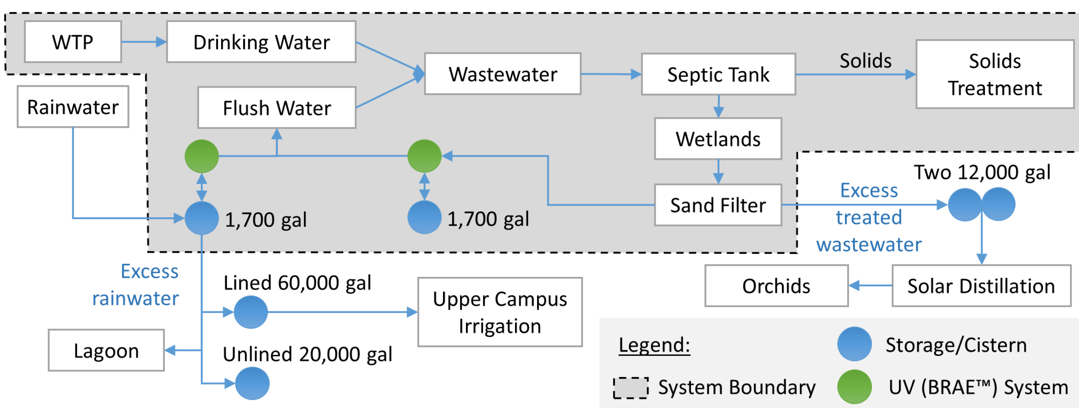

Figure 3. System boundary and schematic of net-zero water systems of case study building.

(WTP = water treatment plant; UV = ultraviolet disinfection)

The NZB minimizes the need for potable water from the local WTP, though state and local regulations prevent the NZB from using recycled water for potable purposes. On average, the building sources 49 gal (185 L) of its total 206 gal/day (780 L) from the city's water supply network for this reason. Detailed water demand data can be found in the Appendix A Table 12. The building then offsets this quantity by sending extra treated water to the upper campus for irrigation; thus, the system meets net-zero requirements for the LBC, and, if not for regulations, is a closed loop. Since the NZB treats all of its wastewater on site, it thus eliminates the need for the services from the local WWTP, though it does have overflow connections for extreme events as required by local authorities.

Since this study focuses on the water service of the NZB, components used primarily for aesthetics (e.g. lagoon), stormwater runoff management (e.g. unlined storage, rain garden), and upper campus irrigation (e.g. solar distillation) are excluded from the system boundary, as shown in Figure 3.

3.2.2 Water demand and functionally equivalent comparisons

To conduct a comparative LCA and ultimately provide guidance to policy makers and building owners, the NZB's water use was compared to that of *two hypothetical reference buildings* that source all of their water from the public WTP and convey wastewater for sanitary treatment to the public WWTP. Comparing the NZB building's water use to two hypothetical reference buildings was necessary to clearly understand how the NZB compares to buildings of varying water-efficiencies. First, the **low-flow reference building (LFRB)** was developed to represent a building with the same internal features as the NZB (i.e. waterless urinals, low-flow fixtures, and high-efficiency appliances), but without the advanced on-site treatment system. The LFRB's total water demand is identical to that of the NZB at 206 gal/day (780 L/day), all of which is sourced from the public WTP and subsequently sent to the public WWTP. Second, the **normal-flow reference building (NFRB)** represents an ordinary building that does not meet any green building standards and does not employ any low-flow water fixtures. This building was calculated to consume 605 gal/day (2,290 L) of municipal water (from the WTP) based on water consumption per person, with an equivalent number of people working in the building as in the NZB. The calculations were based on sources that detailed the water usage of various water fixtures and appliances (Allience for Water Efficiency; U.S. Environmental Protection Agency, 2008). Additional information on the water calculations for the LFRB and NFRB can be found in Appendix A Table 13.

3.2.3 Life cycle goal and scope

The goal of this LCA was to compare environmental impacts of water and wastewater treatment processes required by a net-zero water/net-zero energy building (i.e. NZB) and the two reference buildings (LFRB and NFRB). The functional unit chosen for this study was *one year of a building's water service*, including the water treatment, water use, and wastewater treatment required by a building. Previous LCA studies that considered wastewater treatment used a person-equivalent functional unit, which measures biological oxygen demand (BOD) loading per day (Fuchs et al., 2011; Hospido et al., 2008; Tillman et al., 1998); while water and wastewater treatment is also generally analyzed over a volumetric functional unit (Bonton et al., 2012; Lemos et al., 2013). A general functional unit (one year of a building's water service) that accounts for both water and wastewater treatment allows the three buildings to be compared concurrently, rather than solely in water or wastewater treatment performance.

The comparison of the NZB and reference buildings' systems accounts for impacts in three main areas: water procurement, treatment, and transport; off-site and on-site materials; and waste generation and treatment (gaseous and solid waste in the case of the NZB, and wastewater in the case of the reference buildings). To understand the effects of system lifetime on the annual water demand impacts, the comparison over three assumed lifetimes of the NZB water system was made: 20, 50, and 100 years. The 20-year analysis was selected based on the predicted and/or reported lifespans of some of the water system components, and was also used by other studies that cited similar reasons (Cornejo et al., 2016; Hendrickson et al., 2015). Previous building LCA studies have most often chosen a 50-year building lifetime, but other lifetimes between 50 and 100 years have also been used (Adalberth, 1997b; Aktas & Bilec, 2012a; Alshamrani et al., 2014; Blengini & Di Carlo, 2010; Crawford & Stephan, 2013; Junnila & Horvath, 2003; Junnila et al., 2006; Scheuer et al., 2003). Building lifetime is dependent on a variety of factors including the building function, with institutional buildings often exceeding 100 years, and commercial buildings generally having much shorter lifespans (Kneer & Maclise, 2008). Consideration of different lifetimes also allowed us to conduct a breakeven analysis to determine the lifetime of the NZB's on-site system at which its impacts equal those of the reference buildings.

Figures 4 and 5 show the flow diagrams for the NZB and the reference buildings, respectively. The production phase includes material extraction, processing, and manufacturing of all components of the NZB's water and wastewater treatment system. The use phase of the NZB includes the electricity used for pumping and UV treatment, and materials needed for maintenance and replacement of components. Many of the NZB components (e.g., piping, manholes, storage, and liners) have expected lifetimes of over 100 years, and likely will not need to be replaced (American Water Works Association, 2012; Rowe & Sangam, 2002; Sabouni, 2013). The unit process representing PV electricity accounts for 30-year replacements of the PV panels (Jungbluth et al., 2008), and reported replacement times were included for components such as filters and UV lamps. Pumps, storage tanks, and other remaining components' service lifetimes were assumed based on our best engineering judgment and can be found in Appendix A Table 15. It should be noted that these lifetimes represent the best available estimates for typical conditions; actual replacement and repair needs may vary due to breakage, operating conditions, and technological changes. All three buildings' use phases include the daily services required by the centralized water and wastewater treatment plants, such as conveyance infrastructure, plant infrastructure, electricity supply, and chemical usage. This study did not consider on-site construction activities (i.e., diesel pollutants from construction equipment), or end-of-life phase (i.e., recycling, landfilling, and incineration) due to their typically low impacts (Junnila & Horvath, 2003; Scheuer et al., 2003). Roofing materials, water fixtures, and interior piping were assumed to be manufactured using equivalent materials and processes in all three buildings and were therefore also excluded. These exclusions are not expected to have a significant impact, although there could be some differences in those components across the three buildings.

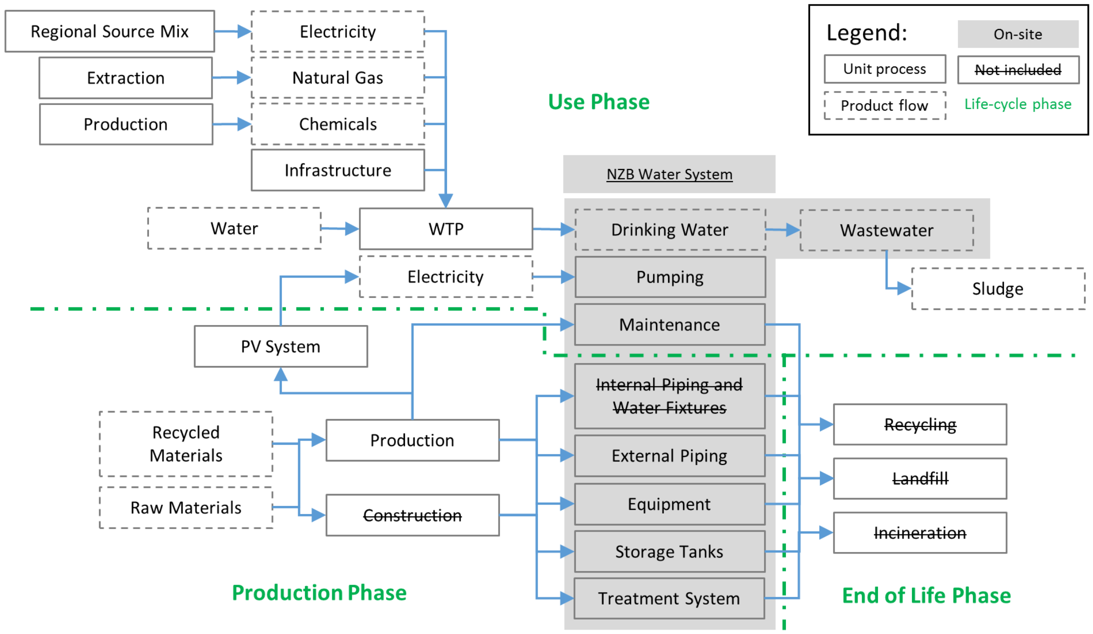

Figure 4. Flow diagram of the net-zero building's (NZB) decentralized water system.

Treatment system includes septic tank, wetlands, sand filters, and UV treatment. Transportation is included upstream of material production and operation of the WTP, as well as for transport of sludge from the NZB. (CSL = Center for Sustainable Landscapes, WTP = water treatment plant, PV = photovoltaic, UV = ultraviolet)

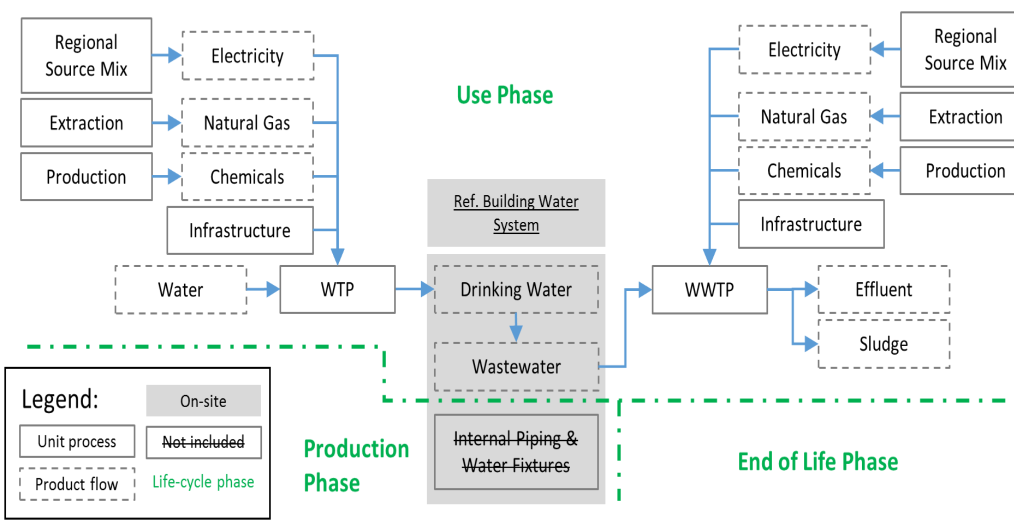

Figure 5. Flow diagram of the reference buildings utilizing a centralized water system.

The low-flow and normal-flow reference buildings' transportation is included upstream of WTP and WWTP operations. (WTP = water treatment plant; WWTP = wastewater treatment plant)

3.2.4 Life cycle inventory and impact assessment

A diagram and a component inventory of the NZB's water system was compiled from the construction documents and submittals, and verified via personal communication with the CSL's director of facilities (Wirick, 2015). On-site materials at the NZB, such as pumps, piping, storage tanks, liners, constructed wetlands, sand filters, UV treatment, and other equipment, were assigned to representative unit processes (listed in Appendix A Table 17) and combined into a single process called net-zero building/decentralized site materials (NZB/D Materials). Material properties for the components of the treatment system were gathered from product documentation or submittals and then used to determine the weight or volume of the contributing materials.

Direct on-site methane (CH_4) and nitrous oxide (N_2O) emissions to air were estimated for the NZB's septic tank and constructed wetlands and are shown in Figure 6 as net-zero building/decentralized direct emissions to air (NZB/D Direct Emissions to Air). The constructed wetlands' emissions were estimated based on results in existing studies (see Appendix A Table 18) (Fey et al., 1999; Fuchs et al., 2011; Johansson et al., 2004; Johansson et al., 2003; Leverenz et al., 2010; Søvik et al., 2006); however, no such studies were found for aerated septic tanks, which likely have different emissions than typical anaerobic septic tanks. Septic tank N_2O emissions were expected to be similar, since they are independent of the oxygen conditions within the tank (U.S. Environmental Protection Agency, 2016), and were therefore based on published values (Leverenz et al., 2010). CH_4 emissions are dependent on the aerobic/anaerobic conditions within the tank and were calculated using a modified EPA methodology (U.S. Environmental Protection Agency, 2016) for estimating emissions from aerobic WWTPs treating domestic wastewater:

$$CH_4 \text{emissions} = BOD_{in} \times DA \times B_0 \times MCF \tag{3-1}$$

where BOD_{in} is the amount of influent organic matter in kg BOD_5 into the tank, DA is the ratio of matter degrading anaerobically within the tank, B_0 is the maximum CH_4-producing capacity for domestic wastewater, and MCF is the CH_4 correction factor. B_0 and MCF are defined by the EPA as 0.6 and 0.3, respectively, for aerobic WWTPs treating domestic wastewater with pockets of anaerobic conditions (U.S. Environmental Protection Agency, 2016). DA was assumed to be 5% in this case based on another study (Scheehle & Doorn, 2001). BOD_{in} was calculated based on actual post-septic effluent readings from the NZB and the estimated BOD removal rate of an aerated septic tank as follows:

$$BOD_{in} = BOD_{out}/(1 - BOD_{RR}) \tag{3-2}$$

where BOD_{out} is the post-septic BOD_5 reading and BOD_{RR} is the BOD removal rate. The removal rate used in this study was assumed at 92% based on results in other studies (2009; Lee et al., 2006). The calculated BOD_{in} was verified by further calculating the BOD production per capita per day based on the daily water use of the NZB and the number of occupants:

$$\text{BOD capita}^{-1}\text{day}^{-1} = BOD_{in} \times W\ /\ P \tag{3-3}$$

where W is the wastewater volume produced, and P is the number of building occupants. The influent BOD was found to be 3,350 mg/L using Equation 3-2, yielding 61 g of BOD production per capita per day using Equation 3-3, which is similar to values reported in other studies (Crites & Technobanoglous, 1998; Machado et al., 2007). There are no expected emissions to land or water at the NZB since all system components are lined and separated from the surrounding soil and treated water is reused within the building.

Electricity consumption of the water treatment system was based on output from the NZB's building automation system (BAS) and the equipment's rated power. The BAS provided real-time data on the NZB's total energy consumption and the times of different water system components' usage. The specific run-time and electricity consumption of individual water pumps and of the UV treatment system were determined by regressing the equipment use-time against the real-time total electricity consumption of the building. BAS data was unavailable for the septic tank aerator; the aerator's rated power was used and a 24-hour per day run-time was assumed to calculate its total electricity demand. The estimated electricity demand was then averaged on an annual basis and linked to the net-zero building/decentralized photovoltaic electricity (NZB/D PV Electricity) process. Since the NZB's PV array exchanges electricity with the grid and is considered net-zero energy on an annual basis, it was adequate to use the average annual water system's electricity demand. This approach would not be valid for off-grid systems or for studies considering temporal variations throughout the year.

The centralized WTP inventory was based on the predefined unit process within the ecoinvent database (Frischknecht et al., 2005), and modified to reflect the local electricity mix and some known material and energy inputs specific to the case study location. Energy consumption, including electricity and natural gas demand, and chemical usage data specific to the local WTP were obtained through personal communication with the plant staff (Cyprych, 2014). Data for the local centralized WWTP was much more limited, and the LCA model in this study relied solely on an ecoinvent unit process with the exception of the electricity mix modification. The electricity mix was determined using US Environmental Protection Agency's (EPA) Emissions & Generation

Resource Integrated Database (eGRID) power profiler online tool (U.S. Environmental Protection Agency, 2014). It was assumed that the modification of existing ecoinvent unit processes was a valid way of representing the centralized WTP and WWTP in the life-cycle framework, though they may not exactly represent Pittsburgh's local plants. The ecoinvent-based WWTP used in this work captures the methane produced in its anaerobic sludge digester and converts it to energy, preventing its emissions (Doka, 2007). Such systems are widely used in Europe; however, WWTPs in the U.S. often capture and flare methane from anaerobic digesters, or use mechanical sludge dewatering, also preventing methane emissions (Stillwell et al., 2010). So, while the local WWTP was not modeled explicitly, it was assumed it has comparably low methane emissions, which is also supported by EPA's greenhouse gas accounting methods (U.S. Environmental Protection Agency, 2016).

All unit processes were chosen from the ecoinvent 3.0 database for methodological consistency (Frischknecht et al., 2005; Moreno Ruiz et al., 2013). This study utilized the US EPA's impact assessment method TRACI 2.1, the Tool for the Reduction and Assessment of Chemical and other environmental Impacts, which includes impact categories shown in Figure 6 (Bare, 2011). This method was chosen based on its relevance to the North American region. Additionally, the Cumulative Energy Demand (CED) method was used to determine embodied energy (Frischknecht et al., 2007a). Statistical uncertainty in life cycle inventory data is captured via Monte Carlo analysis by randomly sampling (10,000 trials) from the underlying probability distributions obtained from the ecoinvent unit process database. The results of uncertainty analysis are shown in Figure 6 with error bars representing 95% confidence intervals. Addressing uncertainty in a statistical manner at the life cycle scale aids in capturing the plausible range for life cycle impact results.

3.3 RESULTS AND DISCUSSION

3.3.1 Comparative results of the NZB, LFRB, and NFRB

Results of the life cycle impact assessment for the three lifetimes of the NZB and the two reference buildings are shown in Figure 6. The solid bars in Figure 6 represent mean values whereas the error bars represent 5^{th} and 95^{th} percentile obtained via Monte Carlo uncertainty analysis. Some of the underlying inventory data in the ecoinvent database is based on relatively low number of samples, or samples with large variability, hence resulting in large spread between the upper and lower bounds in some categories. Additional uncertainty is associated with aggregation of inventory data across spatial and temporal scales in the underlying unit processes. Due to these uncertainties, categories such as carcinogenics and non-carcinogenics may be inconclusive in this case without further improvement to the inventory data. On the other hand, categories like global warming potential, eutrophication, and cumulative energy demand show that the differences between the buildings are significant even considering these uncertainties. All subsequent discussion here refers to the mean values obtained via Monte Carlo uncertainty analysis.

The NZB has lower eutrophication impacts than both reference buildings because the treated wastewater is used for non-irrigation purposes, preventing nutrient release into the soil and groundwater. Centralized wastewater treatment plants emit more in this category due to the nutrient and chemical releases into the receiving bodies of water (Hospido et al., 2004; Kalbar et al., 2013). Other studies have found small-scale decentralized systems to have higher (Cornejo et al., 2016) or equivalent (Machado et al., 2007) eutrophication impacts compared to centralized systems when the treated, nutrient rich water is used for irrigation purposes.

When compared only to the NFRB, the NZB breaks even and performs better in the ozone depletion, respiratory effects, and fossil fuel depletion categories if used for at least 97 years, and in global warming potential (GWP), smog, acidification, carcinogenics, non-carcinogenics, and cumulative energy demand (CED) categories if used for at least 23 years. The NZB is unlikely to ever break even with the NFRB in the ecotoxicity category. The NZB is unlikely to ever outperform the LFRB in any category other than eutrophication. In GWP, for example, the NZB never breaks even with the LFRB because of the baseline on-site emissions and recurring emissions associated with replacement of solar panels and other on-site components. The break-even results were reached by calculating the number of years the NZB building would have to be actively using the water system in order for its impacts to go below the impacts of the reference buildings. Detailed results and break-even times are shown in the Appendix A Tables 15 and 17, respectively.

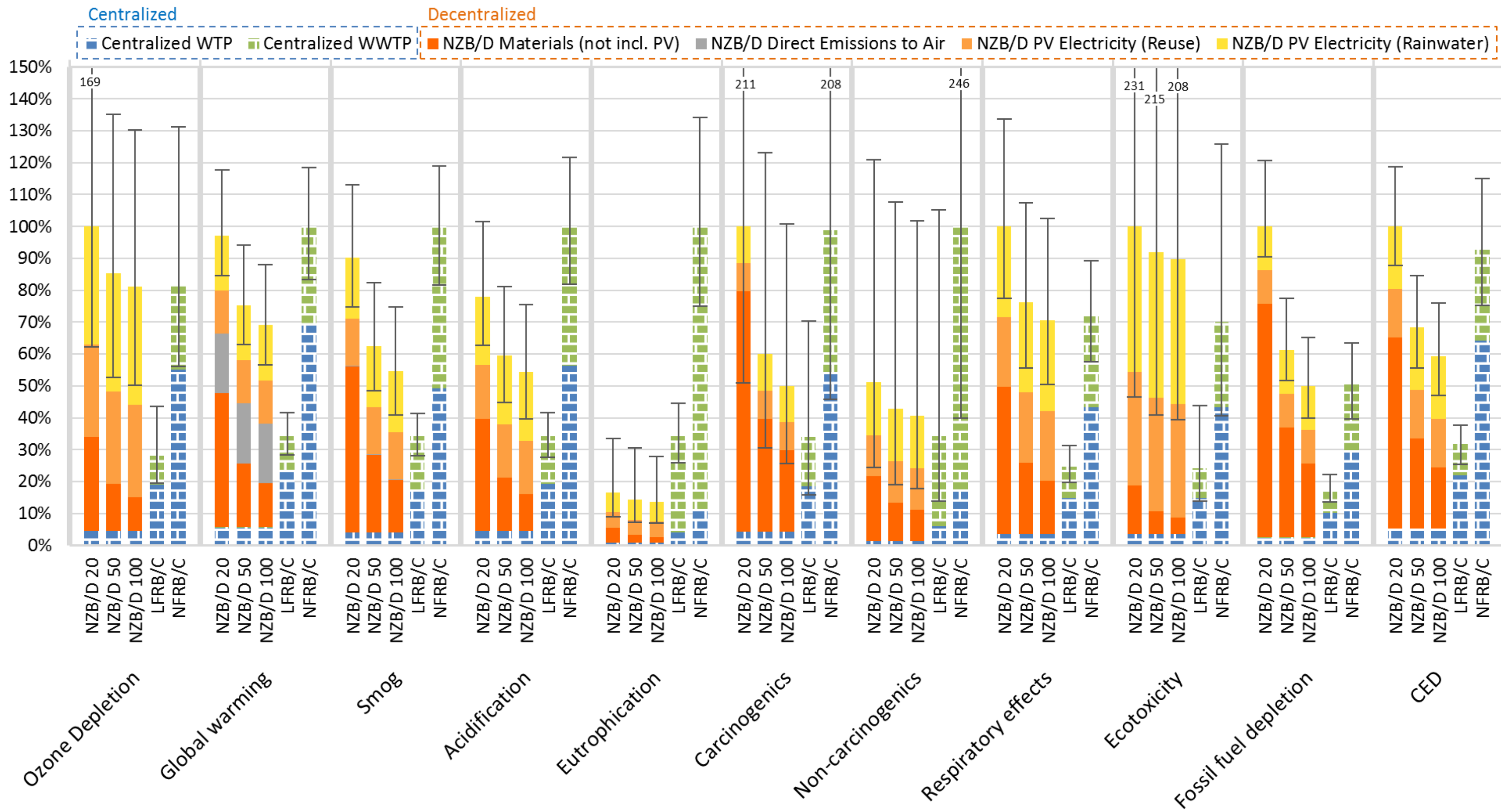

Figure 6. Life cycle impacts of water treatment scenarios.

Life cycle impacts of water systems for decentralized/net-zero building (NZB/D) compared to centralized low-flow (LFRB/C) and normal-flow (NFRB/C) reference buildings. Percentages shown are based on the water demand per year of average building water use, normalized to the worst performer in each impact category. The results show three lifetime scenarios (20, 50, and 100 years) of the NZB. Mean values are shown for all impact categories. The error bars represent the 5th and 95th percentile obtained via Monte Carlo uncertainty analysis. (CED = Cumulative energy demand)

Previous studies reported the total GWP of a similar system with a 20-year analysis period to be 3.3 kgCO_2e/m^3 (Cornejo et al., 2016), which is similar to the 4.4 kgCO_2e/m^3 for the 20-year NZB. GWP of the on-site materials at the 20-year NZB are about 1.4 times higher than the GWP of electricity use, while other studies have found materials to account for anywhere between half to 3 times the GWP of electricity use (Cornejo et al., 2016; Hendrickson et al., 2015). These differences are likely due to the different components and energy requirements within each of the studied systems, particularly associated with septic tank aeration, end-use of the treated water, and different electricity sources.

3.3.2 NZB's direct emissions, energy, and material use

To further understand the results, it is helpful to more thoroughly analyze the sources of the highest impacts within the NZB's direct emissions, electricity use, and material use shown in Figure 6.

An important contributor to the NZB's GWP is the direct on-site emission of methane (CH_4), and nitrous oxide (N_2O). The NZB's septic tank CH_4 emissions were found to be 8 kg CH_4/year (200 kgCO_2e), and its N_2O emissions were 73 g N_2O/year (22 kgCO_2e). The total septic tank GWP contribution was 222 kg CO_2e/year (15-22% of total GWP), while the total contribution of the CW to the NZB's GWP was only 57 kg CO_2e/year (4-6% of total GWP). The NZB's septic tank emissions are relatively low due to its aeration, and are comparable to those of another study that employs a similar treatment technology; this study found the direct emissions to account for 17% of the GWP (Cornejo et al., 2016). *In contrast, if the septic tank was not aerated, its CH_4 emissions would be 4,052 kgCO_2e/year, amounting to 80-87% of the NZB's total GWP*. This estimation is consistent with another recent study that reported its anaerobic settling tank to cause 90% of the treatment system's GWP impacts (Hendrickson et al., 2015). Aerating the NZB septic tank proved to be an important decision preventing significant GWP contributions. There is a tradeoff, however, between aeration and non-aeration; the electricity consumption of the aerator accounts for 24% of the total annual operational electricity use of the NZB's water system. This additional electricity requirement then increases impacts across all impact categories.

On-site PV panels provide most of the electricity for the NZB, and although PV is a renewable energy source and has no direct emissions during its use-phase, it has embodied impacts associated with the production of the panels and other components (e.g. framing, wiring, and inverters) (Fthenakis et al., 2011). The 'Reuse' electricity in Figure 6 accounts for the electricity use of the septic aerator, pumps, and reuse UV treatment, while the 'Rainwater' electricity accounts only for the rainwater UV treatment. The impacts of electricity consumption are mainly associated with the septic tank aeration (24% of electricity related impacts) and the UV treatment dedicated to treating rainwater (56%). Rainwater is seldom used for the NZB's water service; however, close to the 1,700 gal of water in the tank is cycled through the treatment system each night. This inefficiency has been identified as one of the biggest areas of improvement within the NZB's water system.

The initial impacts from the site materials (not including PV), as shown in Figure 7 are largely derived from steel, cast iron, and various plastics (HDPE, ABS, and polypropylene). Periodic replacement of pumps and components within the UV treatment system (UV lamps, filters, and pressure tanks) then contribute to impacts during the use phase of the NZB. Steel and cast iron are major contributors to the overall material impacts due to the large quantities used throughout the system and the materials' energy intensive production processes. Steel was used as reinforcement in concrete structures (manholes, septic tank, etc.), for the enclosure of the UV treatment units, and in various components of the UV system. Cast iron was used in manhole access frames and covers, cleanout covers, and some manhole air vents. HDPE tanks, piping, and liners account for large portion of fossil fuel depletion and embodied energy, mostly due to petroleum production and combustion of natural gas. These plastic materials were assumed to contain 25% recycled content, as per LEED requirements.

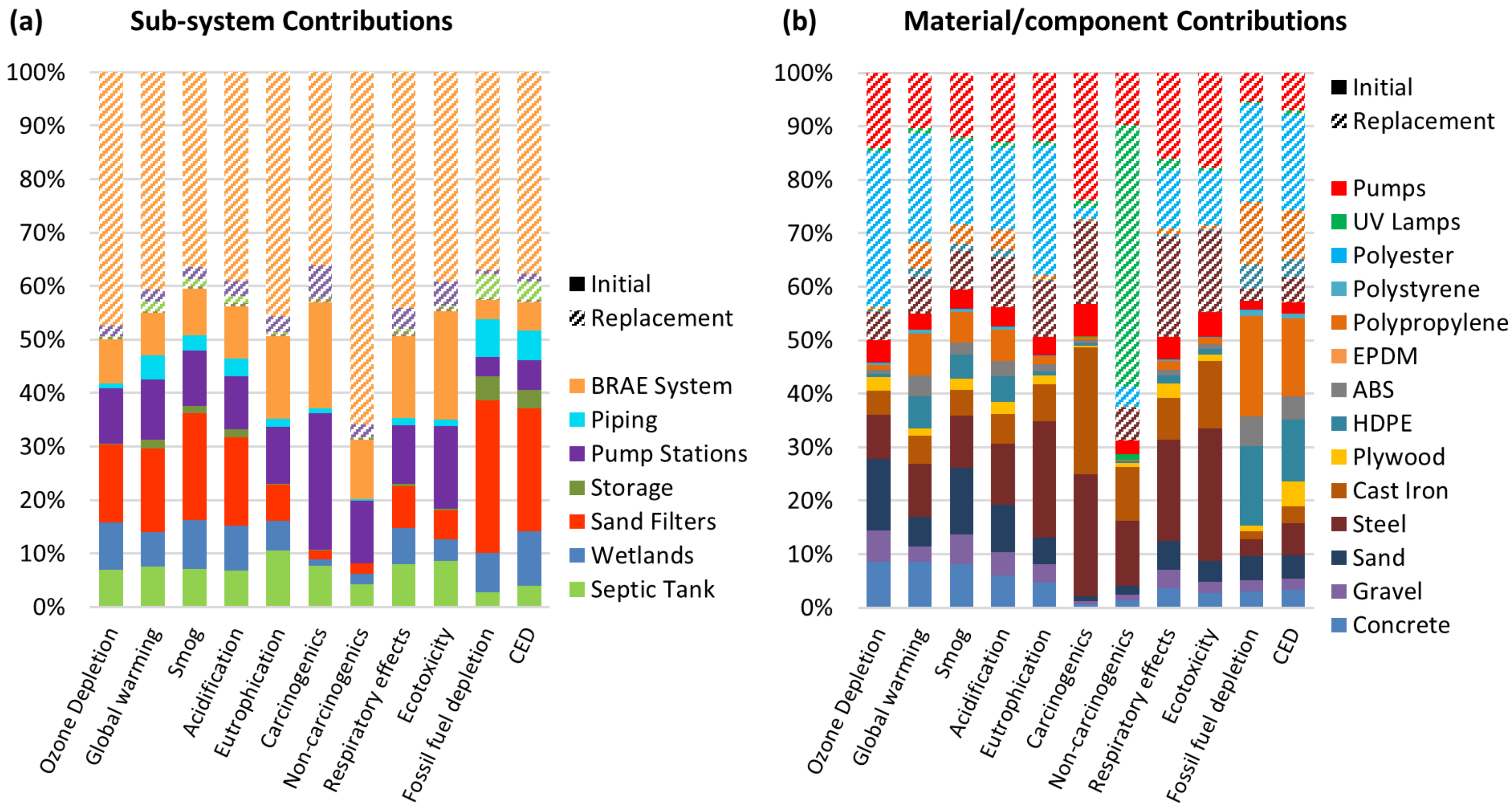

Figure 7. Relative life cycle impact contributions.

Relative life cycle impact contributions of the net-zero building's (NZB) water system materials identified by sub-systems (a) and by materials (b). Replacement impacts represent the total lifetime replacements for the 100-year NZB. Direct emissions, PV electricity, and water treatment plant impacts are excluded from this figure. (CED = Cumulative energy demand)

3.3.3 Limitations & Future Work

One of the central limitations of this study is the use of the adapted ecoinvent unit processes for WTP and WWTP. While generic treatment processes for the two local treatment plants accurately reflect electricity and natural gas consumption, the lack of other plant-specific information (e.g., chemical inputs and waste streams) and modeling of the regional infrastructure (e.g., piping and reservoir network) results in a generic model that may not accurately reflect the actual system in every detail. It is possible that the comparative results would change if these facilities and networks were modeled in greater detail; however, data necessary for such modeling was not available. A future study involving the variability in WTP and WWTP technologies and regional network modeling in conjunction with a comparative analysis of buildings would help in the overall understanding of the two systems.

A future study might better consider the local implications of decentralized water treatment and stormwater management in a centralized combined sewer system, as exists in Pittsburgh. This LCA considered the benefits of the NZB preventing treated wastewater from entering natural waterways. However, it did not measure the benefit that the NZB's stormwater management system has in minimizing the building's contribution to combined sewer overflows (CSO's), nor did it measure the reference buildings' contribution to CSO's via their runoff. Additionally, our study does not consider all the runoff from the reference buildings that is treated as wastewater in a WWTP during non-overflow conditions. This analysis would require sampling or assumptions on runoff water-quality, information on the reference buildings' contribution to local CSO's, and regional water quality data for CSO duration; none of this data was available for this study.

Further study might also consider the break-even point for the scale of decentralized water and wastewater systems; it is possible that, in terms of life cycle environmental impacts, a decentralized water system might better serve a small community than a building. The CSL building does not necessarily represent the future state-of-the-art of decentralized systems; rather, it presents a unique opportunity to analyze possible configurations of decentralized systems. For policymakers attempting to transition into a more sustainable water paradigm, systems analysis is an extremely important precursor to implementing new approaches.

3.4 CONCLUSION

As we design and renovate high-performance buildings, it is important to recognize and consider the potential tradeoffs of advanced decentralized water/wastewater treatment systems so that informed decisions are made beyond the prescriptions of well-intended rating systems. The results show that environmental benefits of decentralized water systems are dependent upon lifetimes, and as such, it would be prudent to have explicit lifetime discussions during design decisions. The results also show that these environmental benefits are dependent on material use, which could potentially inform designers to attempt to reduce the use of high-impact materials. Furthermore, when decentralized wastewater treatment systems include septic tanks, designers should consider implementing aeration, energy recovery, and/or emissions control measures to prevent these subcomponents' high global warming potential impacts.

Operation and maintenance of high-performance systems and buildings can also impact the overall environmental performance. One illustrative example is the frequency of water recirculation in the storage tanks—not all of the water in the two main storage tanks is used for everyday activities; rather, it is cycled through the treatment system every night to prevent supposed water quality deterioration. This frequency is based on manufacturer's guidelines as opposed to performance-based measures, and largely dictates the system's electricity usage. The NZB could lower its energy use if the water recirculation was adjusted to the current demand.

While LCA and systems approaches can provide important insights, the results can be limited as there are region specific advantages not represented in LCA results. For example, the benefits of this system in a water scarce region may outweigh any of the investigated environmental impacts. There are undeniable positive social aspects of the NZB in terms of community and education that are not quantified by LCA but are also sustainability issues that may make projects like the NZB valuable even with technological challenges.

4.0 THE STATE OF LCA FOR SEISMIC DAMAGE REPAIR

This chapter is the first part in addressing Objective B, focusing on understanding the various approaches to including repair of seismic damage in building LCA. The content of this chapter is based on an article titled *Review of approaches for integrating loss estimation and life cycle assessment to assess impacts of seismic building damage and repair* published in the journal *Engineering Structures* (Hasik et al., 2018). An adapted version of the article is being reused with permission from Hasik, V., Chhabra, J. P. S., Warn, G. P., & Bilec, M. M. (2018). Review of approaches for integrating loss estimation and life cycle assessment to assess impacts of seismic building damage and repair. Engineering Structures, 175, 123-137. doi:https://doi.org/10.1016/j.engstruct.2018.08.011. Copyright 2018 Elsevier. The author of this dissertation contributed by reviewing the LCA methods and connection to earthquake engineering. Appendix B provides supporting information related to this chapter.

4.1 INTRODUCTION

Buildings have long been known to consume significant amounts of the world's energy and material resources and are expected to provide people with healthy and safe working and living conditions (William O Collinge et al., 2013; Phillips et al., 2017; Ruuska & Häkkinen, 2014). Sustainability (i.e. the ability to maintain a certain level of function through responsible use of resources) and resilience (i.e. the ability to absorb and quickly recover from disturbances) have emerged as important characteristics being used to evaluate the performance of buildings. Advances in computer technologies and the development of various assessment methods related to sustainability and resilience allow us to analyze and optimize energy, material, health, and safety performance aspects of buildings in the design phase (De Wilde & Coley, 2012). However, buildings are complex systems that are difficult to model and analyze holistically, which means that application of such assessment methods can yield results that may be incomplete, inconsistent, or difficult to validate. This issue of inconsistency between model results has occurred in building energy modelling (Schwartz & Raslan, 2013), embodied energy estimates (Dixit et al., 2010), and life cycle assessment (Al-Ghamdi & Bilec, 2016; Takano et al., 2014), and has also been highlighted in the area of seismic damage environmental impact estimation (Wei, Skibniewski, et al., 2016). Wei, Skibniewski, et al. (2016) previously compared results from multiple studies estimating seismic repair related environmental impacts in terms of embodied energy and found that their results ranged from 2 to 50% of the total building life cycle embodied energy. The large range in the results between studies can be attributed, in part, to different buildings being analyzed, but also due to the differences in methods used for the life cycle assessment and embodied energy.

The literature in the integration of seismic loss assessment and life cycle assessment has grown substantially in the past few years, yet a consensus has not been formed on the best approach. This chapter provides an overview of the approaches to estimating environmental impacts of seismic damage to buildings and investigates the main factors influencing the results and conclusions of this type of assessment. The core studies presenting such approaches are listed in Table 1 and have three aspects in common: (1) they include one or more environmental impact metrics, (2) they utilize damage assessment methods specific to earthquakes, and (3) they develop or apply the assessment methods to buildings. While a number of studies from 2014 and earlier defined their own loss estimation methods (Arroyo et al., 2015; Chiu et al., 2012; Dong & Frangopol, 2015; Menna et al., 2013; Padgett & Li, 2014; Sarkisian et al., 2011; Sarkisian et al.,

2014) (defined as 'other' in Table 1), performance-based earthquake engineering (PBEE) framework has been frequently cited in studies published in 2014 and later (Alirezaei et al., 2016; Belleri & Marini, 2016; J. P. Chhabra et al., 2018; Gencturk et al., 2016; Hossain & Gencturk, 2014; Simonen et al., 2015; Welsh-Huggins & Liel, 2014, 2016, 2017). The Hazus software tool has been used by researchers in this field from the beginning, with only one study using the default regional data (Feese et al., 2014), while most applying building-specific information via the Advanced Engineering Building Module (AEBM) (Comber et al., 2012; Comber & Poland, 2013; Wei, Shohet, et al., 2016; Wei, Skibniewski, et al., 2016). Environmental impacts have been assessed either by using life cycle assessment (LCA) tools and life cycle impact assessments results (e.g., global warming potential, eutrophication potential, etc.) or by applying greenhouse gas emissions factors (defined as 'CO_2 factors' in Table 1). Most studies focusing on the assessment of structural systems have used CO_2 factors or process-LCA to obtain environmental impacts, while studies including non-structural components have used Economic Input-Output-LCA (EIO-LCA) *or* process-LCA. The damage to impact conversion has been done either by using damage costs as an input to EIO-LCA, by using repair-cost ratios to convert from initial to repair impacts, or by developing data specific to damage descriptions (J. P. Chhabra et al., 2018; Welsh-Huggins & Liel, 2014, 2016, 2017).

The development and further refinement of the integrated seismic loss and environmental assessment methods is important for improving the design of resilient and sustainable buildings, by enabling designers and stakeholders to evaluate tradeoffs and identify optimal design alternatives (Calvi et al., 2016; Hasik, Chhabra, et al., 2017). This chapter aims to provide an

Table 1. Studies bridging seismic loss and environmental impact assessment for buildings.

Authors	Year	Publisher	Seismic Loss Method	Environmental Impact Method	Damage to Impact Conversion Method
Chhabra et al.	2017	J. Arch. Eng.	PBEE	Process LCA (SimaPro)	Description + LCA
Welsh-Huggins & Liel		Struct. Infrastruct. E.	PBEE	Process LCA (SimaPro)	Description + LCA
Alirezaei et al.	2016	ICSDEC Conf.	PBEE & Hazus	Process LCA (Tally)	Cost ratio
Welsh-Huggins & Liel		IALCCE Conf.	PBEE	Process LCA (SimaPro)	Description + LCA
Wei et al.		J. Arch. Eng.	Hazus AEBM	CO_2 factors	Description + factors
Wei et al.		J. Perform. Constr. Fac.	Hazus AEBM	CO_2 factors	Description + factors
Dong et al.	2015	Earthq. Eng. Struct. Dyn.	Other	CO_2 factors	Description + factors
Gencturk et al.		J. Arch. Eng.	PBEE	Process LCA (Other)	Description + LCA
Belleri & Marini		Energy & Buildings	PBEE	CO_2 factors	Description + factors
Arroyo et al.		Earthquake Spectra	Other	CO_2 factors	Cost ratio
Simonen et al.		Structures Congress	PBEE	EIO-LCA	EIO-LCA
Padgett et al.	2014	J. Perform. Constr. Fac.	Other	Process LCA (Athena)	Cost ratio
Welsh-Huggins & Liel		IALCCE Conf.	PBEE	Process LCA (Athena)	Description + LCA
Sarkisian et al.		Sustainable Struct. Symp.	Other	CO_2 factors	Description + factors
Hossain & Gencturk		Eng. Struct.	PBEE	Process LCA (Other)	Description + LCA
Feese et al.		J. Perform. Constr. Fac.	Hazus	Process LCA (Athena)	Cost ratio
Comber & Poland	2013	Structures Congress	Hazus AEBM	Input-Output LCA	EIO-LCA
Chiu et al.	2012	J. Arch. Eng.	Other	CO_2 factors	Cost ratio
Comber et al.		Structures Congress	Hazus AEBM	Input-Output LCA	EIO-LCA
Menna et al.		Int. J. LCA	Other	Process LCA	Description + LCA
Sarkisian et al.	2011	AEI Conf.	Other	CO_2 factors	Description + factors

(PBEE = Performance-based Earthquake Engineering, AEBM = Advanced Engineering Building Module, LCA = Life Cycle Assessment, EIO = Economic Input-Output) overview of relevant methods, discuss the application of those methods to case studies and hypothetical scenarios, and identify areas needing further development in order for the approaches to have practical usefulness and consistency for design decision making.

4.2 SEISMIC LOSS ESTIMATION METHODS

Most of the studies considering environmental impacts of buildings due to damage from earthquakes have broadly based their approach on a variety of seismic loss estimation methods. As shown in Table 1, most studies have referred to the Performance Based Earthquake Engineering (PBEE) method (Moehle & Deierlein, 2004), and have used tools and databases developed by the Pacific Earthquake Engineering Research Center (PEER) to relate the structural performance of a building with monetary and other losses (i.e. downtime and casualties) following an earthquake. Some studies have described independent means of estimating probabilistic seismic loss (described as 'other' in Table 1), integrating the different phases of seismic performance assessment to evaluate the environmental performance of buildings. Lastly, the software tool Hazus, developed by the Federal Emergency Management Agency (FEMA), has been used by some studies.

All three groups of seismic loss estimation methods (PEER, Hazus, and other approaches) broadly follow a four step assessment: (1) hazard quantification at the site of interest, (2) evaluation of structural behavior under hazard, (3) estimation of damage in different building components conditioned on the estimated structural response, and (4) calculation of losses to repair/renew different components, as illustrated in Figure 8. Although Hazus describes its calculation module as a six-step approach (Kircher et al., 2006), its method of estimating direct building loss is similar to the general four-step approach, with the exception that hazard and damages are directly correlated by using empirical data and expert judgement, and structural analysis of a building is not explicitly performed. The other variations within studies using similar loss estimation methods are in the different approaches to structural analyses and the translation of damages to environmental impacts. Figure 8 also shows examples of when and which software tools and databases are used in the earthquake engineering part of the assessment as well as the life cycle environmental impact assessment. The list of tools and databases is not exhaustive, but rather an example of what researchers have used for the life cycle environmental impact assessment of seismic damage repair.

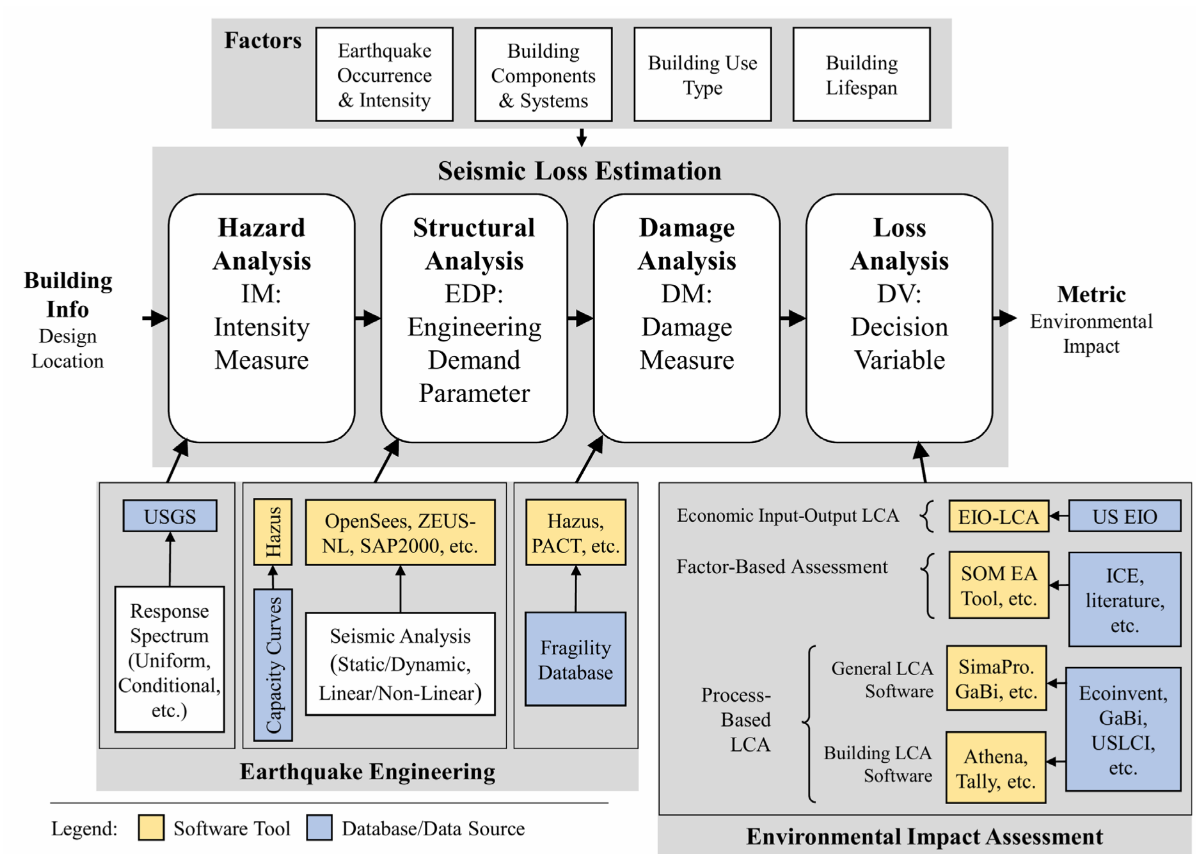

Figure 8. Overview of methods for seismic loss estimation and life cycle assessment.

The tools and databases shown are examples of the typically used resources and are not exhaustive.

4.2.1 Performance-Based Earthquake Engineering

Performance-based earthquake engineering (PBEE) methodology was developed in addition to code-based building design in seismically active regions as a means of communicating the performance of design alternatives to decision-makers (Moehle & Deierlein, 2004). PBEE is based on building specific and component specific damage and repair cost functions and consists of the four main steps shown in Figure 8, which have also been identified as the main steps in general seismic loss estimation (i.e., hazard, structural, damage, and loss analyses).

Hazard analysis constitutes the quantification of seismic hazard at the site of interest. The seismic hazard is probabilistically described using empirical relationships that relate the earthquake intensity measure (IM) with its Mean Annual Rate of Exceedance (MARE), $\lambda_{IM}(im)$ (average number of times an intensity measure will be exceeded per annum). Peak ground acceleration, peak ground velocity, peak ground displacement, and spectral acceleration are all widely used intensity measures, but the spectral acceleration (SA) at the fundamental period of the structure is the most commonly used intensity measure (Shome et al., 1998). In order to improve the explanatory power of scalar intensity measures, vector-valued intensity measures comprising the magnitude of seismic event, source-site distance and an ε parameter (the ε parameter is used to quantify the deviation of the target SA at fundamental period from the median SA at fundamental period predicted by any relevant ground motion prediction equation) have been proposed in the literature (Baker & Allin Cornell, 2005). However, it was recently shown that the response of realistic structures, i.e., complex, non-linear dynamic systems, subjected to seismic acceleration are weakly correlated with spectral acceleration when used as scalar/vector-valued intensity measure (Grigoriu, 2016).

Structural analysis estimates demand on structural members under the quantified hazard. The outcomes of structural analysis are, for example, inter-story drifts, floor velocities, and floor accelerations, that are collectively referred to as engineering demand parameters (EDPs). There are four classes of structural analyses typically used: linear static (e.g., equivalent lateral force method), linear dynamic, nonlinear static (i.e., pushover), and nonlinear dynamic. The computational time increases with the complexity of the structural analysis, from linear static to nonlinear dynamic, and the feasibility of using each of these methods is dependent on the size and complexity of the analyzed structure and set of design alternatives (American Society of Civil Engineers, 2007). For example, simplified analyses using static models and linear analyses can only be used for buildings regular in their floor plans and elevations, having less than 15 stories, and having story drift ratios less than 4 times the yield drift ratio, among other limitations (Federal Emergency Management Agency, 2012a). Conversely, nonlinear dynamic analysis can be used for performance assessment of any structure and any ground shaking intensity (Federal Emergency Management Agency, 2012a). Although it is widely recognized that nonlinear dynamic analysis produces the most accurate estimates of the EDPs for multi-degree-of-freedom building systems, it is computationally expensive. As a result, many researchers have sought lower-fidelity analyses (e.g. linear static and nonlinear static) as a proxy for nonlinear dynamic analysis to lessen the computational burden while producing reasonably accurate estimates of the EDPs. A few of the seismic loss and environmental impact studies have conducted both nonlinear static and dynamic analyses to obtain local and global engineering demand response parameters (Gencturk et al., 2016; Welsh-Huggins & Liel, 2014). Welsh-Huggins and Liel (Welsh-Huggins & Liel, 2014, 2017) performed nonlinear static analysis as a preliminary analysis to study the basic building characteristics like ductility capacity and overstrength ratio, following which, dynamic response history analyses were performed to characterize life cycle environmental impacts. Similarly, Gencturk et al. (2016) performed nonlinear static analysis to determine maximum roof displacement in order to estimate collapse in response history analysis. Other studies following the PBEE methodology have used nonlinear dynamic analysis (J. P. Chhabra et al., 2018; Hossain & Gencturk, 2014; Simonen et al., 2015), while Belleri and Marini (2016) was the only study found to rely solely on nonlinear static analysis.

Damage analysis is a step in which damage in different components is categorized into various discrete states on the basis of the damage severity. These discrete damage states are characterized by fragility curves that represent the conditional probability of exceedance of a given damage state conditioned on the EDPs obtained from structural analysis. The outcomes of damage analysis are damage measures (DMs), which represent the probabilities that different structural and nonstructural components are in each of the discrete damage states. The selection of the type of EDPs depends upon the scope of a study and its component selection which is further discussed in section 4.3.1. Generally, structural systems are prone to damage due to drifts, while non-structural components can be damaged by both drift and acceleration demands. Drift sensitive components are generally considered in all studies, while acceleration sensitive components are considered less often but have been shown to contribute considerably to the repair impacts and costs (J. P. Chhabra et al., 2018; Comber et al., 2012). The use of lower-fidelity structural analysis, such as nonlinear static, requires estimation of the acceleration related EDPs from the drift related EDPs that introduces error, or inaccuracy, into the overall estimate of the EDPs for loss assessment. Some studies have chosen to ignore acceleration EDPs altogether while others have used empirical relationships to relate acceleration related EDPs to drift related EDPs in lieu of performing nonlinear dynamic analysis. However, omission and or approximation has its consequences. For example, a study by J. P. Chhabra et al. (2018) reported acceleration sensitive components to account for about 6% of the total repair related global warming potential over the life of an office building, while Comber et al. (2012) estimated that in certain building types it may be up to about 38%.

The last step of the PBEE framework, **loss analysis**, translates previously obtained damage measures into losses, which are quantified by decision variables (DV). The decision variables allow the design to be quantified in terms of broad metrics that can easily be communicated amongst the design team and decision-makers, and roughly include metrics representing, cost, casualties, and downtime (Federal Emergency Management Agency, 2012a). Clearly, environmental impacts represent losses and thus can be quantified in terms of a decision variable, as illustrated by the growing literature in this area and summarized in Table 1. The different approaches to translating damages to environmental impacts are further discussed in section 4.3.3.

The PEER's PBEE framework and the relevant work done by various researchers on performance based seismic design culminated into a series of volumes collectively referred to as FEMA P-58. FEMA P-58 team has also developed an assessment tool called the Performance Assessment Calculation Tool (PACT), based upon the PEER methodology, which has been used by various researchers to perform damage analysis and loss analysis (Alirezaei et al., 2016; Belleri & Marini, 2016; Gavridou et al., 2014; Sullivan et al., 2014). This tool contains fragility curves and damage descriptions for typical structural and non-structural components used in building construction in order to estimate seismic losses. At the current stage this tool can be used to estimate losses in terms of repair cost, repair time, casualties and injuries. Various researchers have adapted the results of the tool and have added custom fragilities in order to estimate the environmental impacts due to seismic damage (Alirezaei et al., 2016; Belleri & Marini, 2016;

Welsh-Huggins & Liel, 2014). J. P. S. Chhabra et al. (2017) also used the PEER developed fragility database for damage analysis, but without the use of the PACT tool, while Dong and Frangopol (2015) and Gencturk et al. (2016) used literature based values to determine fragilities for select components. More recently, Simonen et al. developed a database of environmental impacts for the full list of component damages in the PACT tool by using the tool's original damage cost estimates and EIO-LCA environmental impact data (Simonen et al., 2018; Simonen, Huang, et al., 2017). It is worth noting that the FEMA P-58 methodology has largely been adopted by Haselton Baker Risk Group toward a comprehensive tool called Seismic Performance Prediction Program (SP3) that can be used by researchers and engineers to assess seismic damage, losses and building repair time.

4.2.2 Hazus-MH

Hazus is used to estimate monetary and social losses primarily at a *regional* scale. The scope of analysis is broader than PBEE which has traditionally been used for assessment at the building scale, as its methodology includes losses due to ground failure, damage to lifelines and transportation systems, inundation, and fire following earthquakes. The direct economic loss estimates also account for both cost of repair and replacement of damaged components as well as non-material costs (e.g., income loss, relocation costs, etc.) (Kircher et al., 2006), which may create problems when relating damage costs to environmental impacts via economic cost ratios or economic input-output LCA, as is further discussed in section 4.3.3.

Hazus uses the capacity spectrum approach to calculate the ultimate spectral displacement of a *building type* under a user defined hazard. The structural capacity is described in terms of the capacity curves which are characterized by the design capacity, that is yield capacity and the ultimate capacity of the structural system. The structural capacities are obtained by choosing a set of parameters which are the function of the type of primary structural system (e.g., steel braced frame or reinforced concrete shear wall), height of the building and the degree of code compliance of the building. The capacity spectrum approach idealizes the multi-degree-of-freedom (MDOF) system as a single-degree-of-freedom (SDOF) system. While this idealization may give consistent results for low-rise buildings or buildings whose response is dominated by the first mode, the contribution of higher modes of vibration can be significant, in particular for tall buildings, which may render the results coarse approximations at best. Hazus has been found to use structural analysis that ultimately leads to underestimation of damages and related losses (Ramirez et al., 2012). The building specific structural frame design is also not explicitly considered in the standard version of Hazus, but its Advanced Engineering Building Module (AEBM) allows for import of custom damage and loss functions for a specific building design (Kircher et al., 2006). Five out of the 21 main studies in Table 1 used Hazus within their framework, three of which used the AEBM module (Comber & Poland, 2013; Feese et al., 2014; Wei, Shohet, et al., 2016; Wei, Skibniewski, et al., 2016). Some studies have used data developed for Hazus but have not used the tool itself (Alirezaei et al., 2016; Arroyo et al., 2015; Sarkisian et al., 2014).

4.2.3 Other approaches

Studies described as ‘other’ in Table 1 defined their own overall approach, but often implement methods and tools similar to those within PEER/PBEE and Hazus. For example, Arroyo et al. (Arroyo et al., 2015) used fragility curves from Hazus to quantify the structural, non-structural, drift, and acceleration based damages specific to a building type (i.e., low-rise, multi-family dwellings with steel and concrete moment frames conforming to high code). They constructed their own hazard curves via Probabilistic Seismic Hazard Analysis (PSHA) procedure, performed structural analysis using Incremental Dynamic Analysis (IDA) (Vamvatsikos & Cornell, 2002), and then calculated repair cost ratios based on vulnerability functions constructed from the previously obtained IDA and fragility curves. A software tool developed by Sarkisian et al. (2014) also uses Hazus based damage estimates for conventional structures but applies independent empirical methods for the assessment of enhanced structures (e.g., base isolated structures).

Other studies have used tools and databases developed by FEMA and PEER for parts of their assessments, together with methods described in the literature. For example, OpenSees structural analysis platform (Mazzoni et al., 2006) and the PEER hazard database have been used with other methods (Dong & Frangopol, 2015; Padgett & Li, 2014). A study by Dong and Frangopol (2015) focused on computational description of the sustainability and resilience of buildings based on previous work by Cimellaro et al. (2010). Within this study, the authors described a set of additional equations for resilience assessment (i.e., considering recovery time and functionality) and performance-based seismic assessment (i.e., vulnerability and consequences of structural failure). Chiu et al. (2012) adopted the empirical model developed by Park and Ang (1985) to evaluate the earthquake induced structural damage by approximating the MDOF structural system as an equivalent SDOF system. Menna et al. (2013) used the methodology for multi-hazard analysis proposed by Jalayer et al. (2011), together with damage descriptions from FEMA 273 (Federal Emergency Management Agency, 1997). They used nonlinear static analysis on a model with SDOF (Menna et al., 2013) and then used component level damage descriptions to define system level (e.g., elevation structures, nonstructural, water and electrical systems, etc.) damage ratios.

There is a multitude of modeling approaches and fidelities in seismic loss estimation; however, the accuracy of the various methods remains largely unknown. Varying degrees of fidelity can be beneficial, but only when the quality of the estimate is understood and general rules about using each approach have been established. There is a need for further validation of PBEE and/or careful sensitivity analysis to identify the primary sources of uncertainty in the loss assessment as well as the environmental assessment and the consequences of approximations.

4.3 INTEGRATION OF ENVIRONMENTAL & LIFE CYCLE CONCEPTS

Life cycle thinking can be used to analyze the environmental impacts of products and processes. For this reason, life cycle assessment (LCA) was developed as a tool for quantifying environmental impacts of products and processes (ISO, 2006), and although it is not the only way of conducting an environmental analysis, its underlying concepts are applicable to any environmental analysis. According to the ISO 14040 standard, LCA studies should include goal and scope definition, inventory analysis, impact assessment, and interpretation of results (ISO, 2006). These steps are to ensure maximum transparency and context for a given analysis and allow for fair comparisons between products or processes. Later, the ISO 21931 standard for assessment of environmental performance of buildings was developed with the aim to standardize the goal, scope and inventory required for environmental analyses of buildings (ISO, 2010).

LCA uses product, material, or process models to track energy, resource, and waste exchanges between and within the natural environment and technosphere (i.e., any engineered product or process that does not occur naturally). The exchanges are all treated as quantitative measurements; for example, generating 1 kWh of electricity from coal could require an input of

0.58 kg of coal and result in an output of 1.10 kg of carbon dioxide into the air. The models typically span the following life cycle stages: raw material extraction, manufacturing, construction, operation, maintenance, repair, end-of-life, and transportation. The inputs and outputs from a model can be further translated from their raw form (e.g., carbon dioxide, methane, etc.) to impact categories (e.g., global warming potential). There are numerous impact assessment methods that use different models to translate raw exchanges into specific impact categories, with the goal to provide results that can be used for decision making (Hischier et al., 2010).

4.3.1 System scope, detail, and comparability

The scope definition in building LCA consists of identifying components included in the assessment, as well as defining the life cycle stages included in the assessment. The ISO 21931 standard for the environmental assessment of buildings divides the life cycle stages into pre-use (i.e. extraction, manufacturing, construction), use (i.e. energy use, water use, maintenance, repair, replacement, refurbishment), and end-of-life stage (i.e. demolition, waste processing, disposal) (ISO, 2010), and a more recent European standard also added a 'beyond life' stage addressing reuse, recycling and recovery potential (EN, 2011). From the perspective of seismic loss assessment, there are two component groups: structural and non-structural. Structural components of a building include soil, foundation, and structural frame, while non-structural group includes all other components, such as envelope, interior, furnishings, service equipment, and others (Federal Emergency Management Agency, 2012b). Previous studies have found structural systems to account for 16 to 65% of the embodied energy in the construction of new buildings (Cole & Kernan, 1996; De Wolf, 2014); however, they typically sustain less damage during disruptive events than non-structural components which are typically more fragile and vulnerable to both drifts and accelerations at lower ground shaking intensities (J. P. S. Chhabra et al., 2017; Comber et al., 2012; Dong & Frangopol, 2015; Menna et al., 2013; Simonen et al., 2018; Welsh-Huggins & Liel, 2016). These findings show one of the reasons why it is important to include non-structural components within the assessment of seismic resilience. Even though not all non-structural components may affect the strength and stiffness of a building, they all can be expected to contribute to the absolute damage and losses due to an earthquake.

Both structural and non-structural components can be further divided into conventional and specialty components, where conventional components may be considered as part of baseline or code-based systems (such as typical structural frames, envelope systems, etc.), while specialty components may include structural enhancements (such as base isolation, damped outrigger, etc.) or components typical to green or high performance buildings (such as green roofs, solar panels, etc.). Conventional components have been most studied based on the relatively good availability of data (both component fragility and environmental impact data) (Welsh-Huggins & Liel, 2014). Specialty components have also been studied; although, they typically depend on additional structural response and environmental impact investigations. For instance, Welsh-Huggins and Liel investigated the structural performance of buildings with conventional and vegetated roofs (Welsh-Huggins & Liel, 2014), for which they developed material inventory and fragility curves based on previous literature. The structural reliability and cost benefits of enhancements such as isolation systems and viscous dampers have been studied using reliability-based assessments and life-cycle costing (LCC) (Alhan & Gavin, 2005; Castaldo et al., 2016; Jia et al., 2014; Tubaldi et al., 2014), but there has not been a study conducting full process-based LCA of these systems. Three studies have investigated differences in damage related impacts in buildings with base isolation systems (Dong & Frangopol, 2015; Sarkisian et al., 2014; Simonen et al., 2015), but only one considered the additional material and production requirements of putting the base-isolation system in place (Simonen et al., 2015). The studies focused on the decreased vulnerability of the building and subsequent reductions in probable seismic damage, and either did not include the environmental implications of installing the systems, or considered it via a percentage increase in cost and applying Economic Input-Output Life Cycle Assessment (EIO-LCA) (Simonen et al., 2015). A full-scale, ISO-compliant, process LCA study of base isolation systems, amongst other specialty systems, could help benchmark the results obtained previously based on cost-ratios or EIO-LCA and would provide additional insight into the environmental cost-benefit of putting such systems in place. It is imperative that more data on specialty systems is developed, if these analyses are to be used confidently for the design of sustainable and resilient buildings.

The selection of components included in an analysis also affects the relative outcomes and conclusions of the analysis, especially if multiple factors and performance metrics are to be compared. For example, including only structural elements and a single environmental impact category in an analysis comparing lifetime casualties with environmental impacts will likely skew the recommendations towards minimizing direct casualties, as seen in Wei, Shohet, et al. (2016). In contrast, including all possible building components (both structural and nonstructural) and a combination of environmental impacts (spanning global warming potential, embodied energy, respiratory impacts, etc.) may result in higher absolute environmental impacts and could make the indirect consequences of environmental impacts more comparable to those of the direct economic losses and casualties from seismic events. This issue of comparability of various metrics (i.e. monetary costs, casualties, and environmental impacts) is also largely dependent on the ability to convert from units of one metric to the other, which is often subjective and situational. The typical approach has been to convert non-monetary metrics to monetary ones. For example, global warming potential impacts typically in units of kg carbon dioxide equivalent (CO_2 eq.) have been converted to monetary costs by applying proposed or enacted carbon tax rates (Arroyo et al., 2015; Wei, Shohet, et al., 2016); however, there is no universally agreed upon carbon tax rate and the proposed and implemented rates have spanned from less than 1 U.S. dollar to over hundreds of U.S. dollars per ton of CO_2 (Arroyo et al., 2015; Clarkson & Deyes, 2002; World Bank, 2016). Similarly, fatalities have been estimated at different rates and monetary values, resulting in studies finding that direct repair costs may be higher than fatality costs (Dong & Frangopol, 2015) but also the opposite (Wei, Shohet, et al., 2016).

Another factor determining the scope and detail of a building LCA is the overall goal. There are typically two types of LCA studies based on the goal: 1) assessing the absolute impacts of a single building, and 2) comparing the relative differences between two buildings. The first type can be exhaustive when applied to whole building LCA studies, or it can be focused on assessing individual building systems, but in both instances the focus is on analyzing the contribution of individual elements to the whole. This type of studies should include all aspects falling within the defined study boundary and satisfying any cut-off rules (e.g. any component contributing to at least 1% of the building's total mass should be included) (ISO, 2017). The second type, a comparative study, focuses on comparing the differences between two buildings. In comparative studies, it is generally required to compare buildings that provide the same function (i.e. same space and use-type assessed over the same time period) (EN, 2011), but unlike in the single building assessment, not all components have to be included. Components that are identical in the compared buildings can be excluded based on the general assumption that their impacts would not differ. It should be noted that this assumption is only valid in cases where the structural performance of a building does not change or affect results of the assessment and should therefore not be used in studies including seismic losses. For example, if there are two buildings that differ only in the type of structural system and have the same envelope systems, then typical comparative LCA studies may choose to exclude the envelope system from the assessment; however, in studies assessing the seismic repair impacts the damages to the envelope system may differ due to differences in the performance of the structural systems even though the envelope systems are the same in both buildings (Dong & Frangopol, 2015), and should therefore not be excluded. In other words, the building should be treated as a system and the performance of one component is dependent (to varying degrees) on the performance of other components and systems.

4.3.2 Environmental impact data

Environmental impact data can be obtained from LCA databases, emission factor databases, literature, etc. Process-based LCA, sometimes referred to as bill-of-materials LCA, requires information about individual material quantities and processing needs. For example, a process-based LCA of a curtainwall glass panel might require data regarding the weight of glass used, amount of electricity used in shaping and cutting the glass, and the distance transported from the manufacturing plant to the construction site. This approach can rely on commercially developed databases such as USLCI or ecoinvent (Franklin Associates, 1998; Weidema et al., 2013), but allows for customization.

EIO-LCA requires product cost information, which can be obtained from cost-estimating resources such as RS Means (RS Means, 2015), and is then translated into environmental burdens through economic sector data (Green Design Institute, 2002). EIO-LCA can be used for the assessment of buildings by either estimating the total cost of a whole building applied to a single sector best representing the building type (e.g. non-residential commercial and health care structures) or by applying individual component costs to more focused manufacturing sectors (e.g. ready-mix concrete manufacturing). The two mentioned approaches are herein called the 'Building EIO' and 'Component EIO' approaches, respectively. EIO-LCA is more comprehensive in the scope of its analysis, as it includes all production exchanges between industries within a country. The scope of process LCA is defined by the analyst and ISO guidelines and could vary from study to study (ISO, 2006). On the other hand, data used for process LCA is continuously being developed and updated, while EIO-LCA in the United States relies on data reported in 2002 and is unlikely to be updated in the near future (Green Design Institute, 2002). Process LCA can also be more applicable for the assessment of individual buildings as its data can be customized to reflect specific spatial and temporal setting, while EIO-LCA (in the U.S.) reflects national averages, and the data cannot be easily customized. Emission factors for specific environmental impacts can also be obtained from entities such as the Environmental Protection Agency (EPA) or from literature. Emissions factors can vary widely depending on the source, as shown in Arroyo et al. (2015).

It is important to note that each data source may include different life cycle stages (i.e., extraction, manufacturing, construction, operation, demolition, disposal, recycling, and transportation) within the specified boundary, which may result in inconsistencies if multiple databases are used interchangeably (Miller & Theis, 2006). While process LCA is often used to assess material related impacts, EIO-LCA also includes service-related impacts, for example the provision of architectural and engineering services. This needs to be considered when using EIO-LCA to obtain data specific to materials only and may require manual exclusion of any service-related impacts or vice versa, inclusion of service-related impacts when using process LCA. The problem is that the disaggregation of EIO-LCA data is fairly difficult undertaking due to the cascading interconnections of the sectors within the input-output framework (Treloar, 1997).

Process LCA data is generally more transparent and allows for easier understanding of effects of upstream processes, but even then, methodological differences can yield varying results (Al-Ghamdi & Bilec, 2016; Herrmann & Moltesen, 2015; Takano et al., 2014). Tools developed specifically for conducting process-based LCA of buildings, such as Athena Impact Estimator for Buildings (IE4B) (Athena Sustainable Materials Institute, 2017) and Tally (KT Innovations, 2017), sometimes use different methods for dealing with allocation of co-products, treatment of reuse, recovery, and recycling, and accounting for biogenic carbon, carbonation, and other aspects of LCA. It is expected that the tools will account for these aspects consistently in the future as new building LCA standards emerge. Some products and unit processes can be modeled independently to expand on the life cycle stages and products covered within existing databases but require additional modeling efforts and likely expert knowledge of LCA, as well as access to general LCA software such as SimaPro (PRé Consultants, 2015) or GaBi (Thinkstep, 2017). A more extensive list of life cycle databases and software and their applicability to different regions and applications can be found in Khasreen et al. (2009). Although the consideration of exact building systems, life cycle stages, and impact categories depends largely on the defined scope of each study, Table 2 shows the commonly included components and life cycle stages for tools and approaches used in seismic repair LCA studies.

Table 2. Component selection, life cycle stages, and impact categories across LCA tools.

Impact categories are based on TRACI 2.1 impact assessment method (Bare, 2012a). Solid dots depict commonly included aspects; hollow dots depict possible inclusion with additional effort.

		Building Systems							Life Cycle Stages							Impact Categories										
#	Method Description	Soil	Foundation	Structure	Envelope	Interior	Services	Furnishings	Manufacturing	Construction	Maintenance	Use	End-of-life	Transportation	Services	Embodied Energy	Global Warming	Ozone Depletion	Acidification	Eutrophication	Smog	Respiratory Effects	Carcinogenics	Non-carcinogenics	Ecotoxicity	Fossil Fuel Depletion
1	Building EIO	●	●	●	●	●	●	●	●	●				●	●	●	●	●	●	●	●	●	●	●	●	●
2	Component EIO	○	●	●	●	●	○	○	●	○	○	○		○	○	●	●	●	●	●	●	●	●	●	●	●
3	SimaPro (ecoinvent)	○	●	●	●	●		○	●	○	○	●	○	○		●	●	●	●	●	●	●	●	●	●	●
4	Athena IE4B		●	●	●	○			●	●	●	●	●	●		●	●	●	●	●	●	●				
5	Tally (GaBi)		●	●	●	●			●	●	●	●	●	●		●	●	●	●	●	●					
6	SOM EA Tool		●	●					●	●				●			●									

To illustrate the differences in the scopes and impact factors of the different LCA methods, tools, and databases, this study applied each of the previously used methods to a hypothetical demonstration building, a 9-story office building adapted from Gupta and Krawinkler (1999). The building information and detailed list of components can be found in the Appendix B. Figure 9 demonstrates the differences in results in the select LCA approaches/tools. Even though the mass quantities of all materials are the same across tools and the material assignments are matched as closely as possible, the global warming potential estimated by each of the methods yields slightly varying results. For example, the highest and lowest estimate between process LCA tools differs by 34%, the closest process LCA result is lower than component EIO by 40% and building EIO results are 14% lower than component EIO results in this case. Non-structural components such as curtain wall and access flooring have been found to vary the most across tools, especially in comparison between process-based LCA and EIO-LCA.

It should be noted that the matching of process-LCA and EIO-LCA impact estimates is especially difficult due to multiple conversion steps, from quantities to cost estimates, to representative EIO sector assignments. Differences between LCA tools and databases have been shown in numerous studies (Al-Ghamdi & Bilec, 2016; Herrmann & Moltesen, 2015; Takano et al., 2014), and need to be considered when studying or comparing the environmental impacts of buildings across studies. Considering the evolving nature of these tools and assessment methods, it is difficult to identify the single best tool; however, it seems that the level of detail and transparency of the tools are the most important characteristics both for use in estimating repair related impacts as well as for allowing for comparisons across assessments.

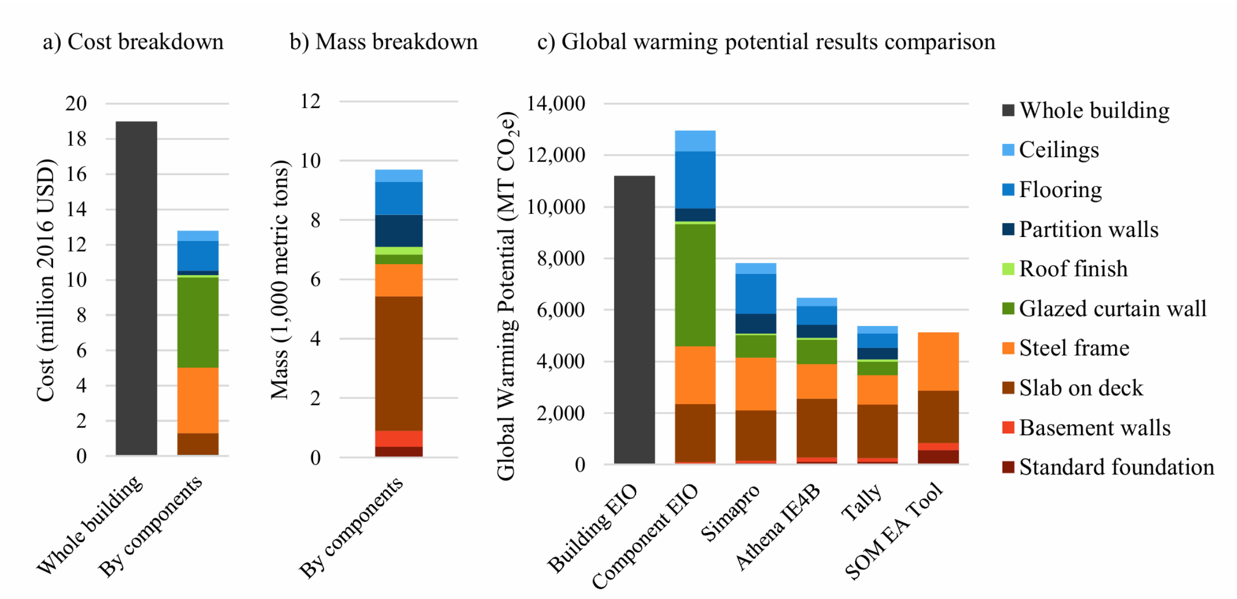

Figure 9. Case study cost estimates, mass quantities, and global warming potential.

Global warming potential results of various LCA tools and approaches are compared. Building Economic Input-Output Life Cycle Assessment (EIO-LCA) results are based on the total building cost and do not provide disaggregation to building systems, hence the cumulative results are reported under the “whole building” category. Detailed list of components and input information can be found in Appendix A.

4.3.3 Translating damages to environmental impacts

Damages and associated repairs have been translated into life-cycle environmental impacts by one of three approaches: (1) *Economic Input-Output LCA (EIO-LCA)* has been directly applied to economic loss estimates (Comber et al., 2012; Simonen et al., 2015); (2) *repair cost-ratios* have been applied to environmental impacts from the pre-use stage (Alirezaei et al., 2016; Chiu et al., 2012; Feese et al., 2014; Padgett & Li, 2014); and (3) *repair descriptions + LCA* have been used to determine environmental impacts of damage scenarios (Belleri & Marini, 2016; J. P. Chhabra & Warn, 2017; Gencturk et al., 2016; Hossain & Gencturk, 2014; Menna et al., 2013; Sarkisian et al., 2014; Wei, Shohet, et al., 2016; Wei, Skibniewski, et al., 2016; Welsh-Huggins & Liel, 2014). The following are expressions of the three approaches for estimating the environmental impacts associated with the repairs of a building after a seismic event:

damage → cost of repair → **EIO-LCA** → life cycle enviro. impact of repair (4-1)

damage → **repair cost-ratio** × pre-use impact = life cycle enviro. impact of repair (4-2)

damage → (**repair description** + **LCA**) → life cycle enviro. impact of repair (4-3)

In the *EIO-LCA* approach, economic loss estimates from a seismic loss assessment can be used as an input to the EIO-LCA tool, either in an aggregated (building EIO) or disaggregated (component EIO) form as discussed in section 4.3.2, with the output of the life cycle environmental impact of the associated repairs. In the *repair cost-ratio* approach, the same economic loss estimates can be compared to the pre-use (also called full replacement) cost of the building or individual components, and the resulting repair to pre-use ratios can be applied to the initial environmental impacts to obtain the life cycle environmental impact of the associated repairs. One limitation of this approach is its assumption that the distribution of labor and material costs is the same for the original construction and the repairs, which is most often not the case. Alternately, the FEMA developed cost-ratios for repair costs of individual damage states can be applied directly to environmental impact estimates. Lastly, the *repair description + LCA* approach consists of developing life cycle environmental impact data based on individual damage descriptions and using that data directly within the seismic loss assessment.

LCA conducted for individual repair descriptions (3) can be considered the most direct impact estimation approach but is time-consuming and may require advanced knowledge of LCA. EIO-LCA (1) and cost-ratio (2) based impact estimates are faster to obtain, in comparison to individual repair descriptions, but may not represent the impacts from repairs accurately. Repair specific material inputs and labor may differ from the materials and labor needed to produce and install complete, new components during the pre-use stage of a building, and repair ratios developed for economic loss analysis may not apply to environmental losses in different environmental impact categories (e.g. global warming potential vs. embodied energy). As Arroyo et al. (2015) highlighted, the environmental impacts can be calculated as a ratio of the impacts associated with the initial production of a part of a building only with the assumption that the part needed for repair is produced the same way. This assumption may not be valid for components and damage states requiring partial repairs, for example the replacement of a gypsum wallboard in a gypsum on steel stud partition wall.

4.4 CONSIDERATIONS DURING THE DESIGN PHASE

4.4.1 Uncertainty, variability, and randomness within models

In general, for the purpose of design, it is prudent to base decision upon both expected values and a measure of risk (Levy, 2015; Markowitz, 1952). The prediction of future seismic events is the main source of uncertainty within hazard assessment. In seismic loss assessment, it is assumed there is an inherent randomness in the magnitude, distance, and time of occurrence of seismic events, and in the structural response of a building given a seismic event (Aslani & Miranda, 2005). These sources of uncertainty are typically captured by using hazard, structural response, and fragility curves. Similarly, environmental impact data includes uncertainty in applicability to specific and future designs. From a building LCA perspective, there is also an uncertainty in predicting the quantity of components within the building during the early design phase (Hester et al., 2017). Dong and Frangopol (2015) was the only study from the earthquake induced environmental loss estimation literature that has considered uncertainty in the estimate of material quantities, although the coefficient of variation and distribution type were based on generic distribution assumptions and did not represent component-specific, experimentally or empirically based values.

One of the aspects introducing uncertainty into LCA studies is the representativeness of existing environmental impact data to specific applications. The time and labor-intensive nature of LCI data development results in relatively infrequent updates to that data which can end up being 10 or more years old, sometimes potentially misrepresenting fast changing technologies and processes. LCA studies concerned with future stages of the building life cycle, such as seismic repair, inherently depend on the assumption that historical LCI data is representative of future repair and replacement. It is known that technological, geographical, and temporal representativeness is a factor on the results of building LCAs and may differ across LCI databases (Takano et al., 2014). One way of including the representativeness uncertainty in LCA has been by using the data quality index developed by Weidema and Wesnæs (1996) which was also adopted by the ecoinvent database (Frischknecht et al., 2005). Even if project specific EI data is known (i.e., the EI data is fully representative of the specific technology, geography, and time in a given LCA study), the dynamic nature of some processes may introduce additional uncertainty in the total environmental impacts over a period of time (William O. Collinge et al., 2013; William O Collinge et al., 2013; Levasseur et al., 2010; Su et al., 2017). For example, global warming potential (GWP) factors typically consider radiative forcing of various greenhouse gasses over a set period of time (e.g. 100 years) based on the radiative forcing profile and atmospheric lifetime of each gas. The same factors are used for current and future releases; however, the accumulation of such gases in the atmosphere means that the impact of greenhouse gases released today may have different effect from the ones released in the future (Kendall, 2012; Levasseur et al., 2010). Some researchers have proposed the use of dynamic and time-adjusted impact factors to address this issue (Kendall, 2012; Levasseur et al., 2010) while the more typical way has been by applying discounting factors (Arroyo et al., 2015; Karimpour et al., 2014); however, some have argued against discounting in environmental LCAs due to the nature of non-monetary values (Wei, Shohet, et al., 2016) and the subjective valuation of multiple generations (Hellweg et al., 2003). Some impact assessment methods provide multiple characterization schemes for enabling the study of short-term, medium-term, and long-term effects, such as in the ReCiPe method (Goedkoop et al., 2013).

The uncertainty associated with the environmental impacts of production of replacement materials and components was considered in only 3 of the 21 studies in Table 1. Dong and Frangopol (2015) used a similar approach to characterizing the uncertainty in the carbon dioxide (CO_2) emission factors as it used for characterizing uncertainty in material estimates, but with larger number of material-specific statistical data. Arroyo et al. (2015) collected material-specific CO_2 emission factors from multiple literature sources and used it in a statistical manner to capture the associated uncertainty. Some LCA databases include statistical uncertainty information for their unit process inventory and also implement established qualitative approaches for factors of representativeness (Weidema et al., 2013). This information was used within the assessment conducted by J. P. S. Chhabra et al. (2017) and propagated via Monte Carlo analysis. However, no existing LCA and repair studies have considered the dynamic nature of processes and changing intensity of environmental impacts that are time dependent, like in the case of GWP. The uncertainty in the inputs into the various seismic loss and life cycle assessments warrants the communication of outputs via probabilistic methods, yet only 4 of the 21 main studies provided probabilistic representation of the results even if they used probabilistic data and presented probabilistic models. Although the task of presenting probabilistic results can be challenging, it is essential for studies aiming to compare many design alternatives and influence decision making from both seismic loss and life cycle assessment perspective, as there is limited value in such studies relying on deterministic results (J. P. Chhabra & Warn, 2017; Lloyd & Ries, 2007).

4.4.2 Number of seismic events

The number of events and intensity of a seismic event that a building is exposed to during its life ultimately determines the extent of damage and needed repairs. There are generally three types of seismic performance assessment: (1) *intensity-based assessment* evaluating the performance under a specified seismic shaking intensity, (2) *scenario-based assessment* evaluating the performance for a specific earthquake magnitude and location, and (3) *time-based assessment* considering all probable earthquakes at a location over a specified period of time (Federal Emergency Management Agency, 2012a). The first two approaches are more straightforward than the third and can be used for validating minimal structural performance of building designs set by code or the owner. They can use any of the structural response analyses mentioned in section 4.2. All of the approaches can be used for comparing alternative building designs, but only time-based assessment is appropriate for an analysis attempting to capture the life cycle of a building.

Time-based assessment can be further divided into *specified* time period and *functional* time period, where the *specified* time period is equivalent to a predefined, fixed time horizon of the assessment while *functional* time period spans from the erection of a new building to its demolition or collapse, according to Chhabra et al. (2018). Some existing studies have used the *specified* time period, equal to the design lifetime of a given building, typically assumed to be between 50 and 100 years (Hossain & Gencturk, 2014; Menna et al., 2013). Using the specified time period; however, relies on the tenuous assumption that a building is replaced by the exact same design in each damage and collapse scenario during that time. Recognizing that collapse is a random event means the building might be in-service for a time that is less than or greater than a specified period of time and that there is a functional life to the building that is defined by the time to collapse. Analysis over the *functional* period of a building can be more realistic from a life cycle perspective and does not rely on the assumption of equal replacement of a building under all circumstances (e.g., after total collapse), but it does currently rely on assumptions related to collapse-level drifts and reparability thresholds (J. P. Chhabra et al., 2018).

4.4.3 Building lifetime

Prediction of the building lifetime is a difficult task but is an important factor in the seismic and environmental assessments. From a life cycle assessment perspective, building lifetime plays a significant role in the conclusions about a building's relative sustainability either due to a building's cumulative impacts from use stage energy consumption, or due to embodied impacts of building components and systems (Aktas & Bilec, 2012a; Hasik, Anderson, et al., 2017). For example, buildings with low initial environmental impact and low lifetime may be less environmentally desirable than durable buildings with higher initial environmental impact, depending on the desired service lifetime and the cumulative life cycle impacts over that lifetime. From structural performance perspective, the probability of occurrence of a seismic event is also dependent on the time horizon of the analysis, in addition to the location, assuming that the structural performance follows a Poisson model. As Gencturk et al. (2016) pointed out, a building life may not be a function of its structural performance in most cases, instead it may be driven by the building's functionality requirements. However, in regions with considerable natural hazards, inadequate structural performance may result in significant damage or collapse of a building, ultimately impacting its actual life or the life of components within the building.

4.4.4 Database and tool integration

Almost all studies presented general frameworks demonstrated on case study buildings with manually obtained data and calculations. While this approach is valuable for analyzing different design alternatives and scenarios individually, it is less likely to be implemented in practice for building design. It may be necessary to analyze large number of design alternatives which may be data and computationally intensive and become time and cost prohibitive. A few researchers have focused on increasing the efficiency of the process of merging earthquake engineering concepts with life cycle assessment by using a Monte Carlo based framework integrating time-based earthquake engineering assessment with an LCA database (J. P. Chhabra et al., 2018), automating the exchange of information between a Building Information Model (BIM) and a structural analysis tool (Alirezaei et al., 2016), and by developing a full-scale tool with user-interface, input manipulation, internal computational engine, database, and graphical output (Sarkisian et al., 2014). Simonen et al. has also developed an environmental impact database consisting of hundreds of components and multiple damage states specifically for the use with data in the PACT tool (Simonen et al., 2018; Simonen, Huang, et al., 2017).

4.5 CONCLUSION

There has been a proliferation of literature on the connection between life cycle environmental impact assessment and seismic loss assessment for buildings over the past decade. From the broader perspective, loss estimation has been done either using engineering methods such as PBEE, or using empirically-based software such as Hazus; environmental impact data has been obtained from EIO-LCA, process-LCA and associated databases, or by using individually published impact factors; and the connection between seismic losses and environmental impacts has been done either directly through EIO-LCA, by use of economic cost-ratios, or by modeling repairs using process-LCA. Different scopes of seismic loss and environmental impact assessments have to be carefully considered, as not all of them are capable of full and accurate analysis of all types of buildings and the full life cycle. While intensity and scenario-based seismic performance assessments have been used to evaluate and compare building performance in different scenarios, they can only capture individual instances of seismic events. When the objective is to estimate the seismic repair impacts throughout a building's life cycle, only time-based assessment including multiple seismic events should be used. In this type of assessment, it is then also necessary to set the design life of the building, which defines the probability of a building's exposure to time- and location-specific seismic hazards. The design life is also important for non-hazard related life cycle issues, such as the typical lifespan of components under normal operating conditions, known as the replacement cycle.

It has been found that non-structural components are typically responsible for a larger percentage of repair impacts over the life cycle of a building in comparison to structural components, especially in structurally resilient but flexible frame designs. The potential damage to non-structural components also depends on the performance of the structural system of a building, creating a dependent relationship between the two systems. For these two reasons it is recommend including non-structural components in similar studies. Non-structural components should be estimated directly via nonlinear dynamic analysis or indirectly via nonlinear static analysis, but should not be omitted altogether, as it may result in an underestimation of losses.

It has also been found that evaluating the environmental impacts of some building components, such as curtain wall, may differ between process-based LCA and EIO-LCA. Since some components, including specialty structural enhancements such as base-isolation, have only been assessed using cost-ratios or EIO-LCA, it would be of value to conduct similar studies using fully process-based LCA for comparison.

Uncertainty, variability and randomness is also critical part of the seismic loss and environmental assessments and should be considered in input data collection as well as for result analysis and communication. It is inherently included in the hazard, response, and fragility curves used in earthquake engineering, and it can also be accounted for in LCA data with the use of data quality indicators and statistical information within databases, therefore it should be propagated and communicated in the results whenever possible. There has not been a study that would investigate the relative comparison of each of the uncertainty sources (i.e. hazard, response, fragility, and environmental impact data) contribution to the cumulative uncertainty. Future studies may investigate the relative uncertainty contributions to understand which are crucial to include in similar assessments.

Finally, there needs to be continuing discussion on the impact of building lifetime on the exposure to hazards (as described in relation to time-based assessments), as well as the effect hazard exposure has on the building lifetime. In other words, the probability of a severe earthquake depends on the time-horizon of the loss assessment and the consequence of such an earthquake may be the collapse of a building before reaching its 'design' life. A pre-defined, 'design' lifetime is too arbitrary to be useful for decision making; however, functional life is difficult to quantify because it is dependent on (1) the hazard environment and complex phenomena such as collapse or (2) socio-economic factors that are difficult to predict. Although it is difficult to predict the functional life of a building, it should not deter researchers from pursuing further investigations on this topic. Understanding functional life is essential to understanding what makes particular building resilient and sustainable.

5.0 PROBABILISTIC LCA OF SEISMIC DAMAGE REPAIR

This chapter is the second part in addressing Objective B, focusing on the development of a framework and inventory for probabilistic LCA of repair of seismic damage to buildings. The content of this chapter is based on an article titled *Probabilistic Assessment of the Life-Cycle Environmental Performance and Functional Life of Building Designs Due to Seismic Events* published in the *Journal of Architectural Engineering* (J. P. Chhabra et al., 2018). An adapted version of the draft manuscript is reused with permission from Chhabra, J. P., Hasik, V., Bilec, M. M., & Warn, G. P. (2018), Probabilistic Assessment of the Life-Cycle Environmental Performance and Functional Life of Buildings due to Seismic Events, Journal of Architectural Engineering, 24(1), 04017035. doi:doi:10.1061/(ASCE)AE.1943-5568.0000284. Copyright 2018 American Society of Civil Engineers. The author of this dissertation contributed by aligning the methodologies of LCA with performance-based earthquake engineering and developing process-based LCA inventory for building component damage repair. Appendix C provides supporting information related to this chapter.

5.1 INTRODUCTION

Climate change effects and environmental issues related to the built environment create an emerging need for designs that consider multiple issues of sustainability, resilience, and safety. Buildings in particular are a major consumer of energy and material resources (Ruuska & Häkkinen, 2014), and are vulnerable to natural hazards such as earthquakes, hurricanes, flooding and others. Damage incurred from a hazard event can lead to additional resource consumption associated with partial repair, or disposal and full replacement, of the building before reaching the target life.

A systems approach, life-cycle assessment (LCA), can be used to assess the environmental performance of buildings. It is a method of quantitative examination of a subject's environmental footprint through the entirety of its life cycle, from raw material extraction to end-of-life. LCA considers a range of impacts, including environmental and human health impacts. Whole building LCAs typically consider raw material extraction, processing, construction, use, and end-of-life phases, and various transportations along the way (ISO, 2006). The use phase can be further divided into operational, maintenance, and extended to damage repair and replacement. Previous LCA studies have demonstrated the majority of impacts occur in the material extraction and operational use phases (Blengini & Di Carlo, 2010; Khasreen et al., 2009; Sartori & Hestnes, 2007; Scheuer et al., 2003); however, as the market shifts towards net zero energy buildings, the impacts related to initial and maintenance material are garnering increased attention (Blengini & Di Carlo, 2010; Court et al., 2014; Flint et al., 2013; Thiel et al., 2013). Additionally, building LCA studies often only consider the pre-use material phase of a building, without accounting for material impacts from repair due to deterioration and hazard-related damage.

Integrating the seismic performance and environmental impact assessments is motivated by the desire to select building designs that minimize economic losses, down-time, casualties, and environmental impact due to hazard events and to reveal tradeoffs amongst design alternatives to support decision-making. In recent literature, efforts have been made to broaden the scope of the performance based design of buildings (Federal Emergency Management Agency, 2012a; Kafali, 2008; Moehle & Deierlein, 2004) beyond monetary losses, down-time and casualties due to seismic events and to include environmental impacts (Arroyo et al., 2015; Chiu et al., 2012; Dong

& Frangopol, 2015; Feese et al., 2014; Gencturk et al., 2016; Hossain & Gencturk, 2014; Menna et al., 2013; Padgett & Li, 2014; Sarkisian et al., 2014; Simonen et al., 2015; Welsh-Huggins & Liel, 2014). Despite growing literature on this topic in recent years, the authors see two gaps, which are explored in this chapter: (1) direct modeling of environmental impacts for a broader set of structural and non-structural components, and (2) accounting for multiple seismic events during the target life of a building while considering uncertainty in its functional life. Inclusion of a broader set of non-structural components, like plumbing and mechanical systems, can provide a more holistic outlook at the importance of mitigating buildings' vulnerability to hazards.

Although a broad set of structural and nonstructural components is typically considered in traditional performance-based design (PBD) studies with monetary losses, down-time and casualties as outputs, it is challenging for PBD studies considering environmental impacts to include the same detailed set of components due to the time, labor, and data intensive nature of environmental modeling. In the light of this challenge, related studies have either relied on economic proxies to estimate environmental impacts (Alirezaei et al., 2016; Arroyo et al., 2015; Chiu et al., 2012; Comber et al., 2012; Feese et al., 2014), or have narrowed down their focus on structural components only (Feese et al., 2014; Gencturk et al., 2016; Hossain & Gencturk, 2014; Padgett & Li, 2014; Sarkisian et al., 2014; Wei, Shohet, et al., 2016; Wei, Skibniewski, et al., 2016). Furthermore, in the seismic performance assessment literature, time-based assessments (Federal Emergency Management Agency, 2012b) are typically used to estimate different performance metrics by implicitly accounting for different possible intensities of seismic loading that might be experienced by a building within a predetermined period of time (typically the target design life). However, a key assumption in the existing literature is the reconstruction of the exact same design in the case of 'premature' structural failure, due to collapse or irreparable damage, under a seismic event to evaluate the seismic performance over the same predetermined time horizon, which is further described below. This study avoids this assumption by simulating the lifetime seismic hazard scenarios and terminates the scenario simulation in the case of collapse or irreparable damage. The time of termination of a lifetime scenario is then identified as the functional life of the building, which can also be used as a new performance metric.

Accounting for repair related material impacts due to hazard events necessitates a probabilistic approach to quantify the associated environmental impacts because of the numerous sources of uncertainty, including the occurrence and magnitude of a hazard event at a given site, the building's response given an excitation, mapping building response to damage in different building components, and the functional life of the building itself. Furthermore, there exists uncertainty in the material quantities required to repair damage and in the environmental impacts associated with the production of a unit of material, or a repair action. Previous PBD-LCA studies have naturally accounted for uncertainty in the hazard event, structural response, and damage analysis, but only two studies have accounted for uncertainty in the use of environmental impact data, and the reported distribution and variance values were based upon general assumptions and approximate estimates not specific to the underlying emission factors (Belleri & Marini, 2016; Dong & Frangopol, 2015). Approaches to quantify the environmental impacts of seismic related repair have adopted the approach of either estimating the environmental performance for different hazard intensities (Dong & Frangopol, 2015; Feese et al., 2014; Simonen et al., 2015) or have evaluated the mean, or median, value of environmental performance indicators over a specified period of time (Arroyo et al., 2015; Chiu et al., 2012; Gencturk et al., 2016; Hossain & Gencturk, 2014; Menna et al., 2013; Padgett & Li, 2014), typically the target design life of the building for the life cycle assessment.

It is possible, however, that the building sustains damage resulting in monetary losses exceeding a significant percentage of the replacement value of the building, or the building collapses, following a seismic event, each potentially resulting in a functional life less than the target life used for the period of the assessment. Functional life should also inform design decision-making because a design with a functional life that is less than the target life could be considered an inferior design. Studies in the literature account for the outcomes of collapse or irreparable damage by assuming the same building design is 'rebuilt' and then proceed to evaluate the building and its environmental performance over the remainder of the predetermined target life. It is also likely that a building in a region of moderate to high seismicity would experience multiple seismic events of varying magnitudes over its functional life. Each of these events could result in the need of material replacement, translating into additional environmental impacts, and should, therefore, be appropriately considered in the assessment. Moreover, from the point of structural reliability, it is necessary to study the distribution of extreme environmental impacts for all earthquakes occurring during a specified period of time, typically the lifetime of the building (Kiureghian, 2005).

An approach to probabilistically assess the environmental performance and functional life of buildings threatened by multiple seismic events is presented. The approach builds on foundational work in performance based design (PBD) (Moehle & Deierlein, 2004) and extends this work to address emerging issues of resilience, sustainability, and their intersection. Specifically, simulating multiple discrete earthquake event scenarios, the approach produces estimates of the functional life of the building: an important metric for assessing the sustainability and resilience of a particular building design. Furthermore, the modeling of individual damage repairs using process-based LCA allows for a direct disaggregation of the environmental impacts in different building component classes without relying on intermediate steps (e.g. applying economic cost ratios to relate initial environmental impacts to repair related environmental impacts or using economic repair costs together with an economic input-output LCA to obtain environmental impacts). The approach quantifies the distribution of environmental impacts due to seismic hazard-related damage and repair for a given building design at a given site, for the entire building and for building component classes, including non-structural, structural, acceleration sensitive and displacement sensitive components. Furthermore, the approach accounts for the possibility of multiple seismic events to account for the variability in functional life due to the possibility of collapse, or irreparable damage, prior to reaching the target life. By producing estimates of functional life and environmental impact by building component class, the approach presented in this chapter is intended to support design decision-making and the design of resilient and sustainable buildings.

5.2 MATERIALS AND METHODS

The approach for integrating the seismic hazard and environmental performance assessment of building designs over their entire functional life is described in this section. Herein functional life is defined as the duration of time from initial use to when the building is deemed irreparable or collapses due to hazard-related damage, and its assessment is further discussed in the 'Case Study' section. This section begins by the description of each phase in the life of a building contributing to its overall impact on the environment and highlights where PBD integrates into the complete life-cycle performance assessment. Focus is then entirely shifted on the damage due to seismic events, describing the approach for explicit consideration of multiple earthquake events in the life-cycle assessment, and estimation of functional life and repair related environmental impacts.

5.2.1 Overview

Figure 10 illustrates the phases of the life-cycle of buildings, and how the seismic performance assessment can be integrated into the traditional building LCA approach. In this approach, the total environmental impact EI_t over the life-cycle of the building is divided into 5 phases: (1) initial raw material extraction, production, and construction, EI_c; (2) maintenance, EI_m; (3) operational use phase, EI_e; (4) damage repair, EI_r; and (5) end of life, EI_d. The EI in each phase is an n dimensional vector of environmental impact metrics. Herein the notation EI_r represents a vector of these metrics, for example:

$$EI_r = [EI_r^1, EI_r^2, \cdots, EI_r^n] \tag{5-1}$$

where EI_r^i could be a metric related to embodied energy, global warming potential, acidification potential, or any other metric of interest, due to damage repair. The notation, EI_r^i can be interpreted as the i-th environmental impact due to damage repair. Herein, the focus is on the environmental impacts due to damage repair following seismic hazard.

Depending on the intensity of ground shaking in a seismic event, the consequences can range from minor, repairable damage to complete collapse of the building, impacting both structural and non-structural components. The environmental impacts (EIs) associated with a hazard event can be attributed to the repair actions required to restore the building to its original state if the building is deemed repairable. If the building is collapsed or is non-repairable, it is considered to have reached the end of its functional life and the EI's can be attributed to end-of-life disposal (EI_d). A building could be considered irreparable if the residual deformation of the building is beyond a threshold value, or if the economic losses due to damage exceed a percentage of the replacement value, typically assumed to be 40-50% (Federal Emergency Management Agency, 2012a).

Building on the approach of Moehle and Deierlein (2004), a four-step assessment is employed to probabilistically describe the hazard-related environmental impacts due to repair for a given building design at a given site accounting for the possibility of multiple seismic events. The four steps include a hazard analysis, a structural analysis, a damage analysis and a loss analysis. The repair related EIs are treated probabilistically by appropriately accounting for the uncertainty in each step of the analysis, including the loss analysis whereby uncertainty in the environmental impacts due to repair material is explicitly considered.

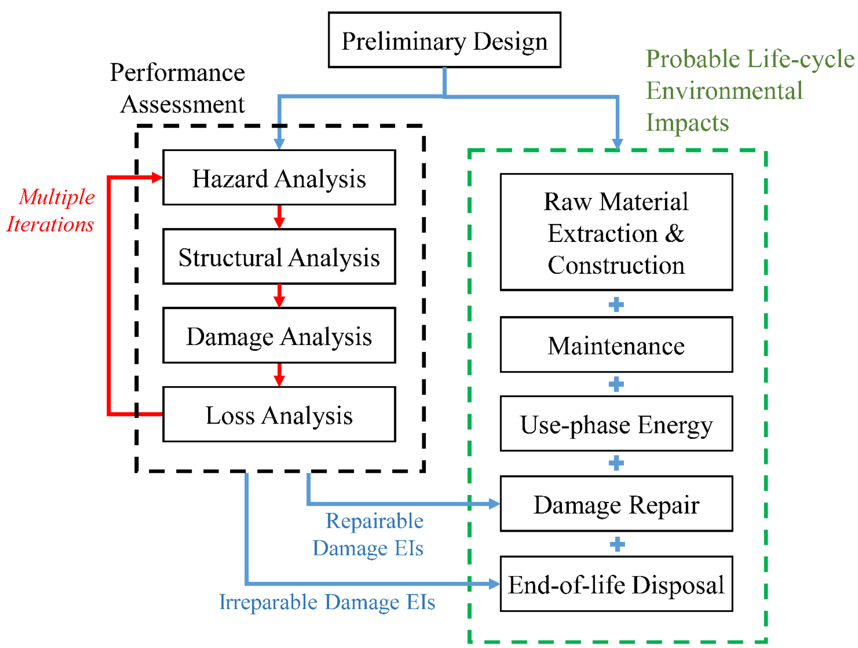

Figure 10. Overview of the different phases in the life-cycle assessment of buildings.

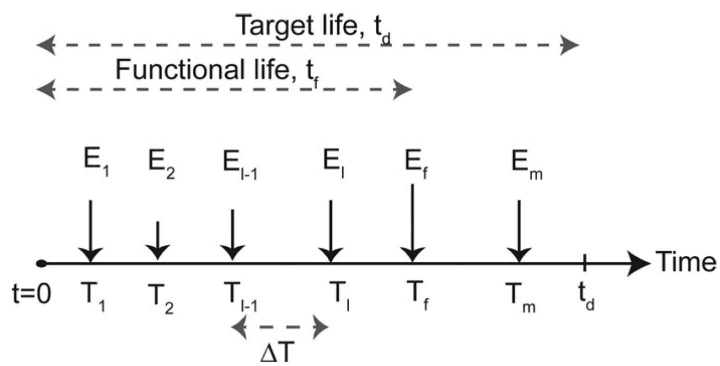

Figure 11. Occurrence of *m* earthquakes over the target design life of a building.

The approach assumes a building at a particular site could be subjected to m random earthquake events $[E_1, E_2, ..., E_m]$ at times $[T_1, T_2, ..., T_m]$ over its target design life, t_d. The building might collapse or be irreparable under event E_f at a time t_f which is less than the target design life, t_d. Here, t_f is used to denote the functional life of the building. An illustration of a hypothetical earthquake scenario for a particular building at a particular site is presented in Figure 11, where the intensity of each event and the time between two consecutive events, ΔT are random variables.

The probability distribution of EI_r^i conditioned on the occurrence of an earthquake event E_l can be calculated from the total probability theorem as follows:

$$P(EI_r^i < ei_r^i \mid E_l) = \int_{dm} \int_{edp} F_{EI_r^i|DM}(ei_r^i \mid dm) \times dF_{DM|EDP}(dm \mid edp) \times dF_{EDP|E_l}(edp \mid E_l) \qquad (5\text{-}2)$$

where $F_{X|Y}(x|y)$ represents the cumulative distribution function (CDF) of a random variable X, conditioned on variable Y. The results of the structural analysis, for example, inter-story drift ratios and floor accelerations, are referred to as engineering demand parameters (EDPs). The results of the damage analysis, for example, probability of being in a minor, moderate and major damage state, are referred to as damage measures (DMs). Eq. 5-2 is based on the assumption that given

dm, the EI_r^i is conditionally independent of *EDP,* and E_l, that is in order to measure environmental impacts due to damage repair, the E_l and *EDP* does not provide any extra information that is not already contained in *DM,* and similarly, given *edp*, *DM* and E_l are also assumed to be conditionally independent (Yang et al., 2009).

Using Eq. 5-2 in conjunction with Monte Carlo (MC) simulation to realize many earthquake scenarios each with the possibility of multiple earthquake events, a distribution of EI_r^i over the functional life of the building can be established. The EI_r^i for a randomly simulated multiple earthquake event scenario can be calculated by summing the impacts from each event of the scenario according to:

$$\left(EI_r^i\right)_{t=t_f} = \sum_{l=1}^{f}\left(EI_r^i\right)_l \tag{5-3}$$

where $\left(EI_r^i\right)_l$ is the i-th environmental impact due to repair actions following the l-th earthquake event and f is the number of seismic events over the functional life in the considered scenario. Eq. 5-2 can be explicitly solved to calculate the EI_r^i for a single earthquake event of a given intensity if closed forms expressions are available for each CDF. Unfortunately, the CDFs are a function of many variables which are specific to a given building design, and therefore it is difficult, if not impossible, to obtain closed form expressions. Instead, a MC based approach is used in this study to simultaneously evaluate Eqs. 5-2 and 5-3. Further, in this study it is assumed that the environmental impacts under a seismic event are independent of the damage incurred under any previous event and the building is renewed after every seismic event not resulting in failure.

A flowchart for implementing the approach to estimate the environmental impacts due to hazard-related damage and repair, EI_r^i is presented in Figure 12. Broadly speaking, under earthquake ground shaking the buildings performance can be categorized as: (1) collapse, (2) irreparable due to the severity of damage and/or residual drifts, and (3) repairable. Categories 1 and 2 represent the end of the functional life of the building. The resulting EIs can be attributed to the end-of-life disposal (see Figure 10); however, end-of-life EIs are outside the scope of this study. For category 3, the EI_r^i depend on the extent of damage in individual building components. In the MC scenarios comprising of all category 3 events, the functional life can be set equal to target life of the building. However, in the scenarios comprising of category 1 or category 2 events, the functional life can be set equal to the time of occurrence of first category 1 or category 2 event. Specific details pertaining to the estimation of the repair related environmental impacts for category 3 events and functional life are presented in the following sections.

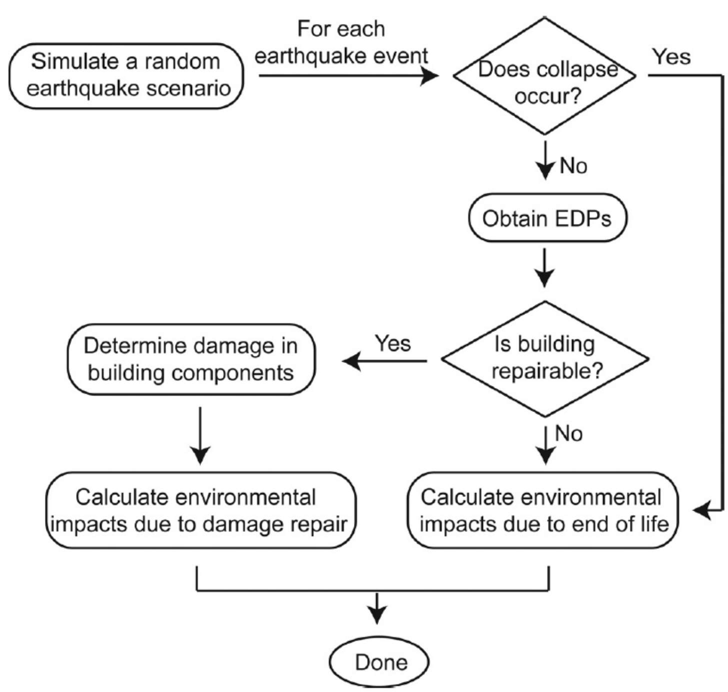

Figure 12. Calculation of environmental impacts due to hazard-related damage and repair.

5.2.2 Approach for simulation of multiple random earthquake scenarios

The seismic hazard at a given site can be described with a curve of the mean annual rate of exceedance, λ_{IM} for different levels of a seismic intensity measure, IM (Cornell, 1968), commonly referred to as a hazard curve. Assuming the number of seismic events over a fixed time can be appropriately modeled by a Poisson counting process, the probability of occurrence of m events over the target design life of the building, resulting in intensity greater than im can be calculated as follows:

$$P(im; M = m, t_d) = \frac{(\lambda_{IM}(im) \times t_d)^m \times e^{-\lambda_{IM}(im) \times t_d}}{m!} \tag{5-4}$$

where $\lambda_{IM}(im)$ is the mean annual rate of exceedance of seismic intensity im.

In this study, the spectral acceleration at the first mode period of the structural system, $SA(T_n)$ is used as the IM. For illustrative purposes a seismic hazard curve for a generic site in Los Angeles (U.S. Geological Survey) is shown in Figure 13, where, $(\lambda_{IM})_{max}$ corresponds to the minimum intensity capable of causing any significant damage in the structure and the $(\lambda_{IM})_{min}$ corresponds to the intensity that reflects the maximum value of selected performance measures (complete damage), and the values of these parameters can be chosen according to the provisions of Federal Emergency Management Agency, FEMA (2012a). According to FEMA (2012a) guidelines for time-based performance assessment, the intensity range between $(\lambda_{IM})_{max}$ and $(\lambda_{IM})_{min}$ is used for performance assessment in this study.

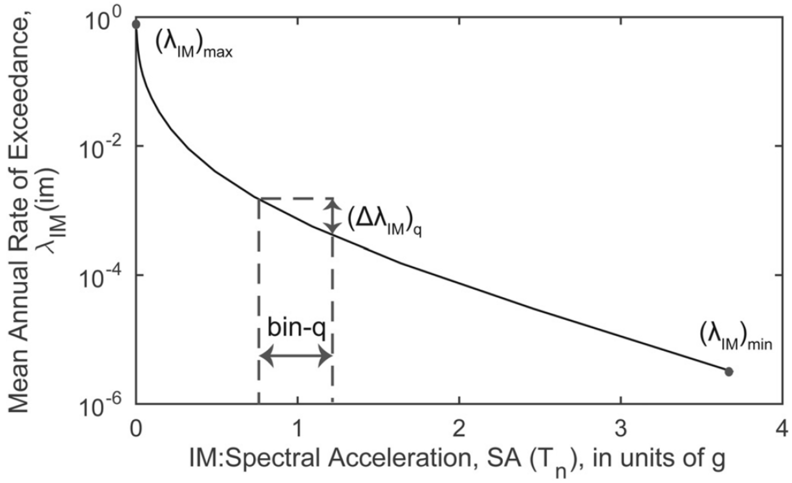

Figure 13. Hazard curve of a typical site in Los Angeles, California.

Based on the assumption of poison counting process for number of seismic events, the time between the occurrences of two consecutive earthquakes, ΔT can be assumed to follow the exponential distribution with following CDF:

$$P(\Delta T < t) = 1 - e^{-(\lambda_{IM})_{\max} t} \tag{5-5}$$

In this study simulation of a multiple earthquake scenario is considered as a two-stage process, where first a scenario comprising seismic events with intensity greater than $(\lambda_{IM})_{max}$ is randomly generated and then an intensity is assigned to each seismic event. In the first stage, different values of ΔT are sampled by using Eq. 5-5 such that:

$$\sum_{l=1}^{m} (\Delta T)_l \le t_d \quad \text{and} \quad \sum_{l=1}^{m+1} (\Delta T)_l > t_d \tag{5-6}$$

where t_d is the target design life and m is the number of sampling points needed such that Eq. 5-6 holds. Here m also represents number of seismic events in the randomly generated earthquake scenario. In the second stage of the simulation intensities are assigned to each seismic event by uniformly discretizing the hazard curve between the considered intensity ranges into multiple bins. Irrespective of the intensity of the seismic event, the average number of seismic events annually occurring in the considered intensity range is given by $(\lambda_{IM})_{max}$-$(\lambda_{IM})_{min}$. The probability of occurrence of seismic event with $SA(T_n) \in$ bin-q is given by:

$$P\left(SA\left(T_n\right) \in bin-q \mid E_l\right) = \frac{\left(\Delta\lambda_{IM}\right)_q}{\left(\lambda_{IM}\right)_{\max} - \left(\lambda_{IM}\right)_{\min}} \tag{5-7}$$

where $(\Delta\lambda_{IM})_q$ is the mean annual rate of occurrence of seismic events with intensity in bin-q. It can be seen that the probability of sampling any bin is directly proportional to $(\Delta\lambda_{IM})_q$. Hence assuming uniform bin size and convex non-increasing hazard curve, Eq. 5-7 would place high density over low intensity events and low density over high intensity resulting, resulting in frequent occurrence of low intensity events and infrequent occurrence of high intensity seismic events in a randomly simulated earthquake scenario. Intensity bins can be assigned to each of the m seismic events in a randomly generated earthquake scenario by independently sampling m bins from the distribution given in Eq. 5-7. In this study, an earthquake event in bin-q is assumed to have an intensity equal to the spectral acceleration at the center of the bin, hereafter denoted by $SA(T_n)_q$. Hence multiple earthquake scenarios can be simulated by sampling inter-event times using Eqs. 5-5 and 5-6 and assigning an intensity to each event by sampling from Eq. 5-7.

5.2.3 Probable life cycle environmental impacts due to damage repair

Individual components within a building can be categorized into performance groups, such that a common EDP can be used to estimate the damage sustained by all components and subcomponents within a group under earthquake ground shaking (Federal Emergency Management Agency, 2012a). For example, all partition walls in a particular direction on a given floor can be considered as a single performance group because their seismic performance can be assumed to depend on the same EDP, i.e. the inter-story drift ratio at the given floor level if it is reasonable to assume the floor diaphragm is rigid. Earthquake related damage in different performance groups can be categorized into discrete damage states; each indicating the severity of damage. The probability of exceedance of a particular damage state in a performance group conditioned on the corresponding EDP can be described using fragility curves. For example, Figure 14 presents a set of illustrative fragility curves for a drift sensitive performance group with three damage distinct states, specifically minor, moderate, and major damage. Hence, given the results of the structural analysis (i.e. EDPs) the probability of being in a particular damage state in different building components can be calculated from the performance group specific fragility curves. For sequential damage states, the probability that a damage state is exceeded without exceeding the next higher damage state is determined according to:

$$P'(DS_k \mid edp) = P(DS > DS_k \mid edp) - P(DS > DS_{k+1} \mid edp) \tag{5-8}$$

where $P(DS>DS_k|edp)$ is the probability of exceedance of the k-th damage state conditioned on the value of *edp*. For the most severe damage state the value of $P(DS>DS_{k+1}|edp)$ is equal to zero. The fragility data to describe damage in different building components is obtained from Performance Assessment Calculation Tool (PACT) (Federal Emergency Management Agency, 2012a) and implemented in MATLAB (2014) for this study. If the building is determined to be repairable (category 3), it is assumed that all the components are brought back to their original state after every category 3 earthquake event, hence the same fragility curves are used for consecutive earthquake events.

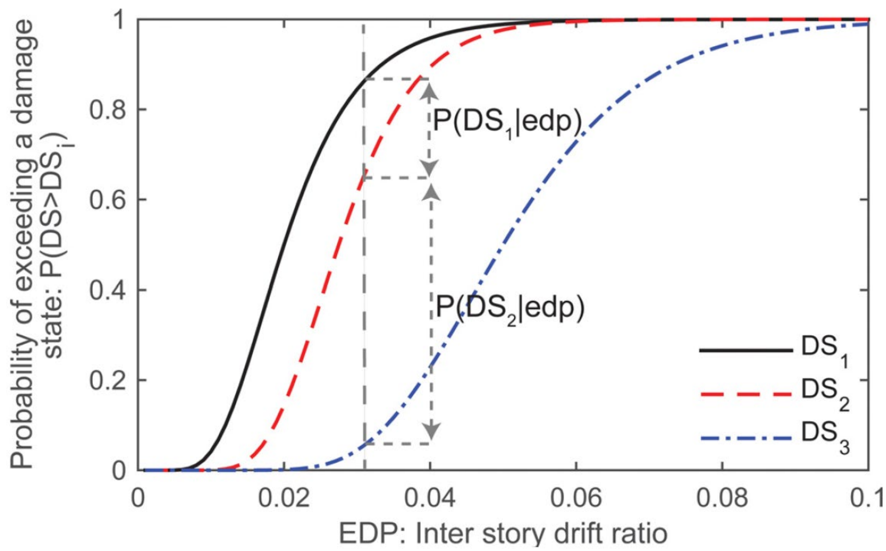

Figure 14. Example of fragility curves to demonstrate fragility analysis.

Repairing of components requires labor or input of new materials, and each building material, component, and system has environmental impacts associated with its production, installation, and disposal. These impacts can be obtained by using process-based LCA approach, which accounts for energy and resource flows between processes and tracks and translates their corresponding demands and emissions into different categories of environmental impacts. In accordance with the ISO 14040 standard (ISO, 2006), LCA studies follow a four-step approach that includes: (1) goal and scope definition, (2) creation of a model of the studied product's life cycle and collecting data, also called inventory, (3) impact assessment, and (4) interpretation. Life cycle inventory (LCI) databases contain unit process data to facilitate complete life cycle assessments (Frischknecht et al., 2007b; Trusty & Deru, 2005). Since these databases are meant to be representative of a broader set of products and processes of similar type, they are often based on large numbers of specific product samples. Some databases, such as the Ecoinvent database (Weidema et al., 2013) used in the subsequent case study, disclose statistical information about the variability in data representing each type of product or process. However, there are other factors influencing the representativeness of the data, those being statistical (i.e. reliability, completeness), temporal, geographical, and technological factors (Weidema et al., 2013). The Ecoinvent database incorporates this type of uncertainty in its data by using a Pedigree Matrix (also known as Data Quality Index) approach developed by Weidema et al. (2013). This approach can be applied to any LCA study or environmental impact data development regardless of the underlying database used.

The steps taken in calculating the environmental impacts of each component are as follows: (1) determine the component's material composition, (2) determine the amount of each material, (3) link materials with unit processes within an LCI database, and (4) calculate the total life-cycle resource consumption, emissions, and associated impacts. Material quantities for each building component can be determined based on various sources such as construction documents, submittals, product specifications sheets, environmental product declarations, and literature. These sources were used for the case study application and are shown in Appendix C Table 24 for the specific components used. Each component can first be analyzed for the different subcomponents and materials it is composed of, and the amount of each material can then be estimated based on the specific geometry, material density, shipping weights, and/or material weight distributions. Each component or subcomponent can then be assigned to the best representative unit process available in the LCI database and evaluated using impact assessment method chosen by the investigator (e.g. TRACI 2.1, Cumulative Energy Demand, etc.). LCA software such as SimaPro 8.1 can be used to perform the uncertainty analysis for uncertainty information appended to the underlying LCI databases, as described above (PRé Consultants, 2015).

Once environmental impact data is obtained for each subcomponent (e.g. tape, paste, paint, wallboard, stud, and screws) per unit of a corresponding component (e.g. 1 m^2 of partition wall area), that data can then be used for the calculation of environmental impacts due to damage state specific repair actions. In this study the damage/repair assumptions developed in FEMA (2012a) are used to obtain repair actions for different damage states for each building component. For example, presented in Table 3 are the related environmental impacts for different subcomponents needed for the complete construction of 1 sq. ft. of a typical partition wall. If the partition wall incurs minor damage, a typical repair action would include taping joints and repainting; however, under severe damage state it undergoes significant cracking/crushing of gypsum board and buckling of studs and is repaired by replacing the gypsum board, studs, tape, and paint along the entire length of the wall. Hence, the environmental impact data to repair different subcomponents of the partition wall can be grouped and appropriately mapped to damage state specific repair actions to probabilistically assess the environmental impacts of different levels of damage in a partition wall. Table 4 presents an illustrative mapping of damage state to environmental impact for a typical partition wall, where the coefficient of variation captures the dispersion of the metric about its mean. For example, for any given damage state, keeping the expected value of repair related environmental impacts constant and increasing the coefficient of variation would result in an increase in dispersion of results. This procedure can be followed for all studied building components and integrated with the performance assessment procedure discussed in prior sections to calculate the total repair impacts due to each earthquake event, and over the functional life of a building.

5.2.4 Case Study

This section describes the application of the approach to estimating the EIs and functional life of a nine-story steel office building located in Los Angeles, CA. Illustrations of the building's layout in plan and elevation are shown in Figure 15 (Gupta & Krawinkler, 1999). The building was designed in accordance with the provisions of UBC 1994. It was assumed to be built on a stiff soil (Site Class D) site located at 34.05372°N and 118.24273°W. The lateral load resisting system consists of steel moment resisting frames in each orthogonal direction along the outer perimeter of the building with gravity columns in between. A detailed description of the design can be found in Gupta and Krawinkler (1999).

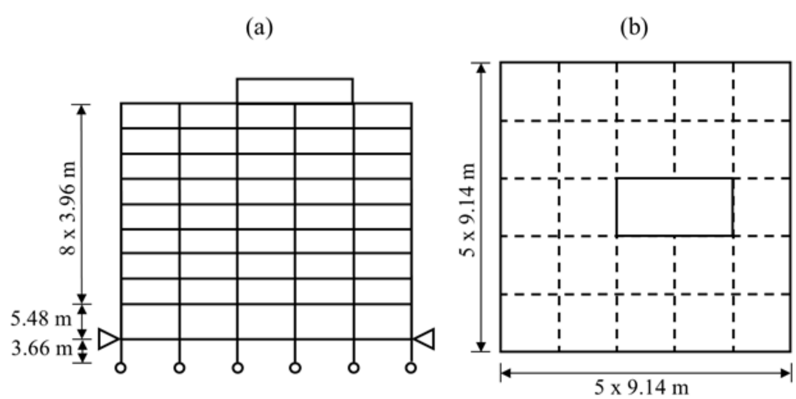

Figure 15. Elevation (a) and floor plan (b) of the study frame.

Table 3. Example of environmental impacts for 1 sq. ft. of typical partition wall.

Subcomponent	Material	Weight per unit (kg/m^2)	Global Warming Potential (kg CO_2 eq.)	
			Median	Coefficient of variation (%)
Wallboard	Gypsum board	40.496	1.678	12.3
Metal stud	Galvanized steel	3.989	0.793	11.7
Joint compound	Joint compound	1.386	0.007	6.0
Paint	Alkyd paint	0.312	0.165	139.0
Hardware	Galvanized steel	0.078	0.014	11.8
Tape	Drywall tape	0.005	0.002	13.6

Table 4. Mapping damage state to environmental impacts.

This example shows global warming potential due to repair actions for a typical partition wall.

Damage State no.	Description of Damage State	Repair actions	Global warming potential (kg CO_2 eq. per 1300 sq. ft/121 sq. m of wall area)	
			Median	Coefficient of variation (%)
1	Screws pop-out, minor cracking of wall board, warping or cracking of tape.	Retape joints, paste and repaint both sides of 50 foot length of wall board.	11	131
2	Moderate cracking or crushing of gypsum wall boards	Remove full 100 foot length of wall board, install new wall board, tape, paste and repaint.	2259	19
3	Significant cracking and/or crushing of gypsum wall boards - buckling of studs and tearing of track	Remove and replace full 100 foot length of metal stud wall, both sides of the gypsum wall board and any embedded utilities, and tape, paste and repaint.	3299	13

The goal of this case study is to estimate the probable environmental impacts associated with the repair phase and to estimate the functional life of this building using the approach described in the 'Methodology' section. The functional unit is 1 building providing 225,000 sq. ft. of office space over the functional life of the building (based on a 50-year design life). The scope of the study is limited to the repair phase which includes raw material extraction, production, and transportation associated with the repair of individual building products. A process LCA was conducted for the structural components specified in Gupta and Krawinkler (1999) and for the individual non-structural building components specified in the PACT Normative Estimation Tool (Federal Emergency Management Agency, 2012a) based on the building type, size, and use. A list of all the building components considered in the assessment is presented in Table 5.

Table 5. List of structural and non-structural components.

Group	Category	Components
Structural	Super Structure	Steel column base plates, bolted shear tab gravity connections, welded steel moment connections, welded column splices, steel wide flange sections
Non-Structural	Enclosure	Curtain wall, concrete tile roof
	Interiors	Wall partition, stair case, raised access floor, suspended ceiling, pendant lighting
	Services	Traction elevator, hot water piping, cold water piping, sanitary waste piping, chiller, cooling tower, HVAC sheet metal ducting, HVAC drops/diffusers, variable air volume box, air handling unit, fire sprinkler water piping, fire sprinkler drop

Material quantities for whole new components were obtained using the procedure described in chapter 5.2.3 and assigned to unit processes from the Ecoinvent 3.0 database (Weidema et al., 2013). Damage and repair descriptions from the PACT fragility database were then used together with the whole component material estimates to obtain damage specific repair actions and impacts. Detailed material estimates for all components are provided in the Appendix, Table 24, and the detailed repair descriptions and assumptions for all components and their damage states are provided in the Appendix C Table 25. Due to the additional complexity in material takeoffs and more detailed damage and repair descriptions for elevators, Appendix C Table 26 and Table 27 show the elevator quantities separately from the rest of the estimates. Data was not available for all of the elevator components which is reflected in Appendix C Table 27 accordingly. It is important to note that the material estimates are deterministic values based on each component's design specifications (e.g. partition wall: 1.25 in by 3.62 in, 25 gauge, stud spaced 16 in o.c. with ½ inch gypsum wallboard and paint on both sides) or a representative product (e.g. curtain wall: Tubelite 400 Series Curtainwall, double glazed with ¼ in glass panels). Conversely to the deterministic material quantities, the emissions and resource consumption for individual unit processes are probabilistic values based on the Ecoinvent LCI database. This database provides statistical information based on obtained sample data and uses a data quality index approach for estimating other uncertainty factors related to representativeness. This approach can account for the reliability, completeness, and temporal, geographical, and technological correlations (Weidema et al., 2013). For example, environmental impact data based on European steel production procedures in 1990 may be expected to be similar but contain a degree of uncertainty when applied to U.S.-based LCA in 2016 and can be captured via the data quality index. Ecoinvent uses predominantly lognormal distributions to characterize uncertainties within its models

(Weidema et al., 2013), which is also the assumed distribution for characterizing the environmental impact data in this case study.

The U.S.-based TRACI 2.1 assessment method (Bare, 2012b) was used for the life-cycle impact assessment of each component and their individual damage states. This method evaluates ten impact categories, including global warming potential (GWP), acidification, smog formation, ozone depletion, eutrophication, ecotoxicity, carcinogenics, non-carcinogenics, respiratory effects, and fossil fuel depletion. For brevity, only GWP is reported as an illustrative impact category in this study, as it is the most commonly studied and most well-developed category. TRACI uses the 100-year horizon GWP, which considers the radiative forcing of various greenhouse gasses (e.g. CO_2, CH_4, N_2O, HFCs, etc.) over a period of 100 years and reports it in units of CO_2 equivalent (IPCC, 2006). Since each gas has a unique radiative forcing profile and atmospheric lifetime, there has been an ongoing discussion of the best way of reporting GWP, with some researchers suggesting dynamic, time-adjusted GWPs (Kendall, 2012; Levasseur et al., 2010). Although the time of the release of greenhouse gasses may be especially important in regards to infrastructure with long life-spans, refining the methodology for calculating GWPs is not the focus of this study.

The structural analysis (that is the determination of the EDPs) was performed using a two-dimensional (2D), plane frame model of the building's lateral load resisting system in OpenSees (Mazzoni et al., 2006). The beam elements were modeled as linear elements with concentrated plasticity at each end. The plastic hinges were modeled by zero-length elements and assigned 'Steel01' material with yield moment equal to the yield moment capacity of the beams and with very large initial stiffness. The beam yield strength was set equal to 36 *ksi* (248 *MPa*) according to Gupta and Krawinkler (1999). The column elements were modeled as nonlinear beam column elements with fiber cross-section and five Gauss integration points along each element. The column yield strength and strain hardening ratio were set equal to 50 *ksi* (345 *MPa*) and 3% respectively as taken in Gupta and Krawinkler (1999). The gravity loads carried by the gravity columns were assigned to a single pin-ended column in order to simulate the *P*-Δ effects (Foutch & Yun, 2002) from the gravity load on the lateral force resisting system.

From an Eigen value analysis, the first mode period of the frame was found to be equal to 2.24 seconds. Rayleigh damping was assumed with damping ratio for the first mode period and 0.2 seconds period equal to 0.02 for nonlinear response history analysis. As described in the 'Methodology' section, the parameters of the hazard curve for the specific site were obtained from the United States Geological Survey website (U.S. Geological Survey, 2015). $(\lambda_{IM})_{max}$ and $(\lambda_{IM})_{min}$ were set equal to $0.61\text{x}10^{-1}$ and $1.87\text{x}10^{-4}$, respectively, following the recommendations by Federal Emergency Management Agency (2012a). The hazard curve between $(\lambda_{IM})_{max}$ and $(\lambda_{IM})_{min}$ was discretized into 12 bins (denoted IL 1 - IL 12) for the performance assessment. Three higher intensity levels (IL 13 - IL 15) were also considered for collapse evaluation. Table 6 summarizes the central intensities $SA(T_n)_q$, mean annual rate of exceedance of central intensities $(\lambda_{IM})_q$ and mean annual rate of events with intensity in a particular bin $\Delta(\lambda_{IM})_q$. Note that the $SA(T_n)_q$, shown in Table 4 are not precisely at the center of the chosen bins. Small flexibility was allowed to facilitate hazard deaggregation using the USGS hazard deaggregation tool as described later in the text.

Table 6. Discretization of hazard curve for performance and collapse assessment.

Intensity Level	$SA(T_n)_q$ (in g)	$(\lambda_{IM})_q$	$\Delta(\lambda_{IM})_q$
IL 1	0.06	3.30E-02	4.06E-02
IL 2	0.11	1.39E-02	1.13E-02
IL 3	0.17	6.93E-03	4.70E-03
IL 4	0.24	3.51E-03	1.65E-03
IL 5	0.28	2.44E-03	1.06E-03
IL 6	0.35	1.41E-03	6.31E-04
IL 7	0.40	1.05E-03	3.92E-04
IL 8	0.46	6.84E-04	1.97E-04
IL 9	0.51	5.13E-04	1.71E-04
IL 10	0.56	4.04E-04	1.32E-04
IL 11	0.63	2.69E-04	6.20E-05
IL 12	0.68	2.01E-04	4.80E-05
IL 13	0.78	1.34E-04	---------
IL 14	0.84	1.01E-04	---------
IL 15	0.98	5.00E-05	---------

Structural collapse must be assessed to determine whether the structural performance falls in the repairable or irreparable category for a given event (see Figure 12). For this case study, the structural collapse assessment was done using the multiple stripe analysis (MSA) (Baker, 2013) at the 15 intensity levels listed in Table 6. Sets of 40 ground motions were chosen for each intensity level according to Lin et al. (2013). The conditional spectrum was used as the target spectrum for ground motion selection and scaling (Jayaram et al., 2011). The conditional spectrum was chosen instead of the uniform hazard spectrum in order to avoid the inherit conservatism of the uniform hazard spectrum and to choose ground motion records having spectral shapes representing the spectra of historical ground motions at different intensity levels (Baker, 2010). The first mode period (2.24 sec) of the frame was used as the conditioning period to obtain the conditional spectrum. The USGS hazard deaggregation tool (U.S. Geological Survey, n.d.) was used for hazard deaggregation and generation of conditional spectrum at each intensity level with Campbell and Bozorgnia (2008) ground motion prediction equation. Earlier studies have reported the maximum inter-story drift ratio capacity of steel frame buildings without connection failure to be between 7-10% (Liu et al., 2003; Yun, 2000). The value of 7% was used in this study for the threshold for the collapse assessment instead of a more rigorous collapse assessment. Unfortunately, more rigorous collapse assessment techniques that are computationally tractable are not currently available in the literature. Figure 16 presents the results of multiple stripe analysis in terms of peak inter-story drift versus spectral acceleration and the collapse threshold of 7%. Values exceeding the threshold are shown by black circle markers. The principle of maximum likelihood estimation was used to determine the parameters of a lognormal fragility curve using the data obtained from multiple stripe analysis (Shinozuka et al., 2000) shown in Figure 16. The median value and dispersion of collapse spectral acceleration were calculated to be 1.06g and 0.32 respectively. Figure 17 presents the resulting collapse fragility curve that was used to determine whether the building collapsed or not (Figure 12) for a given event in the MC framework.

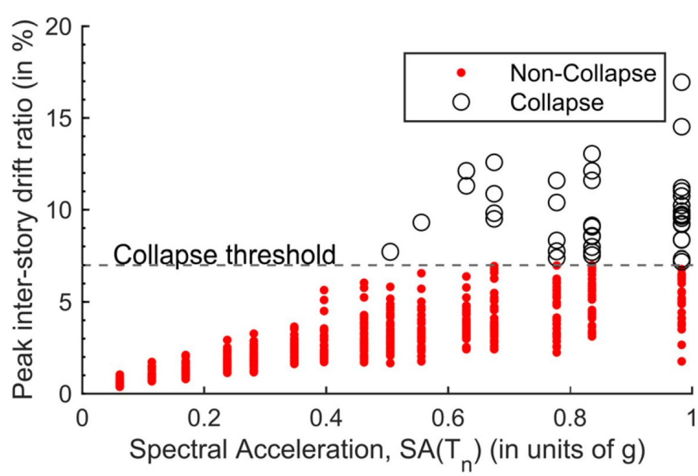

Figure 16. Results of MSA on case study building frame.

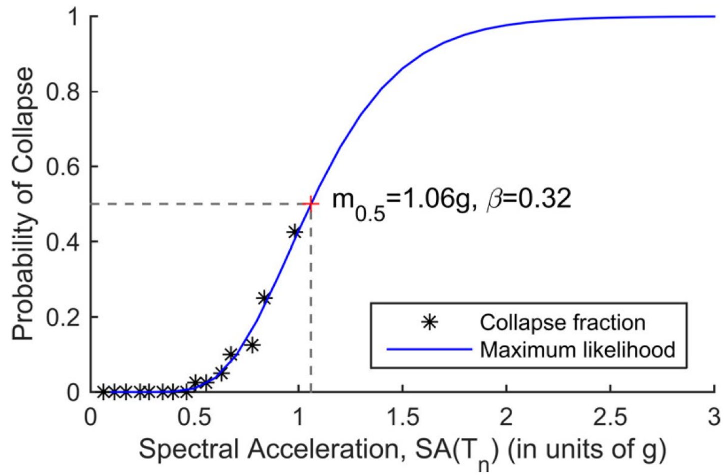

Figure 17. Collapse fragility curve.

The peak inter-story drift ratios, peak floor accelerations and peak residual inter-story drift ratio were then used as EDPs in this study. Ideally, structural analysis should be performed with a unique ground motion for every earthquake event in the MC simulation. However, due to the large computational cost of nonlinear response history analysis, this is not computationally viable. Since EDPs have been shown to be lognormally correlated random variables, the approach proposed by Yang et al. (2009) was used to simulate EDP vectors, $\underline{edp}$, for different events in the MC simulation according to:

$$\underline{edp} = \exp(M_{\ln X} + D_{\ln X} L \underline{y}) \tag{5-9}$$

where X is a matrix of EDPs with number of rows equal to number of ground motions chosen for structural analysis and number of columns equal to number of EDPs needed for performance assessment, $M_{\ln X}$ is the column vector containing mean values of $\ln X$, $D_{\ln X}$ is the diagonal matrix containing standard deviations of $\ln X$, L is the lower Cholesky matrix of the correlation matrix of $\ln X$ and $\underline{y}$ is a column vector of zero mean uncorrelated Gaussian random variables.

The peak residual inter-story drift ratio was used as the criteria for assessing reparability (see Figure 12). According to FEMA (2012) Table C-1, major structural realignment is required to restore lateral stability for inter-story drift ratio greater than 1% and the required repair of the structure may not be economical or practically feasible. Hence in this study, the peak residual inter-story drift ratio below which the structure could be repaired was assumed to follow a lognormal distribution with median and dispersion equal to 1% and 0.3, respectively. The initial cost of the building was estimated at 28 million (in 2011 U.S. dollars) based on building type, size, and location and using the RS means database (RS Means, 2015). According to Federal Emergency Management Agency (2012a), past studies suggest that 40% of the replacement cost is a reasonable total loss threshold for many buildings; therefore, this study assumed that the decision maker would not repair the building if its repair cost were greater than 40% of the replacement cost. Otherwise, if deemed 'repairable', the inter-story drift ratios and floor accelerations were used for damage assessment and to estimate the EIs using Eq. 5-2.

The damage evaluation for both structural and non-structural components was performed in MATLAB (2014) together with the fragility database available in PACT (Federal Emergency Management Agency, 2012a). As described in the 'Methodology' section, the probable EIs due to each repair action for a given damage state were obtained using process-based LCA approach for each repair scenario described in the PACT database. Detailed damage descriptions and associated impact data for all components can be found in Appendix C Table 25. For each realization of the simulation not resulting in collapse, the damage states of different components were estimated, and the corresponding repair related EIs and repair costs were calculated. The building was deemed irreparable in realizations where the repair costs or residual inter-story drift ratio exceeded the above defined thresholds. In all the repairable events, the EI_r for all individual components were summed to obtain an estimate of the total EI_r in a single earthquake event and Eq. 5-3 was used to obtain an estimate of EI_r for a given random earthquake scenario. In the earthquake scenarios with all repairable events, the functional life was taken equal to the target design life of the building. However, in the scenarios comprising of collapse causing or irreparable events, the functional life was taken equal to the time of occurrence of first collapse causing or irreparable event.

5.3 RESULTS AND DISCUSSION

The EIs due to repair actions were estimated in terms of their global warming potential; however, the proposed methodology is sufficiently general so that other environmental impacts from damage could be assessed. The target design life of the building was assumed to be 50 years for the assessment. Per the 'Methodology' section, some earthquake scenarios lead to performance in the irreparable category resulting in the building's functional life being less than its target design life. Such outcomes result in a plethora of alternatives for determining the future based on the decision maker's utility function, for example, rebuild identical building (unlikely), rebuild different building, sell property, re-develop, etc. Rather than rely on a tenuous assumption, for example, "rebuild identical building", in this study the outcome of irreparable performance was used to estimate the functional life of the building as metric for design decision-making. One challenge with making decision based on functional life and the associated distribution of EI_r over the functional life is the possibility of a short functional life ($t_f << t_d$) having correspondingly low environmental impacts due to repair event, though a design with a functional life less than the target design life should be considered a poor design. However, this challenge can be easily overcome by comparing designs with respect to their functional life as well as their environmental performance in a multi-criteria context and eliminating designs with 'low' functional life or by analyzing designs with on their environmental performance per year of functional life. Appropriate methods for comparing design alternatives are the topic of ongoing research.

The distributions of EI_r were calculated over the functional life of the building by performing MC simulation with 10^5 scenario realizations. To evaluate convergence of the MC simulation, the 95% confidence intervals of the expected value of global warming potential are calculated for different numbers of MC realizations. A convergence metric, ε is defined to evaluate the convergence of MC simulation as follows:

$$\varepsilon = \frac{UB_z - LB_z}{SS_\infty} \tag{5-10}$$

where UB_z and LB_z are the respective upper and lower bounds of the confidence intervals for the sample statistic obtained with z MC realizations and SS_∞ is the value of sample statistic at convergence. Figure 18 shows the sample statistic, 95% confidence intervals and the ε for the expected global warming potential as a function of number of MC realizations. The confidence intervals are calculated by using bias-corrected accelerated method (BC_a) (Efron & Tibshirani, 1994) with 1000 bootstrap replications. It can be seen from Figure 18 that with 10^5 scenario realizations, the ε is 'fairly' small (≈1%) and the MC simulation can be assumed to have converged.

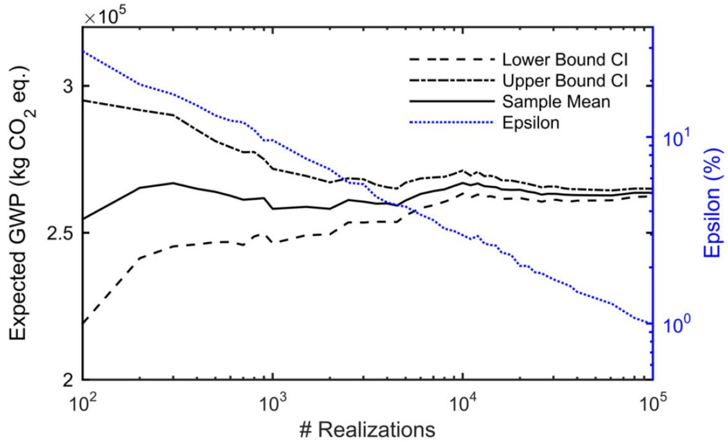

Figure 18. Convergence analysis of the MC distribution to derive the distribution of GWP.

(Note: CI = confidence interval)

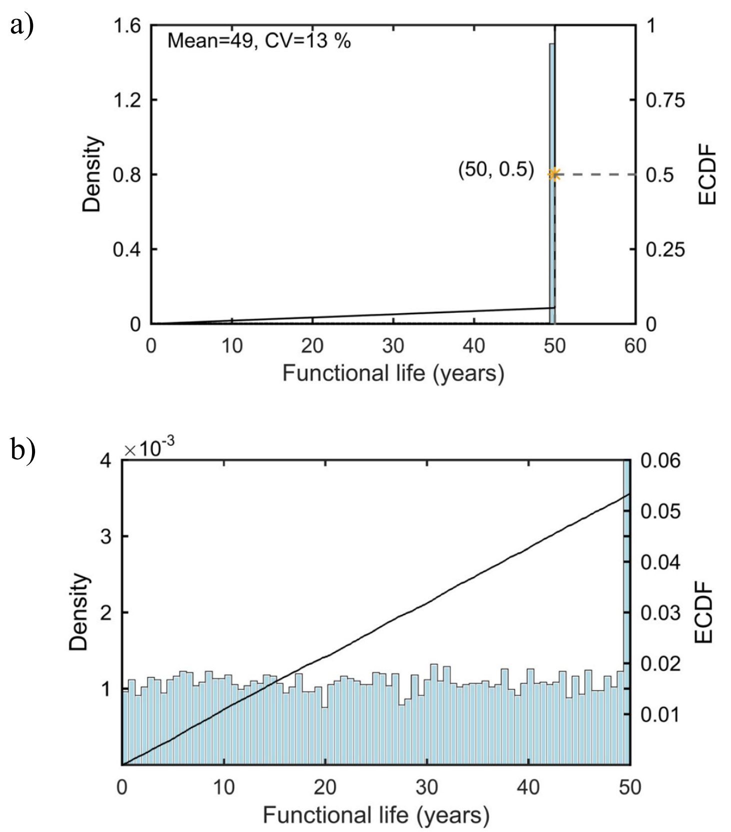

Figure 19. Distribution of functional life conditioned on target life of 50 years.

Part (a) shows complete distribution; (b) zoomed-in view to illustrate reduced functional life due to premature failures.

Based on 10^5 MC realizations, the average functional life of the building, given a target life of 50 years, was found equal to 49 years with a coefficient of variation equal to 13%. Figure 19a shows the empirical density and the empirical cumulative distribution function (ECDF) of the functional life (the empirical density of a random variable represents the fraction of observations in a specified bin divided by the width of the bin, and the empirical cumulative distribution function represents the fraction of observations of the random variable resulting in value less than the specified value). Based on the set of assumptions considered in this study, it can be seen that the probability of functional life being less than target life is ≈5%, and most of the functional life density is concentrated at 50 years. This means the building design could be considered a 'good' design in that it nearly achieves the target design life of 50 years for the given site and hazard. Further, the Figure 19b shows a zoomed in view to illustrate reduced functional life due to premature failures. The figure shows that the 5% cumulative density of premature failures is almost uniformly distributed between 0-50 years.

An advantage of the approach developed in this study is the ability to identify the contribution of individual building component categories to the total repair related EIs. Addressing the multiple issues of sustainability, resilience, and safety in design requires informed decisions based not only on aggregate performance metrics but also identification of key contributors. For example, in Figure 20, the EIs due to repair are disaggregated based on categories of structural vs. non-structural components and acceleration-sensitive versus drift-sensitive components. The figures show the empirical density, empirical cumulative distribution functions (ECDF) for structural, non-structural, drift sensitive and acceleration-sensitive components and also summarize the mean, median and the coefficient of variation (CV) of the corresponding metrics. The results shown in Figure 20 indicate that the environmental impacts due to seismic related repairs is largely from damage to non-structural components (expected value of GWP = 262,035 kg CO_2 eq.) whereas structural components contribute less toward the environmental impact (expected value of GWP = 1,587 kg CO_2 eq.). Furthermore, the drift-sensitive non-structural components constitute a larger portion of the environmental impact (expected value of GWP = 232,846 kg CO_2 eq.) than acceleration-sensitive non-structural components (expected value of GWP = 30,776 kg CO_2 eq.). Although the case study building design could be considered 'good' in terms of functional life from the results presented in Figure 19, there are considerable EI_r from damage to non-structural components and more specifically drift-sensitive non-structural components. Therefore, the environmental performance of the design could be improved by decreasing inter-story drifts without increasing floor accelerations using seismic isolation or viscous fluid dampers for instance.

For the case study building, a flexible moment frame, the structural components were seen to contribute little to the total EI_r and the non-structural damage was seen to contribute most greatly to the EI_r. The reason for this result is because the minor damage states (DS_1) of many of the structural components were characterized by a median inter story drift ratios between 3% - 4% and the moderate damage states (DS_2) were characterized by a median inter-story drift ratios between 4% - 7%, much larger than the non-structural components. The non-structural components showed significant contributions to the EIs because these components are damaged at relatively low inter-story drift ratios or floor accelerations. For example, the partition wall fragility data indicates they will undergo moderate damage and major damage at median inter-story drift ratio equal to 0.71% and 1.20% respectively, well below the inter-story drift ratios required to induce structural damage.

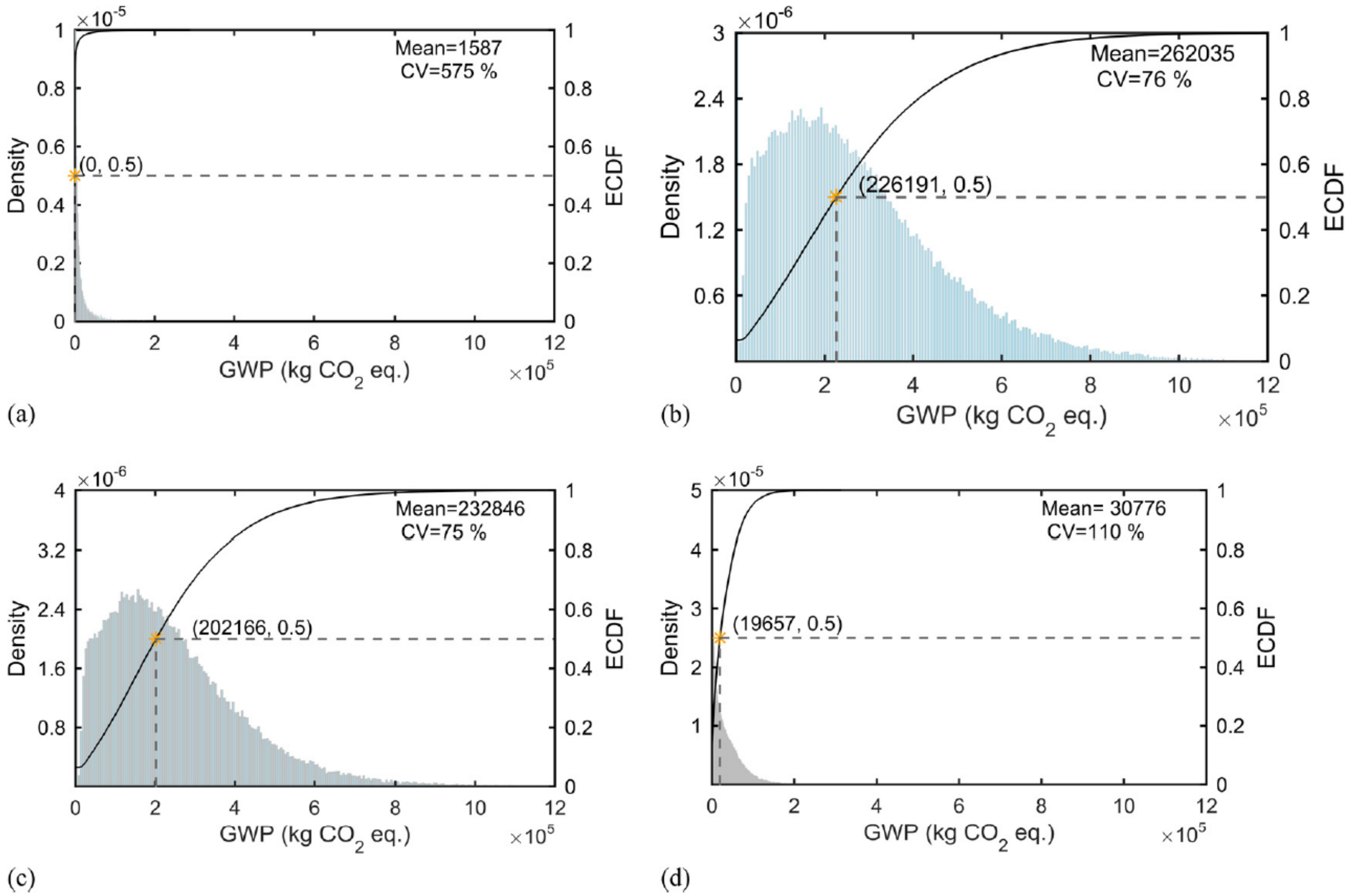

Figure 20. Disaggregation of GWP due to repair actions into component groups.

The results are calculated over the functional life of the building and highlight the contribution of (a) structural components; (b) nonstructural components; (c) drift-sensitive components; (d) acceleration-sensitive components.

Furthermore, the repair of most of the structural components in DS_1 involved welding, which did not contribute significantly towards the environmental impacts related to repair when compared with complete replacement of structural components that would follow from the major damage state. Further, seismic events capable of damaging structural components in DS_2 were not that common for the specified target design life of 50 years, and the few instances of significant structural damage either fell in the irreparable category because of the cost of repair exceeded 40% of replacement cost and/or the residual drift fell in irreparable category. Figure 21 presents the aggregated distribution of GWP calculated over the functional life of the building.

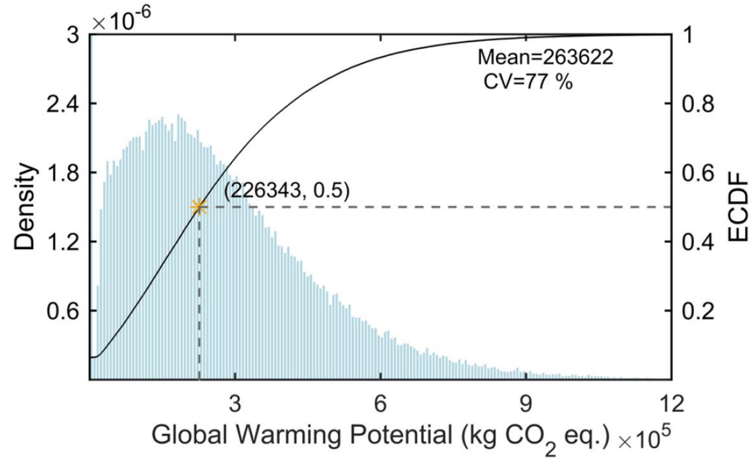

Figure 21. GWP due to repair actions over the functional life of the building.

The aggregated distribution of GWP reflects the total environmental impacts (EI_r) from all components/categories considered for performance assessment of this particular building design. These distributions can be used for the purpose of design decision making, in that, a design with a lower expected value of GWP would be preferred over a design with a higher GWP all other being equal. In general, when comparing design alternatives both environmental impact and functional life criterion should be considered in a multi-criterion context because a design with lower environmental impact might not be preferred if the functional life is also low. Various decision theoretic techniques like maximum return criterion, maximum expected return criterion, maximum expected utility criterion, among others, can be used to make such comparison, however, the exercise of comparing design alternatives is beyond the scope of this study. The mean value of the global warming potential calculated over the functional life was found equal to 263,622 kg CO_2 eq. with a coefficient of variation equal to 77%. To put this in perspective, the total replacement of the building would result in about 8,220,774 kg CO_2 eq., meaning the mean lifetime repairs account for about 3% of the replacement GWP. Comparing the mean GWP of drift sensitive and acceleration sensitive components, it can be seen that the drift sensitive and the acceleration sensitive components contribute approximately 88% and 12% towards the total repair-related GWP.

It should be noted, the results presented in this section are only for illustration of the utility of the approach and are specific to the numerical example considering the 9-story steel moment frame, the structural and non-structural fragilities obtained from the Performance Assessment Calculation tool, PACT (Federal Emergency Management Agency, 2012b) and component specific environmental impact database developed in this study. As such, general conclusions should not be drawn. However, the illustrative results show the value of disaggregating the EIs by building component categories and in estimating the functional life for design decision-making. Modification to the structural design, non-structural components, fragility database, environmental impact database, target design life of the building, etc., could change the amount and distributions of EIs due to repair.

5.4 CONCLUSION

The outcome of this study is a rationale probabilistic approach to quantify the environmental performance and functional life of buildings subjected to multiple hazard events over a target design life. The approach accounts for uncertainty in the intensity and time of occurrence of events, structural analysis, estimate of damage as well as uncertainty and variability in environmental impacts from material production. The environmental performance indicator, global warming potential, was calculated directly from the materials needed to repair different structural and non-structural components from earthquake-related damage. The approach accounts for the fact that a building designed for a certain target life can undergo 'irreparable' performance before reaching the target design life and hence provides a means to estimate the functional life and the environmental impacts over the functional life. The outcomes of the performance assessment are in the form of a probability distribution of the environmental performance indicator, global warming potential, conditioned on a target design life of a building for the entire building system and individual components. The results in this format can be readily integrated with the results of conventional LCA phases such as construction, maintenance, use phase energy, and the resulting metric can be used to reveal the tradeoffs amongst different design alternatives for completing objectives such as environmental performance, costs, and hazard-related economic losses. By considering damage at the individual component level, the approach presented here can be used to determine the distribution of damage amongst building component categories, for example, structural versus non-structural, to identify the most effective alternative design strategies for improving the environmental performance and functional life of a building.

The utility of the approach is demonstrated through application to a 9-story steel office building designed for the seismic hazard level in Los Angeles, CA. Process-based LCA is used for the analysis of individual structural and non-structural components, on a material level, to obtain environmental impacts of the production of those components. Having this set of data allows for a direct association of environmental impacts to damage state specific repair actions. The obtained data also include uncertainty information that is carried throughout the assessment. The results of the case study are analyzed to identify the contribution of different structural components, non-structural components, drift sensitive components, and acceleration sensitive components to the total environmental performance. The illustrative results from the case study highlight the utility of the environmental performance and functional life estimates for the purpose of design decision-making. For the specific building design considered in the case study, it was seen that both the acceleration-sensitive and drift-sensitive components had a significant contribution in the total repair related environmental impacts which are unlikely to be adequately captured using nonlinear static analysis procedures, for example, push-over analysis. The results presented here are specific to this case study building and the fragility data used in this study and cannot be generalized.

Limitations of the current study are summarized next. (1) Variability of functional life only due to failure under seismic events was considered in this study. It is noted that the vulnerability to non-seismic hazards, extensive structural deterioration, and change in occupancy can also result in reduction of the functional life of a building design; (2) the effect of structural deterioration on building performance is neglected in this study; (3) only the environmental impacts due to seismic hazard-related repair actions are considered and the study does not include the on-site construction, regular maintenance, operation, and end-of-life disposal; and (4) apart from the uncertainty in the environmental impact data considered in this study additional uncertainty, or variability, is introduced from the component and material estimation process and the selection of the most appropriate unit processes from a life cycle database, neither of which are captured in this study's uncertainty data. Although the above-described limitations are worthwhile research pursuits, they are beyond the scope of the current study. Future studies may consider a complete set of building components, the impact of structural deterioration on its environmental performance, and examine buildings of different use.

6.0 BUILDING LCA SENSITIVITY STUDY

This chapter is focuses on addressing Objective C. The goal is to understand the influence of design decisions across a wider range of life cycle stages when incorporating findings from Objectives A and B. Appendix D provides supporting information related to this chapter.

6.1 INTRODUCTION

Buildings account for over 40% of energy use and 30% of greenhouse gas emissions globally (Levine et al., 2007). With residential and commercial building space expected to continue to rise (Abergel et al., 2017) there has been a substantial push towards more sustainable and resilient buildings. There have been many approaches to address building performance in this area including changes in mandatory building codes, development of rating systems, creation of qualitative assessment and guidance documents, and development of quantitative assessment tools (Hasik, Chhabra, et al., 2017). Despite the growing knowledge in this field and options in quantitative assessment tools, there often seems to be narrow focus on assessing individual performance aspects of buildings independently instead of understanding them holistically (N. Wang et al., 2017). Additionally, many sustainability and resilience strategies are most effective when considered from the early onset of design, but in current practice they are often not considered and evaluated until the later phases (Schlueter & Thesseling, 2009). To address these issues, this study focuses on quantitative analysis of sustainability and resilience of buildings from a broader life cycle perspective while utilizing approaches feasible for early design phases.

Life cycle assessment (LCA) is one of the most frequently used tools for quantifying environmental aspects of sustainability, as it provides ways of assessing resource and emissions flows throughout the life cycle of products and processes. Similarly, life cycle costing (LCC) is also utilizing the life cycle approach, but from an economic perspective. Resilience, while inherently related to sustainability (Hasik, Chhabra, et al., 2017), focuses on the ability of products and systems to react and adapt to disruptions or deviations from normal operations (Fiksel, 2003; Holling, 1973). One of the most common ways of studying and addressing the resilience of buildings has been through assessment of potential effects of natural hazard events on their structural integrity, for which there have been various developed assessment methods (Hasik et al., 2018; Matthews et al., 2016). This study focuses on using a life cycle perspective together with resilience.

Most early whole building LCAs were done as retrospective case studies of residential, office, and educational buildings (Adalberth, 1997b; Junnila et al., 2006; Scheuer et al., 2003). While case studies are valuable for improving our understanding of building's environmental performance, they have limited potential in providing widespread guidance to other buildings due to buildings' functional and temporal specificity. We know that buildings have many attributes (e.g. based on aesthetic, psychological, space, energy, and other requirements) that make them unique and difficult to compare. Nevertheless, Scheuer et al. (2003) specifically was one of the most complete early building LCA studies, accounting for the most LCA stages and functional aspects such as on-site material use, operational energy use and source types, and water demands and treatment. Most subsequent whole building LCAs have focused mainly on material use and/or operational energy use. Figure 22 shows the various life cycle stages identified in international standards (EN, 2011; ISO, 2010) and the subjective frequency of investigation in building LCA literature.

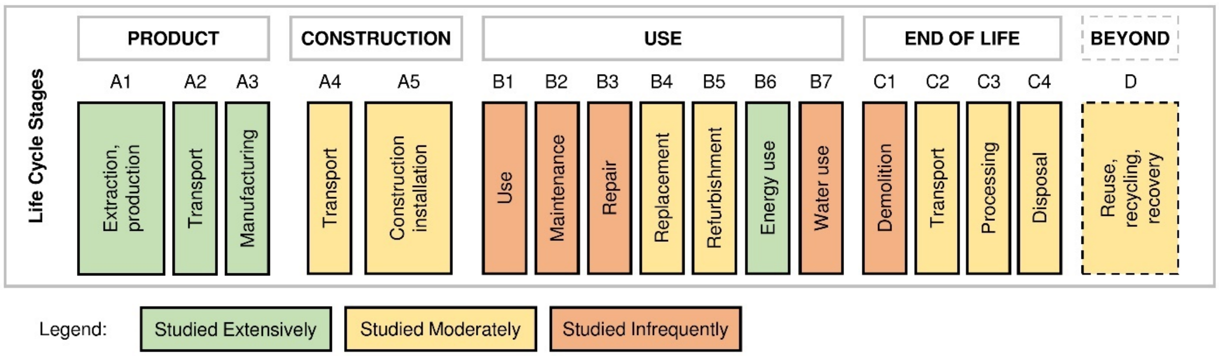

Figure 22. Frequency of investigation of various building life cycle stages.

(adapted from ISO 21931 (ISO, 2010) and EN 15978 (EN, 2011))

Related to LCA, the energy demand as well as energy related impacts are usually calculated based on reported numbers for case study buildings or have been obtained using simulation results (Adalberth, 1997a, 1997b; Stephan et al., 2012). Bawden and Williams used national energy consumption database to obtain energy demand and then applied factors to obtain the total energy related impacts (Bawden & Williams, 2015), while Berggren et al. used similar approach but using energy demand data from a different database of green building certified in Europe (Berggren et al., 2013). Al-Ghamdi and Bilec (2015) have also investigated differences of material and energy-use related environmental impacts across multiple locations around the world based on model simulations.

As shown in Figure 22, operational water use is also listed in the ISO 21931 (ISO, 2010) and EN 15870 (EN, 2011) standards for environmental impact assessment of buildings; however, it is almost entirely missing in building LCA literature due to perceived low importance. There have been numerous water and wastewater life cycle studies outside of the building LCA literature (Kavvada et al., 2016; Machado et al., 2007; Shehabi et al., 2012; J. R. Stokes & Horvath, 2009), with some of these studies being conducted by researchers informing certification schemes (Sisolak & Spataro, 2011; Spataro et al., 2011); however, the knowledge is not always successfully relayed to building designers. Major LCA databases such as ecoinvent (Wernet et al., 2016) or GaBi (thinkstep AG, 2019) do contain data needed to include water-related impacts. Although this generic data may not exactly represent processes and infrastructure in specific locations, it can still provide a useful context for other areas of the building assessment. The disconnect between water and building related life cycle studies has resulted in some progressive buildings in pursuing treatment technologies detrimental to some aspects of their environmental performance (Hendrickson et al., 2015). Studies focused on comparing varying treatment types have found great differences in impacts and have pointed out the potential significance of water treatment when related to buildings.

With increasing concern over the resilience of infrastructure, there have been efforts to bring resilience aspects into the LCA field. This has included efforts to bridge the development in the hazard loss assessment and performance-based design field with LCA specifically related to earthquake (Hasik et al., 2018) and hurricane engineering (Matthews et al., 2016). Including these aspects may help in addressing the current limitation of building LCA which focuses largely on material quantity reduction and consideration of component service life based mainly on assumptions. Including potential repair demands based on hazard damage can capture the benefits of enhanced structural systems and need for premature replacement of damaged components. Repair is also listed in the ISO and EN standards; however, limitations related to data availability and approaches to such assessment have left this stage largely unaddressed. Simonen et al. (Simonen et al., 2018) were also the first authors developing a database related specifically to this stage.

Including some of these other life cycle stages may become more important with the shift in building technologies improving energy efficiency, enabling more on-site resource harvesting, and using advanced structural systems (Belleri & Marini, 2016; Berggren et al., 2013; Blengini & Di Carlo, 2010).

Parametrization and sensitivity studies in LCA generally fall within two categories: 1) studies aimed at understanding how study setup, assumptions, and LCA methods affect study outcomes, and 2) studies aimed at understanding the variability in life cycle results for alternative building designs. Studies falling within the first category have investigated the sensitivity of environmental impacts to service life of building components (Aktas & Bilec, 2012b; Carlisle & Friedlander, 2016; Hoxha et al., 2014), building lifetimes and study periods (Aktas & Bilec, 2012a), life cycle inventory data and tools (Al-Ghamdi & Bilec, 2016; Häfliger et al., 2017), changes in boundary definitions (Häfliger et al., 2017), variability in component quantities (Hoxha et al., 2014), and level of detail in modeling components (Kellenberger & Althaus, 2009). Studies in the second category have typically aimed to improve the understanding and selection of the best physical designs of whole buildings (e.g., size, shape, orientation, etc.), systems, and materials (e.g., wall types, window types, HVAC types, etc.). Studies in the second category are also more aligned with the nature of this study; however, they have typically narrowed down their focus on embodied impacts from production of envelope systems and the effects on operational energy use.

One of the earlier studies in the second group was a multi-objective optimization study by W. Wang et al. (2005), which considered life cycle costs and environmental impacts related to inputs consisting of varying envelope parameters and building shapes. Similarly, Basbagill et al. (2013) used EnergyPlus, RS Means cost data, Whitestone maintenance database, Excel, and Matlab to obtain impacts for almost 6000 unique design combinations. The parametric aspects of the study considered varying material types and thicknesses for structural, envelope, interior, and equipment components, as well as building shape, and number of floors. More recently, multiple studies have focused on using parametric approaches to identify significant model inputs and interaction effects between energy demand, thermal comfort, daylight and the embodied impacts of materials in various envelope systems (Hester et al., 2017; Hester, Gregory, et al., 2018; Hester, Miller, et al., 2018; Østergård et al., 2017; Rodrigues et al., 2018). Although research in this area is growing, a study by Bukoski et al. (2017) have done one of the only parametric studies that looked at varying types of structural systems and operational energy sources.

Parametric and sensitivity studies have the potential to find optimal solutions as opposed to the traditional one-at-a-time approach (Østergård et al., 2017). Conversely, most building LCA tools are setup for manual comparisons of individual design alternatives. While valuable for making material selections during later stages of project delivery, this approach limits the ability to consider the effects, interactions, and tradeoffs of more widespread design changes. Certification systems such as LEED currently address building LCA from material use and require percentual reductions from an arbitrary reference design (USGBC, 2014). Living building challenge requires carbon emission reductions, where life cycle assessment can be helpful for documenting such reductions and can span both material and energy impacts, but often overlooks other life cycle aspects (McLennan & Brukman, 2012). One of the major hurdles for implementation of building LCA in practice has been the difficult task of identifying useful benchmarks. One recent development in this area has been a study by Simonen, Rodriguez, et al.

(2017) where the authors collected a most extensive collection of cumulative LCA results to date. While this study was a significant step towards creating a more standardized and level playing field, it still considers a relatively small sample size of buildings relative to the wide range of possibilities.

No study to date has looked comprehensively at a wide variety of impact categories and costs for varying building designs across different locations while accounting for material, energy, and water performance of buildings simultaneously. There are two main objectives this chapter aims to address: 1) include typically excluded water and repair stages within a whole building life cycle study, and 2) consider multitude of options within various building design and service parameters to understand the range of effects on the building's economic and environmental performance. Additionally, the study uses the same approach for the analysis of conceptual building designs in two different locations to consider some of the geographical effects on the results. The objectives are achieved using life cycle assessment, life cycle costing, and hazard loss assessment in a broader building life cycle framework; the broadest set of parameters in this kind of assessment to date known to the authors. The presented approach or an adapted version of thereof could potentially be used for benchmarking or decision making in LCA and green building rating systems based on specific building type and location.

6.2 METHODS

6.2.1 Framework & tools

The first part of this chapter focuses on establishing the framework for a parametric assessment of building performance using LCA, LCCA and hazard loss assessment methods. Figure 23 shows the overview of the simulation, beginning with 1) the specification of general building characteristics, model design options, and service options, followed by 2) energy simulation (using EnergyPlus in this study) of all physical variations of the building, 3) application of predefined service-related scenarios and calculation of material costs and impacts, and 4) results analysis. The entire simulation shown in Figure 23 was coded with Python programming language to allow for automation and easy adjustment of parameters of interest. Various data inputs are needed throughout all phases of the simulation and are further discussed throughout the rest of this section.

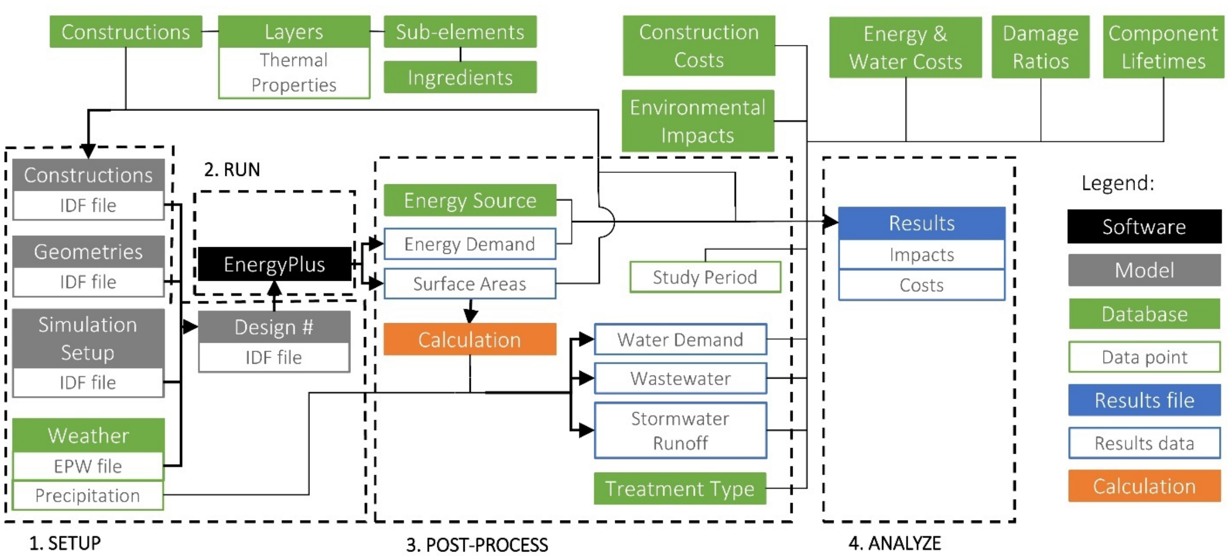

Figure 23. Overview of the simulation setup.

(IDF = EnergyPlus input data file, EPW = EnergyPlus weather fie)

6.2.2 Scope and boundaries

Figure 24 shows the life cycle stages and building systems included in the sensitivity analysis. At the building scale, the boundary focuses on materials, components, and systems that typically have the largest share of material-related impacts, are affected by the changes in the building's shape, or affect the building's energy consumption. More specifically, this includes structural, enclosure, and some interior components (further discussed in section 6.2.3). Standard mechanical, electrical, and plumbing (MEP) systems within the building are excluded due to no expected changes between building design alternatives and the difficulty of modeling those systems for LCA purposes; however, any MEP components related to on-site water conveyance, storage, and treatment as well as on-site energy generation (i.e. photovoltaic installations) are included for designs utilizing those systems. This makes the system boundaries for both the off-site and on-site energy generation and water treatment comparable. Note that life cycle stages A4 & A5 are not included in this study; however, the impacts in those stages are typically low relative to product-stage impacts (Scheuer et al., 2003).

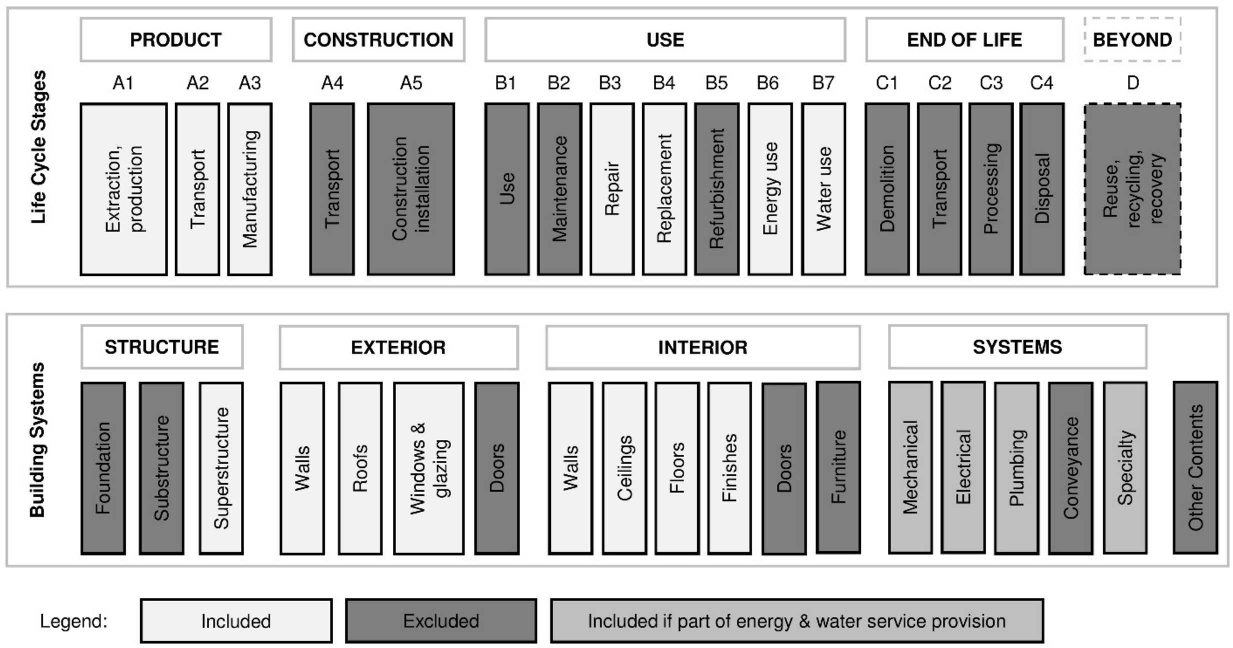

Figure 24. Scope of included life cycle stages and building systems.

6.2.3 Study & model setup

6.2.3.1 Project & climate setup

The onset of discussions about a new building typically has some broader project objectives firmly set. In this case, the following parameters were considered as known and fixed: building use type, gross building area, study period, and location. Keeping these parameters constant for a given project ensures comparability of various design and service options. Fixing some of these parameters is also equivalent to defining the functional unit in LCA studies and ensuring fair comparison across alternatives. This study focuses on the assessment of medium office buildings and could easily be adjusted for use on other use types, depending on the availability of related models and data (e.g., energy model inputs, water consumption profiles, etc.).

The buildings are analyzed in two locations, Philadelphia, Pennsylvania and Oakland, California, with the intention to understand how varying climatic conditions, hazard exposures, infrastructure systems, and service cost scenarios affect the results. Climate data for these locations includes 1) weather files for the energy models, 2) design day files for sizing HVAC systems and 3) precipitation data for stormwater runoff calculations. Weather files and design day files were obtained from the EnergyPlus website, while precipitation data was obtained from the National Oceanic and Atmospheric Administration (NOAA).

Sensitivity of HVAC system and operational parameters were not the focus of this study and were, therefore, fixed at a single option, although their parametrization could be implemented in future studies or practical applications. Other studies have already investigated these parameters' effect on operational energy use of commercial (Heller et al., 2011) and residential buildings (Hester et al., 2017).

Table 7. Fixed project and design parameters.

Parameter	Details
Gross area	~ 5,000 m^2
Building type	Medium office building
Shape	Rectangular
Aspect Ratio	1.5
Floor to ceiling height	2.74 m
Floor to floor height	3.96 m
Perimeter zone depth	5 m
Slab on grade type	Slab A*
Interior floors	Floor A*
Structural frame type	Moment frame
HVAC system	ASHRAE 90.1-2013 Medium Office defaults (exported from OpenStudio)
Schedules & Loads	ASHRAE 90.1-2013 Medium Office defaults (exported from OpenStudio)
Occupancy	ASHRAE 90.1-2013 Medium Office

* Additional material details are provided in Appendix D

Table 8. Location sensitive parameters.

Parameter	Details
Energy sources	Grid mix and solar potentials for a given location
Structural quantities	Dependent on wind and seismic loading of a specific location
Water runoff	Depends on rainfall and snowfall in a given location
Damage repair	Depends on the probabilities of seismic damage in a given location
Energy use	Depends on the climatic conditions in a location

Table 9. Parameters and options for sensitivity analysis.

Parameter	Options
Stories	3, 6
Exterior wall types*	Exterior Wall A, Exterior Wall B
Window types*	Single glazed, Double glazed
Window-to-wall ratios	0.1, 0.33, 0.6
Roof types*	R15 XPS, R40 XPS, R15 PIR, R40 PIR
Structural materials	Steel, Concrete
Energy sources	NERC Grid-Mix, On-Site Solar
Potable sources	Centralized Conventional, Centralized Direct Filtration
Sewage treatment	Centralized, On-Site Septic Aerobic, On-Site Septic Anaerobic
Runoff treatment	Centralized, None
Total combinations:	4,608

* Material composition, physical properties, and service lives of components are included in Appendix D

6.2.3.2 Building design

The building geometry is based on the Department of Energy (DOE) Medium Office Reference Building model (Deru et al., 2011) with adjusted dimensions. The DOE model for medium office building is a 3-story, square building and includes four perimeter zones, one core zone, and one plenum zone on each level (shown in Figure 25). The geometry is adjusted for the sensitivity analysis based on inputs of gross building area, building shape, aspect ratio (north-south to east-west length), floor-to-ceiling height, floor-to-floor height, number of stories, and window-to-wall ratio (WWR). Some of these parameters are fixed according to Table 7 while number of stories and window-to-wall ratios are adjusted according to Table 9.

All surfaces defined in the energy model also require all of the construction layer properties, including roughness, thickness, conductivity, density, specific heat, thermal absorptance, solar absorptance, and visible absorptance for opaque surfaces and u-factor, solar heat gain coefficient, and visible transmittance for windows. These properties were obtained from the National Renewable Energy Laboratory's (NREL) OpenStudio and Building Component Library datasets (National Renewable Energy Laboratory, n.d.-a) and are shown in the Appendix. Some of the properties, such as thickness and density, are also used to create quantity estimates for material impact and cost calculations. Depending on the impact and cost factors' unit of measurement, the algorithm automatically converts the area quantity to either area, volume, or weight quantities using the other dimension and physical information associated with each surface (e.g. thickness) and material (e.g. density). This approach of automatic unit conversion is crucial for components or materials which use different approaches for estimating impacts and costs. For example, clay bricks may have an environmental impact factor for 1 kg of clay brick material, while its cost factor is based on 1 m^2 of wall area using brick of a certain size.

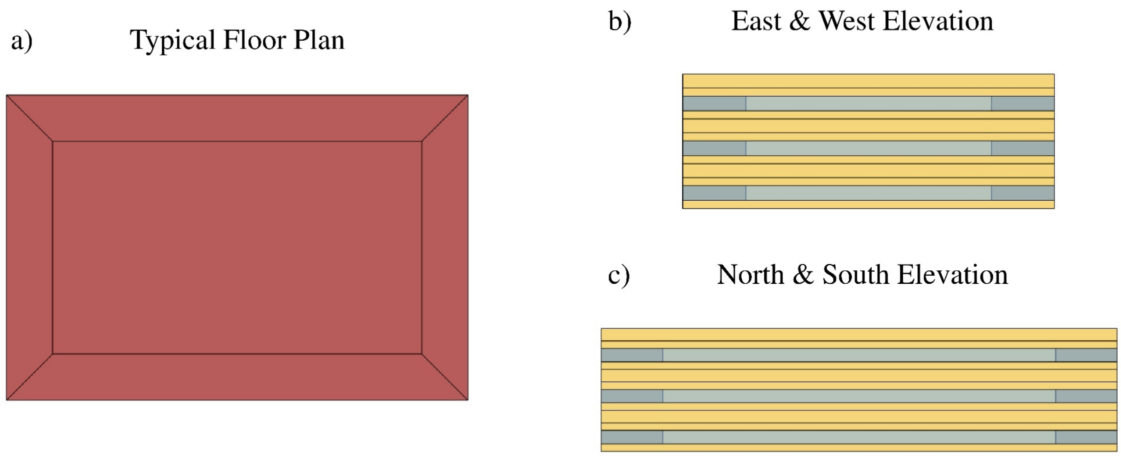

Figure 25. The Department of Energy Medium Office Reference Building model.

The figure shows the base model's a) typical floor plan with four perimeter zones and one core zone, b) east and west elevation, and c) north and south elevation with glazing and plenum spaces.

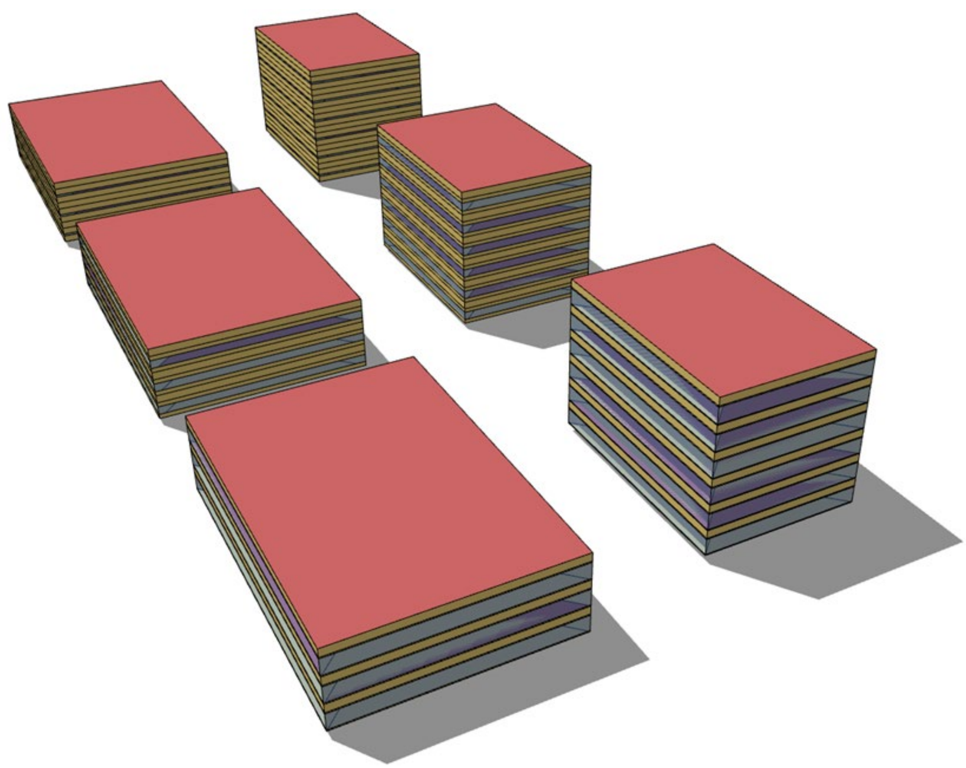

Figure 26. Building shape and window-to-wall ratio variations.

Building shapes include 3-story and 6-story buildings with window-to-wall ratios of 0.1, 0.33, and 0.6.

Structural quantities were obtained from the Skidmore, Owings and Merrill Environmental Analysis Tool™ (SOM EA Tool™) (Skidmore Owings & Merill, n.d.). This tool was developed by SOM structural engineering team based on data from hundreds of SOM projects and an observation of general trends in various structural systems. The structural quantities for the superstructure are determined based on the following 4 parameters: main structural material, number of stories, wind loading, and seismic loading. The tool's superstructure quantities include floor materials which were also included in the energy model and were therefore subtracted to avoid double-counting. Although the SOM EA Tool allows for analysis of multiple types of superstructure systems, this study only considered conventional steel and concrete moment frames. The decision to limit the analysis only to these two systems was based on the limited choice sets in the Hazus software for loss analysis and the assumptions that moment frames are the most representative of the general building stock in the presented scenario.

Cost data for all building materials come from RS Means Building Component Cost book (RS Means, 2016) and environmental impact data is obtained from the ecoinvent database (Wernet et al., 2016). Most of the components considered in this study are components which can be shipped long distances from their manufacturing facility, justifying the use of national or even global average data for environmental impact assessment. However; one unique material in this sense is concrete, which is typically a material sourced locally and its associated impacts may be highly dependent on the regional material extraction and supply networks (Athena Sustainable Materials Institute, 2016). This study does not take this geographic uniqueness of concrete (and other materials) into account and could be addressed in future studies of this kind.

The physical model and component information is then used to run EnergyPlus simulation for each building design scenario and obtain the energy consumption estimates for the particular design, further linked with service options discussed in section 6.2.3.3 for cost and environmental impact calculations. Water consumption is based on the buildings gross area and building type using US average data from the 2012 Commercial Buildings Energy Consumption Survey (U.S. Energy Information Administration, 2017). The on-site water treatment scenarios discussed in section 6.2.3.3 also require input of building occupancy, which use the same approach as the energy model's DOE reference building national average data for occupancy based on a building type. For example, office buildings are expected to provide about 18.6 m^2 of space to each occupant, which can be used to calculate the total occupancy of the building (Deru et al., 2011).

6.2.3.3 Service options

The electricity demand of a particular building design is combined with the type of electricity supply option, which includes either a location-specific grid-mix source or an on-site photovoltaic (PV) system installation (as shown in Table 9). It should be noted that in the PV scenarios showcases an idealized scenario where there is no space limitation constraint put on the size of the system (e.g. roof area) and there is no consideration to the temporal variations and potential need for energy storage. The cost of grid electricity was obtained via an application programming interface (API) service from the U.S. Energy Information Administration (EIA) (U.S. Energy Information Administration, 2019) and applied to the specific energy consumption of each building design scenario on a kWh basis. Similarly, PV system installation costs were obtained via an API service from the NREL Open PV project which collects non-utility-based PV system data from actual projects around the United States (National Renewable Energy Laboratory, n.d.-b). Solar energy potential for sizing of the on-site PV system was also obtained via an API service from NREL's PV Watts project (National Renewable Energy Laboratory, n.d.-c). Environmental impact data for the grid-mix electricity is based on ecoinvent data for each of the US-based regions defined by the National Energy Reliability Corporation (NERC). The PV system environmental impact data is also based on ecoinvent data and scaled to the size needed to supply each building design with enough energy, similarly as in the cost calculations.

Environmental impact data for centralized water and wastewater treatment was based on ecoinvent inventory with adjusted electricity supply mix for the NERC region where the building is located. This approach captures the average centralized treatment operations but does not capture the location-specific differences in treatment plant management, which could substantially change the outcomes (Chini & Stillwell, 2018) and could be addressed in future studies. Environmental impacts for on-site treatment systems considered physical infrastructure, operational energy use, and direct emissions and were based on data from a study by Hasik, Anderson, et al. (2017) and scaled to the size of the buildings considered in this study. The data includes both initial and recurring impacts associated with on-site treatment systems. The costs associated with an on-site water treatment system were obtained from the EPA's Onsite Wastewater Treatment Systems Manual (U.S. Environmental Protection Agency, 2002) and also include both capital and recurring costs. Water and wastewater costs are based on a U.S. Department of Energy report (U.S. Department of Energy, 2017) which collected the potable water and wastewater treatment costs for consumers in about 20 major cities around the US. The provided information includes the utility name, city, state, and cost data in 2016 US dollars per 1,000 gallons (3.78 m^3) of water. While there may be slightly different rates for commercial customers, these rates are expected to be roughly representative of rates for office buildings.

6.2.3.4 Repair & replacement

Regular replacement of components in the building is approached using typical component service life method, where the component impacts and costs are multiplied by the number of units needed in the building over the study period. This is an idealized and simplified scenario used in most building LCA tools and assumes equal replacement in the future regardless of technological changes or maintenance regimes. In the sensitivity analysis specifically, most of the structural systems are expected to last the entire study period, while glazing systems, gypsum board walls and ceilings, and roof membranes are defined as having a 40-year service life and carpet having a 15-year service life (all assumed component service lives are provided in Appendix D).

Costs and impacts in the repair stage are based on hazard loss assessment coupled with LCA and LCCA. Specifically, this study used an approach that uses the Hazus tool (Federal Emergency Management Agency, 2018) developed by the Federal Emergency Management Agency (FEMA) for regional studies on earthquake, hurricane, and flooding hazards. This tool is more appropriate for regional studies of the general building stock instead of single building designs but it does feature the Advanced Engineering Building Module that can be used for analyzing individual buildings (Federal Emergency Management Agency, n.d.). It was deemed suitable enough for this study based on the early design (low specificity) focus, investigation of a "typical building", and the design size and simplicity. The specific data used in this study was based on default Hazus models for office buildings built with steel and concrete moment frames and designed to a high code, which were most representative of the conditions studied in this study.

While the Hazus tool provides results in economic costs of damage to the study building it does not provide environmental impact estimates. Environmental impacts were calculated by applying the economic loss ratios to groups of components (i.e. structural, non-structural drift-sensitive, non-structural acceleration-sensitive, contents) to the initial manufacturing and construction impacts of the building (Hasik et al., 2018). The loss ratios represent the annualized losses from a probabilistic seismic loss assessment aggregated over the study period of the analysis. It should be noted that probabilistic seismic loss results are ideally represented with probability distribution functions; however, Hazus and this study rely on a deterministic representation by using only the median values. Additionally, Hazus enables the loss assessment associated with other natural hazards such as hurricanes and flooding, which could be implemented in future studies.

6.2.4 Decision metrics

Decision metrics (also referred to some as decision variables or design objectives) considered in this work consist of economic costs and various environmental impact categories. All economic cost data in this study uses US dollar as the currency; however, different tools within this study may rely on different reference years and are adjusted accordingly using the RS Means historical cost index (RS Means, 2016). All results shown in this study represent the 2016 US dollar currency, based on the main data source used for this purpose. Environmental impact results are based on the TRACI 2.1 characterization method (Bare, 2012a). Although this method covers 10 different impact categories by default, this work focused on a narrowed down scope including only the 6 impact categories that are typically reported for LEED certification and in environmental product declarations (EPDs). This includes the following impact categories: ozone depletion potential (ODP) in kg CFC-11 eq, global warming potential (GWP) in kg CO_2 eq, smog formation potential (SFP) in kg O3 eq, acidification potential (AP) in kg SO2 eq, eutrophication potential (EP) in kg N eq, and fossil fuel depletion (FFD) in MJ surplus (USGBC, 2014).

While many of the methods used within this assessment are simplified approximations of the general building stock, they are expected to be sufficient in this work for understanding the relative influence of various aspects of typical buildings. More robust tools and methods could be used within individual parts of the overall framework for improving the utility on specific projects.

6.3 RESULTS AND DISCUSSION

6.3.1 Overall results across locations

The simulations for all the combinations of the parameters from Table 9 yield 4,608 unique buildings in each of the studied locations. Figure 27 shows the total life cycle results for a 60-year study period for each of the 4,608 buildings across all metrics. Each building is represented by a single circle. As an example, the black circles represent a single building design and service combination scenario out of the 4,608 possibilities (the building's parameters are shown in Table 10). Many of the buildings' totals in a given metric are so close to each other that they form a visually continuous line, but in fact they are many clustered circles. This clustering indicates that there are many buildings whose design or service decision differences yield very small differences to the overall results in that metric. Conversely, large gaps between these clusters indicate a major influencing factor splitting the results clusters apart. For example, all environmental metrics for buildings in Philadelphia show two major clusters which are associated with the buildings' use of either grid (upper cluster) or solar (lower cluster) electricity in their use stage. On the other hand, the ozone depletion category for Oakland buildings appears almost fully continuous, indicating that there are more equal contributions to the life cycle impacts across all the different design and service aspects. Most of the environmental impact metrics only show one major split, indicating that the influence of other factors (e.g. shape, window-to-wall ratio, etc.) is more evenly distributed. The cost metric shows a hint of additional splits, especially in the Oakland buildings, indicating multiple factors with larger differences in influence on the overall results. More on the influence of individual design decisions is discussed in section 6.3.3.

The presented analysis approach can be used in practice to gain an understanding of the design's reductions from worst case scenarios in each of the metrics. In other words, the generated results can be used as benchmark values specific to the building under study. This way of visualizing the results also allows for seeing tradeoffs across different metrics. For example, the select buildings in Figure 27 were picked as the buildings with the lowest GWP, and also happen to have close to the lowest ODP, SFP, AP, and FFD; however, they are not amongst the buildings with the lowest cost. Table 10 shows the select buildings' parameters, i.e., the parameter combinations that result in the lowest GWP in each respective location. While most of the parameters between the lowest GWP designs in Oakland and Philadelphia are the same, there are changes in the window type, roof type, and structural material parameters. The selections indicate that the Philadelphia building benefits from the increased insulating properties of the double-glazed windows and thicker roof insulation even though it increases its embodied GWP. Conversely, in the milder Oakland climate the embodied GWP of those components becomes more important and having a low window-to-wall ratio and well-insulated walls is sufficient for reducing operational energy use. It is likely that if the accompanied database and number of possible parameters increased, there would be even larger number of observed tradeoffs between locations, decisions, and metrics, and could be further explored in future studies.

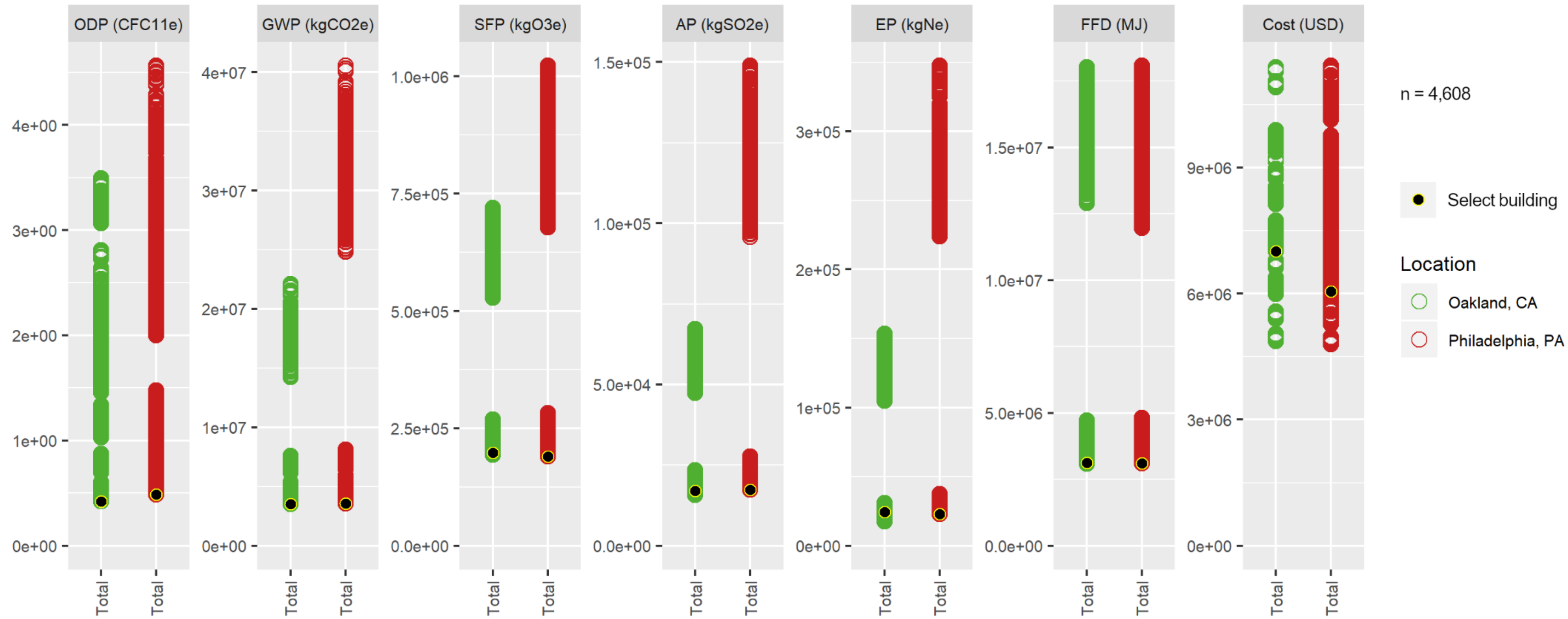

Figure 27. Overall life cycle impacts and costs for 4,608 buildings.

Each circle represents a building with unique design and service parameters from Table 9.
A select building is highlighted as an example of a single unique design and service combination scenario.

Table 10. Parameters and global warming potential results for select buildings.

The buildings shown have the lowest total global warming potential over a 60-year study period.

	Oakland	Philadelphia
Stories	6	6
Window-to-wall ratio	0.1	0.1
Exterior wall type	Exterior Wall B	Exterior Wall B
Window type	Single Glazed	Double Glazed
Roof type	PIR R15	PIR R40
Structural material	Steel	Concrete
Energy source	On-Site Solar	On-Site Solar
Potable source	Centralized Direct Filtration	Centralized Direct Filtration
Sewage treatment	Centralized Treatment	Centralized Treatment
Runoff treatment	None	None
GWP (kgCO2e)	3,185,787	3,247,521

6.3.2 Performance across life cycle stages

Figure 28 shows the results for the same 4,608 buildings as in Figure 27 (representing design and service variations from Table 9), except the results are broken down by life cycle stages. In other words, where each circle in Figure 27 represented the total result for each building, in Figure 28 that total result is broken up into five circles each showing the contribution of a particular life cycle stage (i.e. manufacturing, repair, replacement, energy use, and water use). The result show that, as expected, operational energy use amounts to significantly higher impacts and costs across both locations, and that those impacts and costs are higher in Philadelphia than Oakland. This finding is not surprising based on previous studies and mostly reinforces that knowledge. The likely reason for Philadelphia having higher environmental impacts in this stage is due to the harsher climate and fossil-fuel-heavy electricity grid. The lower end of the energy use stage's environmental impacts is associated with the sourcing of electricity from on-site solar panels. Figure 29 shows the same results but only for the 2,304 buildings with on-site photovoltaic systems, in which case the impact of other stages becomes almost equally if not more important. This is true especially in the ozone depletion, global warming potential, and eutrophication impact categories, where the importance of building material and water related impacts increases. Another interesting finding when focusing on costs between the scenarios with only on-site solar energy and both solar and grid sources is the fact that solar electricity is in the lower range of costs of energy use in Oakland and upper range in Philadelphia. This means that while the environmental benefits are similar in both locations, there are location-specific economic tradeoffs.

Material manufacturing impacts are low relative to the complete energy source scenarios but show noticeable spike in the ozone depletion impact category. The relative influence of the material manufacturing stage to the energy use stage in the solar energy source scenarios is almost identical across global warming potential, smog formation, and fossil fuel depletion categories. The manufacturing-related economic costs appear to have a relatively large and even spread between the individual data points, indicating many similarly priced design alternatives amongst the studied set of designs. The costs of materials are also seen to be relatively closer to the energy use stage costs than is the case across the environmental metrics. It should be noted that the results show the total life time impacts, and therefore the manufacturing stage relative to use stage impacts change relative to the length of the study period. In other words, if a 30-year study period was considered instead of the 60 years, the relative influence of the manufacturing stage would increase, while with a longer study period it would decrease (contingent on the replacement periods for various types of components and materials).

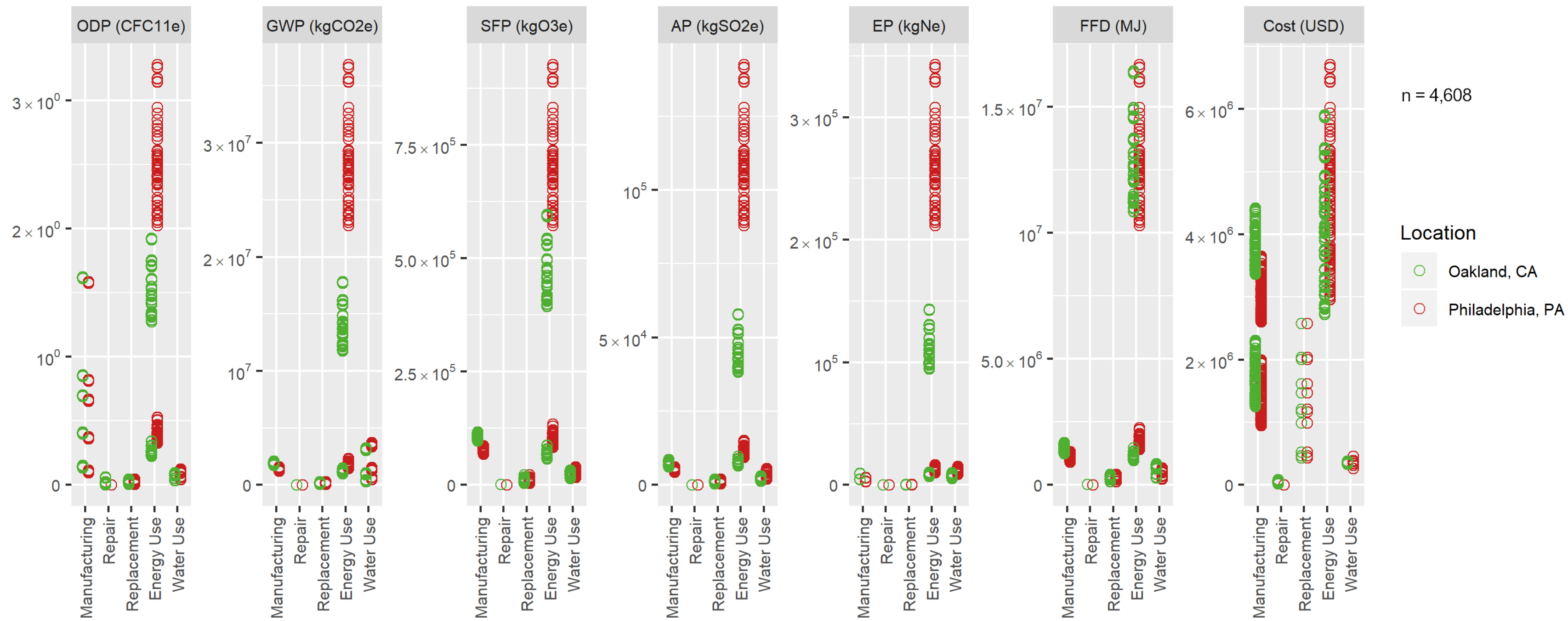

Figure 28. Impacts and costs for 4,608 buildings broken down by life cycle stage.

Each circle represents the total for each of the 4,608 buildings (parameter combinations based on Table 9) related to a specific life cycle stage for a study period of 60 years.

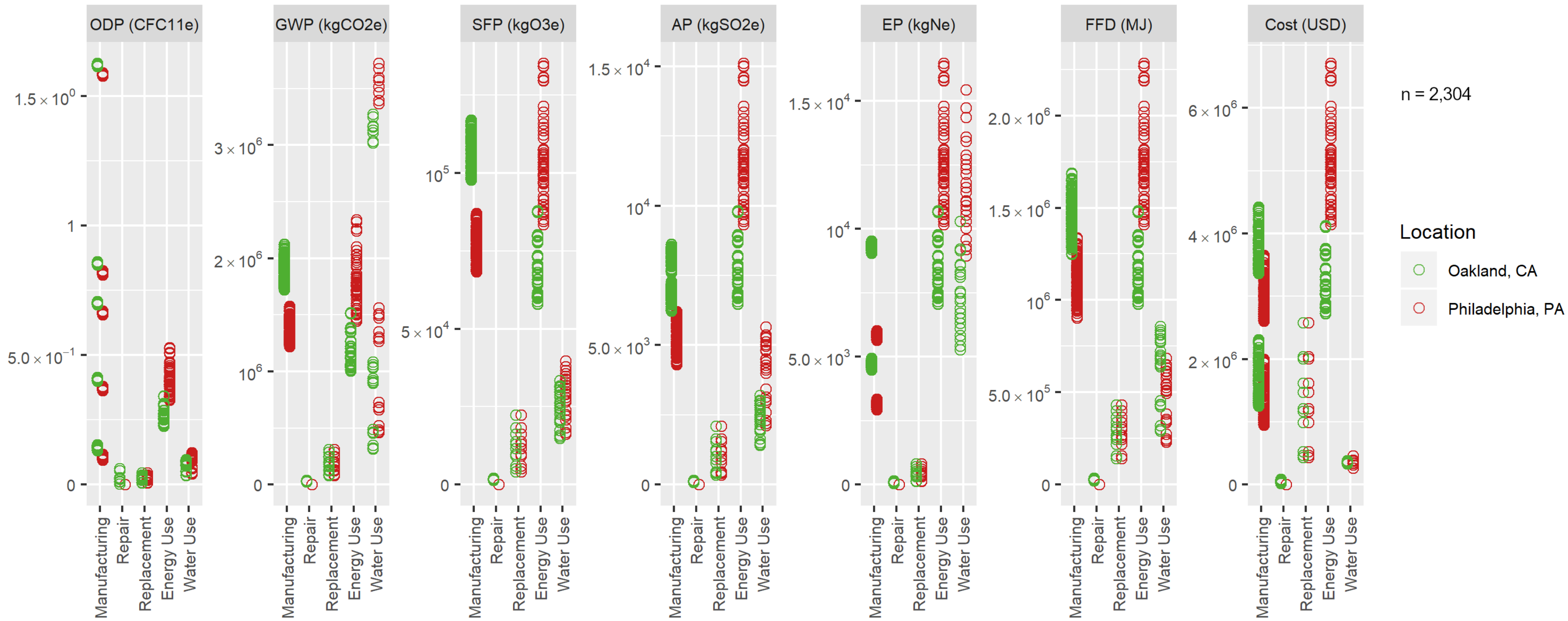

Figure 29. Impacts and costs of 2,304 buildings with on-site photovoltaic systems.

All other parameter combinations are based on Table 9 and the results reflect the same 60-year study period.

The repair stage impacts are found to be very close to zero, except in the ozone depletion potential category in Oakland, CA. The Hazus-based, probabilistic, median loss estimates for the 60-year study period amounted up to 1.37% and 4.03% loss in structural and non-structural components, respectively, for the buildings in Oakland, CA, a location with high seismic activity potential. In Philadelphia, PA, the same component groups amounted to less than 0.01% and 0.04% of probable losses over 60 years, considering there is a very low probability and magnitude of seismic activity in the region. These numbers are slightly lower than what other studies of environmental impacts from seismic damage have found (J. P. Chhabra et al., 2018; Wei, Skibniewski, et al., 2016). It should also be noted that the probability distribution of such assessments may vary widely due to the nature of these events. This means that for a specific seismic event and building, the actual impacts and costs may be significantly higher. For example, in the case of a building collapse, the repair related impacts and costs could equal or exceed the total impacts and costs of the manufacturing stage. While the results of this study find the repair stage to be almost negligible, it does not mean that it truly is the case in real life. Instead, the findings may point more towards the difficult task of considering sustainability and resilience quantitatively using a single assessment and visualization approach. Future studies may explore other approaches for communicating resilience aspects from a life cycle perspective.

Lastly, while the water use stage environmental impacts are relatively low in the general scenario, they are comparable to material manufacturing stage in categories such as global warming potential and eutrophication potential. This is likely due to the potential greenhouse gas emissions from anaerobic systems (Hasik, Anderson, et al., 2017; Hendrickson et al., 2015) and direct emissions to water bodies from centralized treatment systems. The water use costs are very low compared to the other aspects of the buildings.

Table 11. Interaction table for input parameters and results.

	Stories/shape	Exterior wall type	Window type	Window-to-wall ratio	Roof type	Structural material	Energy source	Potable source	Sewage treatment	Runoff treatment
Stories/shape		ME	ME	ME	ME	M	E			W
Exterior wall type				ME			E			
Window type				ME			E			
Window-to-wall ratio							E			
Roof type							E			
Structural material										
Energy source								W	W	W
Potable source										
Sewage treatment										
Runoff treatment										

M = affects results related to material use
E = affects results related to energy use
W = affects results related to water use

6.3.3 Design and service option influence

The following section aims to better understand how the individual design and service decisions influence the overall impacts and costs. This was not an easy task given the study setup and various interactions between the factors (e.g., energy sources, stories, wall types, etc.). All of the interactions that are known and/or built-in to the simulation algorithm and post-processing calculations are shown in Table 11. The table shows which factors interact with each other and which part of the results they influence (e.g., material, energy, or water-related impacts and costs). Instead of using typical statistical approaches such as analysis of variance or regression, the random forest algorithm was used to obtain the influence parameters in this study.

Figure 30 shows the Mean Decrease in Accuracy (%IncMSE) results from the random forest analysis. The random forest algorithm randomly selects a (test) subset of observations and predictor variables and tests its ability to predict results in the rest of the dataset (the validation subset). The %IncMSE shows how much influence dropping a particular factor has on the algorithm's ability to accurately predict the validation subset results. When applied to this study, the algorithm's prediction ability is influenced by 1) the individual factors' influence on the total results, but also by 2) the factors interaction, and 3) the range of levels within each factor (e.g., the variety of studied wall types).

Figure 30 reveals which of the factors has the largest, independent, relative influence on the total results in each location and metric. The most influential parameter across all metrics was found to be the type of energy source supplied to the building, which is consistent with the findings discussed in the previous section. The second most important factor across all metrics was the window-to-wall ratio, which affects the energy-efficiency, but also material quantities related to the buildings' envelope. Most of the parameters influencing the energy-efficiency of the buildings are more influential in Philadelphia than in Oakland due to the differing climates. Sewage treatment shows high influence in the GWP category, showing similar or higher influence than some of the more typically addressed building design decisions, such as wall and glazing types, window-to-wall ratios, and roof types. This is due the potential of on-site anaerobic systems having large direct emissions of greenhouse gases (Hasik, Anderson, et al., 2017; Leverenz et al., 2010); this study shows just how influential the selection of a sewage treatment type is in the overall building performance. In ODP, roof type is the second most influential factor. In this case, the only differences across the roof types were the types of insulation used (extruded polystyrene vs. polyisocyanurate), indicating large differences in the materials' impacts in this category are likely due to the types of blowing agents used during their manufacture. The last most apparent finding from Figure 30 is the influence of window types, window-to-wall ratios, and structural materials alongside stories and energy sources on the cost metric. This indicates the wide-ranging differences in costs of various options within these factors and the similarity in the potential for cost reductions. Overall, the fact that some of the factors do not show large influence does not mean they do not affect the results; it means they do not have as much weight in affecting them independently. In other words, a decision in a factor that shows larger influence in Figure 30 indicates there is a design option that is clearly better than others, while low influence indicates there are tradeoffs across multiple factors and they need to be considered simultaneously on a building-by-building basis.

The presented results are from simplified, early conceptual design models and are therefore not expected to be able to provide exact prediction of the buildings final impacts, and rather serve as a means of relative comparison of design alternatives and reveal the worst-case impact scenario for potential benchmarking of later project stages. The following section addresses some of the similarities and differences from actual projects and more detailed models.

6.3.4 How do the results compare to other references?

While there is no established way of validating results of LCA and LCCA, the best way of checking the results is by comparing inputs to other projects or conducting a sensitivity analysis. This study already presents the results of a sensitivity analysis and adding parameters would increase the study complexity and execution time. Instead, some of the midpoint quantities and endpoint results were compared to real projects and other references.

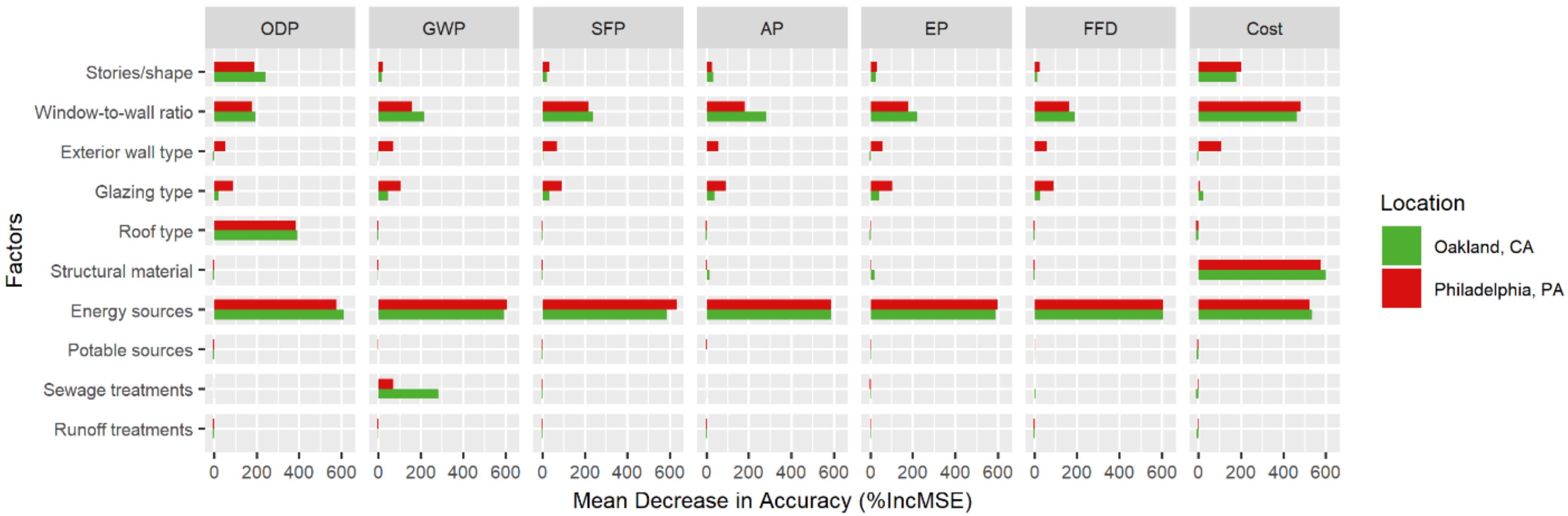

Figure 30. Importance plot of design and service parameters on performance metrics.

ODP = ozone depletion potential, GWP = global warming potential, SFP = smog formation potential, AP = acidification potential, EP = eutrophication potential, FFD = fossil fuel depletion

Since energy use was one of the main contributors to impacts and costs, this study included a check of the validity of the midpoint energy use estimates. To check that the estimated Energy Use Intensity (EUI) for the modeled buildings is realistic, it was compared it to the original DOE Reference Buildings (ASHRAE 90.1-2013 version) in OpenStudio (Deru et al., 2011; Goel et al., 2014) and to data from CBECS 2012 dataset (U.S. Energy Information Administration, 2012). The DOE data presented here is related to the medium office building reference model located in the two studied locations. The CBECS data was filtered by census region (i.e., Pacific for Oakland, CA and Middle Atlantic for Philadelphia, PA), primary building activity (i.e., office), and size (i.e., 2,300–9,300 m^2). For Oakland, CA, CBECS and DOE median EUIs amount to 136 and 83 kWh/m^2/year, respectively. This study's median EUI for that location was 92 kWh/m^2/year, or about 33% lower than CBECS median and about 10% higher than the DOE reference building values. For Philadelphia, PA, CBECS and DOE median EUIs amount to 149 and 107 kWh/m^2/year, respectively, as compared to 122 kWh/m^2/year in this study (i.e., about 18% lower than CBECS median and about 12% higher than DOE). These results show that the EUIs estimated in this study are well within the expected range. It should be noted that this study and the DOE reference buildings have identical HVAC systems, loads, and schedules, and differ only in geometries and constructions, which is the reason for the difference in the EUI. This study and the DOE results also show an idealized scenario of newly constructed buildings, while the CBECS data shows data for a more heterogenous set of real buildings affected by other environmental and operational factors.

Material quantity estimates are crucial for calculating manufacturing, repair, and replacement results. To ensure that the model inputs and algorithm yielded realistic values, the material-related GWP results were checked against reported values from 5 building projects within the two regions this work focused on. Although detailed information about these buildings could not be disclosed, they were of similar use type and size and in the general vicinity of the studied locations. The impacts shown are representative of main structural and envelope components, with some interior finishes being included as well. The results study boundaries may not be fully equivalent in all scenarios but are expected to provide an adequate range for checking the validity of the results in this study.

Figure 32 shows the results of the global warming potential per 1 m^2 of gross building area across the 5 reference buildings and across all the unique physical designs considered in this study (192 unique physical design combinations). Although 5 reference buildings are a relatively small sample size, the global warming potential in those cases ranged between 143-538 $kgCO_2e/m^2$ with the median being about 250 $kgCO_2e/m^2$. In comparison, the embodied global warming potential of materials in this study was found to range between 252-458 $kgCO_2e/m^2$, with a median of 350 $kgCO_2e/m^2$. Overall, the results of the sensitivity study appear within a reasonable range with respect to other studies and projects, reinforcing the validity of the results.

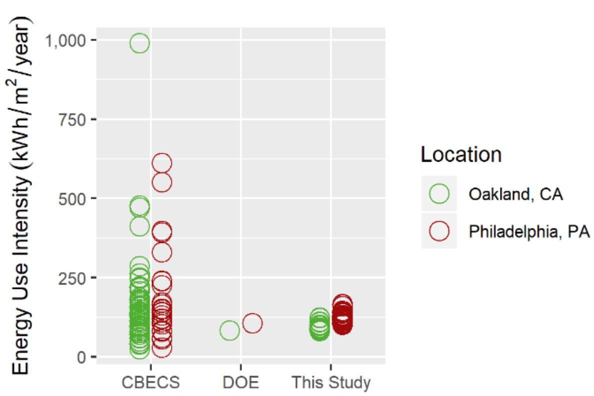

Figure 31. Energy use intensity comparison to reference data.

Reference data includes results from the Department of Energy (DOE) reference buildings and Commercial Buildings Energy Consumption Survey (CBECS).

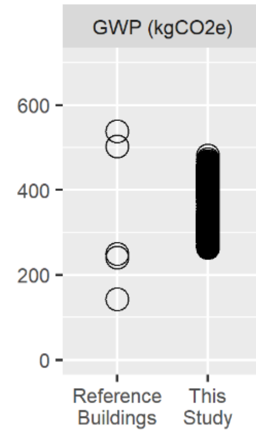

Figure 32. Embodied material global warming potential comparison to reference projects.

Reference buildings represent results from whole building LCA of 5 case study buildings.

6.4 CONCLUSIONS

This chapter provides a framework for a comprehensive life cycle sustainability and resilience assessment of buildings. As such, it approaches closer to reporting on the overall building performance in most of the life cycle stages prescribed in the ISO and EN standards for sustainability assessment of buildings. The application of the framework on the sensitivity study used a combination of modeled and average reported data, making it sort of a hybrid approach. Future studies could make more homogenous approach in either full bottom-up modeling of all aspects or top-down assessment based entirely on reported data.

Overall, the influence of grid-based electricity was found to be the overwhelming contributor to the environmental impacts of all the building design options across both locations. In the cost metric, it is not as influential, and instead, material aspects can be the primary reason for high costs. The energy related impacts can be greatly reduced with the use of on-site solar panel systems, which then shifts the remaining burdens to the water resources and embodied impacts of materials, especially in ozone depletion, global warming, and eutrophication potential categories.

Analysis of the influence of individual design and service parameters reinforced the findings of the visual analysis of the life cycle stages. It again indicated the overwhelming influence of the type of energy source across all metrics. The second most often influential factor was the number of stories each building had, which is also linked to the energy consumption of the buildings. Other aspects such as roof types, sewage treatment type, window type, window-to-wall ratios, and structural materials were all influential in individual metrics, such as ODP, GWP, and costs.

Most design optimization efforts focus on minimizing the energy and water demand of buildings; however, the source type for those resources (e.g. electricity from solar vs. coal) can be more influential from an environmental impact perspective. Future studies could explore a wide range of building systems, building designs, building types for the sensitivity analysis by expanding the underlying databases. Other efforts could focus on more sophisticated regionalization of the approach and data. The presented sensitivity study also did not consider uncertainty related to upstream data, such as the uncertainty in the representativeness of the environmental impact data and costs, and the uncertainty related to performance modeling, such as predicted energy consumption and lifetime damage repair. Future studies could investigate the significance of including such uncertainty data in similar sensitivity studies and for design decision making.

7.0 CONCLUSIONS AND FUTURE WORK

The overarching goal of this dissertation was to explore ways of including missing stages in building life cycle assessment and understand their influence on building sustainability and resilience from a broad perspective. The two missing stages explored in this work included water use and material repair stages which were then added into a holistic assessment including other material use and direct energy use stages.

The question of how designers and policy makers should consider water treatment in the context of high-performance, net-zero buildings was approached though a building-scale water system LCA. Considerable negative effects were found affecting the global warming potential impacts related to on-site water use. It was also found that designers and building owners may not be familiar with this issue and conducting life cycle assessment for the water use and sewage treatment related to buildings may help them identify it during design. There may be a few mitigation strategies for preventing these high global warming potential impacts of on-site water treatment systems, such as aeration and small-scale digesters.

The second question of addressing structural and non-structural integrity of buildings simultaneously with building life cycle environmental performance was explored through the integration of the LCA approach with various seismic loss assessment approaches. The dissertation presented a literature review on the possible approaches for this integration and subsequently focused on the development of a more sophisticated, probabilistic approach and inventory for including this stage within whole building LCA. The results revealed that the findings of these combined assessments may vary widely, both based on the approach taken for their integration as well as on the approach for analyzing and communicating their results. Due to the different nature of seismic and other hazard events, it can be difficult to add results of seismic loss assessments to the typical whole building LCA in the traditional format.

The dissertation culminated in a sensitivity analysis integrating multitude of building performance assessment methods and tools to understand the relative influence of different life cycle stages and building design decisions from a broader perspective, and that including methods and findings from the other parts of this dissertation. The framework for conducting such an expanded assessment was presented and applied to study design decisions for medium office buildings. The influence of wastewater treatment related environmental impacts was found to be considerable in comparison the typically studied energy use and material manufacturing impacts and reinforced the conclusion that this stage should be included in building LCAs. Conversely, repair impacts appeared miniscule relative to other stages; however, this could point to the ineffectiveness of simplified approaches for addressing this stage, rather than point to the stage's significance for the sustainability and resilience of buildings.

Future work related to this research may focus on creating larger databases that would aid the consideration of water and repair related aspects within building LCA. The building performance in these areas is also dependent on regional differences which may require additional research into the regionalization of such data and the regionalization of building LCA in general. Future research could also consider other natural hazards such as hurricanes, flooding, and fires. In order for these assessments to be useful they need to be integrated into the traditional building design process and ultimately implemented within other tools already used by architects and engineers.

APPENDIX A

SUPPORTING INFORMATION FOR EVALUATING THE LIFE CYCLE ENVIRONMENTAL BENEFITS AND TRADEOFFS OF WATER REUSE SYSTEMS FOR NET-ZERO BUILDINGS (CHAPTER 3)

A.1 Water and energy demand data

Data in Table 12 was acquired from the net-zero building's building automation system. Water demand of the reference buildings was calculated using typical use patterns and consumption data for the fixtures and appliances shown in Table 12. Unit consumption estimates for conventional and low-flow fixtures and appliances were based on typical industry values. Sources consulted for these calculations all included high and low estimates for conventional buildings, which were then averaged for the final conventional estimates. Use patterns were optimized so that the net-zero building (NZB) demand data matched the actual potable and non-potable demand data shown in Table 12, and the same use patterns were used to calculate the normal-flow reference building's (NFRB) consumption. The NZB uses low-flow fixtures and appliances equivalent to the ones used in the low-flow reference building (LFRB). Total building consumption was calculated for the occupancy of the NZB, which services 40 full time employees.

Table 12. Net-zero building average daily water demand by month.

Data shown represents the volume (in gallons) of (a) potable water sourced from WTP, (b) treated and reused wastewater, and (c) total water demand of the building.

(a)		2014	2015	2016	Mean
Potable water	January	441*	118	46	82
	February	60	113	85	86
	March	42	62	56	53
	April	50	35	45	43
	May	62	47	45	51
	June	48	56	37	47
	July	41	465*	51	46
	August	28	112	52	64
	September	22	24		23
	October	30	27		28
	November	38	26		32
	December	30	27		29
				Mean:	49

(b)		2014	2015	2016	Mean
Reused water	January	117	98	216	143
	February	212	76	227	172
	March	187	77	276	180
	April	106	24	302	144
	May	158	137	312	202
	June	213	191	270	225
	July	126	164	230	173
	August	147	107	54	103
	September	131	165		148
	October	132	246		189
	November	22	192		107
	December	62	224		143
				Mean:	161

(c)		2014	2015	2016	Mean
Total demand	January	558**	215	262	198
	February	272	189	312	258
	March	230	139	332	234
	April	156	59	347	187
	May	219	183	358	253
	June	261	248	307	272
	July	167	629**	280	204
	August	175	219	106	167
	September	153	189		171
	October	162	273		218
	November	60	219		139
	December	92	251		172
				Mean:	206

*Outlier demand data were excluded from the mean calculations, as these represent potential issues within the system and do not represent regular operating conditions.
**Calculated *total demand* data impacted by the outliers in *potable water* demand. Only the *reused water* demand was used to calculate the *total demand* means for these months.

Table 13. Water demand calculations.

Calculations for reference buildings (b) based on equivalent use patterns and conventional and low-flow fixture/appliance consumption rates (a).

(a) Items	Use type	Typical use		Conventional (NFRB)	Low-flow (LFRB & NZB)	Units
Toilets	Non-potable	5	times/person/day	2.6	1.2	gal/flush
Urinals	Non-potable	5	times/person/day	2.0	0.0	gal/flush
Bathroom sinks	Potable	5	times/person/day (15 sec/use)	1.9	0.5	gal/min
Kitchen sinks	Potable	20	seconds/person/day	2.5	1.5	gal/min
Dishwasher	Potable	0.5	time/day (every other day)	12.5	5.5	gal/use

(b)	Conventional (NFRB)	% of total	Low-flow (LFRB & NZB)	% of total
Total building consumption (gal/day)	605.4		207.8	
Potable water consumption (gal/day)	132.1	22%	47.8	23%
Non-potable water consumption (gal/day)	473.3	78%	160.0	77%

Water use reduction from low-flow to conventional: 66%

Table 14. Net-zero building average annual energy data.

Values in parentheses represent the component contribution to the water system's total consumption.

Energy generation	**kWh**	
Building total	134,977	
Energy consumption		
Building total	120,023	
Water system	6,776	
Rainwater UV treatment	3,812	(56.3%)
Reuse UV treatment	1,230	(18.2%)
Pump 1 (septic to wetland)	80	(1.2%)
Pump 2 (wetland to sand filter)	12	(0.2%)
Pump 3 (sand filter to building)	9	(0.1%)
Septic tank aerator	1,633	(24.1%)

Note: Building automation system provided cumulative electricity consumption for both UV treatment systems, which were then separated based on the runtime of each system, assuming both systems draw same amount of power when in use. This may not accurately reflect each UV system's consumption separately due to changing factors like cistern water volume and filter cleanliness, which may result in varying electricity draws from each system at different times.

A.2 Material quantities and replacement times

Table 15. NZB water system material quantities and replacement times.

System	Component	Subcomponent	Material	Length, Volume or Area		Unit Weight		Total Weight		Service life (years)	
Septic tank	Concrete Tank	Precast Concrete	Concrete, 20MPa	84.11	ft3	150.00	lbs/ft3	12,617.04	lbs	100	assumed
		Reinforcing	Steel, reinforcing	-		-		982.96	lbs	100	assumed
	Risers	Riser (2x)	HDPE	-		7.40	lbs/ea	14.80	lbs	100	assumed
		Riser Cover (2x)	HDPE	-		7.00	lbs/ea	14.00	lbs	100	assumed
	Aerator	Air Compressor	1/4 hp Rocking Piston	-		-		17.00	lbs	25	assumed
		3/8" Tubing	LDPE	20.00	ft	0.02	lbs/ft	0.49	lbs	25	assumed
		Diffuser Membrane	EPDM	-		0.50	lbs/ea	0.50	lbs	25	assumed
		Diffuser Ring	Polypropylene	-		1.00	lbs/ea	1.00	lbs	25	assumed
		Diffuser Base	Polypropylene	-		4.50	lbs/ea	4.50	lbs	25	assumed
	Filter	Filter Housing	HDPE	3.67	ft	0.83	lbs/ft	3.04	lbs	50	assumed
		Biotube Filter Cartridge	Polypropylene	3.00	ft	1.47	lbs/ft	4.41	lbs	50	assumed
Constructed wetlands	Structure	Concrete Saddles (12x)	Concrete, 20MPa	8.64	ft3	150.00	lbs/ft3	1,295.91	lbs	100	literature
		Styrofoam insulation	Expanded polystyrene	378.00	ft2	0.32	lbs/ft2	120.49	lbs	100	assumed
		Wood formboard	Plywood	378.00	ft2	1.42	lbs/ft2	536.76	lbs	100	assumed
	Fill	Pea Gravel	Gravel, round	180.00	ft3	111.62	lbs/ft3	20,091.60	lbs	100	assumed
		Gravel	Gravel, crushed	720.00	ft3	85.00	lbs/ft3	61,200.00	lbs	100	assumed
	Liners (2x)	HDPE liner	HDPE	711.00	ft2	0.20	lbs/ft2	139.36	lbs	100	literature
		Geotextile liner	Polypropylene	1,422.00	ft2	0.11	lbs/ft2	158.00	lbs	100	literature
	Infiltration Chambers (3x)	Infiltrator	Polypropylene	3.00	ft	2.00	lbs/ft	6.00	lbs	100	assumed
		4" Air Vent	HDPE	2.00	ft	0.83	lbs/ft	1.66	lbs	100	assumed
		4" HDPE pipe	HDPE	3.00	ft	0.83	lbs/ft	2.49	lbs	100	literature
	Level Control Basin	Poly Basin	HDPE	-		-		22.00	lbs	100	assumed
		Lid	Steel, low-alloyed	-		-		14.00	lbs	100	assumed
		3" ABS pipe	ABS	2.00	ft	0.75	lbs/ft	1.50	lbs	100	literature
Sand filters	Cell 1	Sand	Sand	1,080.00	ft3	93.60	lbs/ft3	132,000.00	lbs	100	assumed
		Geotextile liner	Polypropylene	1,212.00	ft2	0.11	lbs/ft2	134.67	lbs	100	literature
		HDPE liner	HDPE	1,212.00	ft2	0.20	lbs/ft2	237.55	lbs	100	literature
		Infiltration chambers (2x)	Polypropylene	180.00	ft	5.22	lbs/ft	940.24	lbs	100	assumed
		Geotextile chamber liner	Polypropylene	736.00	ft2	0.11	lbs/ft2	81.78	lbs	100	literature
		Air vents (6x)	ABS	12.00	ft	1.07	lbs/ft	12.84	lbs	100	assumed
		Distribution pipe (2x)	HDPE	180.00	ft	0.34	lbs/ft	61.20	lbs	100	literature
		Underdrain pipe	HDPE	90.00	ft	1.90	lbs/ft	171.00	lbs	100	literature
	Cell 2	Sand	Sand	864.00	ft3	93.60	lbs/ft3	80,870.40	lbs	100	assumed
		Geotextile liner	Polypropylene	978.00	ft2	0.11	lbs/ft2	108.67	lbs	100	literature
		HDPE liner	HDPE	978.00	ft2	0.20	lbs/ft2	191.69	lbs	100	literature
		Infiltration chambers (2x)	Polypropylene	144.00	ft	5.22	lbs/ft	752.19	lbs	100	assumed
		Geotextile chamber liner	Polypropylene	592.00	ft2	0.11	lbs/ft2	65.78	lbs	100	literature
		Air vents (6x)	ABS	12.00	ft	1.07	lbs/ft	12.84	lbs	100	assumed
		Distribution pipe (2x)	HDPE	144.00	ft	0.34	lbs/ft	48.96	lbs	100	literature
		Underdrain pipe	HDPE	72.00	ft	1.90	lbs/ft	136.80	lbs	100	literature

Table 16. NZB water system material quantities and replacement times. (continued)

System	Component	Subcomponent	Material	Length, Volume or Area		Unit Weight		Total Weight		Service life (years)	
Storage	Reuse Tank	1700 gal tank	HDPE	-		270.00	lbs/ea	270.00	lbs	50	assumed
	Rainwater Tank	1700 gal tank	HDPE	-		270.00	lbs/ea	270.00	lbs	50	assumed
Pump stations & manholes	Reuse manhole (sand filter to building)	Precast concrete box	Concrete, 20MPa	50.08	ft3	150.00	lbs/ft3	7,512.00	lbs	100	literature
		Iron cover	Cast Iron	-		255.00	lbs/ea	255.00	lbs	100	assumed
		Iron frame	Cast iron	-		165.00	lbs/ea	165.00	lbs	100	assumed
		Vent pipe	Cast iron	5.00	ft	8.00	lbs/ft	40.00	lbs	100	assumed
		Vent pipe anchor	Concrete, 20MPa	2.00	ft3	150.00	lbs/ft3	300.00	lbs	100	assumed
		Pump P3	1/7 HP Little Giant	-		-		10.65	lbs	20	assumed
	Manhole #9 (septic to constructed wetland)	Precast concrete box	Concrete, 20MPa	50.08	ft3	150.00	lbs/ft3	7,512.00	lbs	100	literature
		Iron cover	Cast Iron	-		255.00	lbs/ea	255.00	lbs	100	assumed
		Iron frame	Cast iron	-		165.00	lbs/ea	165.00	lbs	100	assumed
		Vent pipe	Cast iron	5.00	ft	8.00	lbs/ft	40.00	lbs	100	assumed
		Vent pipe anchor	Concrete, 20MPa	2.00	ft3	150.00	lbs/ft3	300.00	lbs	100	assumed
		Pump P1	1/3 HP Goulds	-		-		56.00	lbs	20	assumed
	Manhole #10 (constructed wetland to sand filter)	Precast concrete box	Concrete, 20MPa	50.08	ft3	150.00	lbs/ft3	7,512.00	lbs	100	literature
		Iron cover	Cast Iron	-		255.00	lbs/ea	255.00	lbs	100	assumed
		Iron frame	Cast iron	-		165.00	lbs/ea	165.00	lbs	100	assumed
		Vent pipe	Cast iron	5.00	ft	8.00	lbs/ft	40.00	lbs	100	assumed
		Vent pipe anchor	Concrete, 20MPa	2.00	ft3	150.00	lbs/ft3	300.00	lbs	100	assumed
		Pump P2	1/3 HP EBRA	-		-		11.00	lbs	20	assumed
Piping	Wastewater piping	6" ABS pipe	ABS	125.00	ft	1.88	lbs/ft	234.75	lbs	100	literature
		2" ABS pipe	ABS	410.00	ft	0.38	lbs/ft	154.57	lbs	100	literature
		6" ABS pipe	ABS	55.00	ft	1.88	lbs/ft	103.40	lbs	100	literature
	Sewage cleanouts (4x)	4" ABS pipe	ABS	3.00	ft	1.07	lbs/ft	3.21	lbs	100	literature
		Cap & gasket	ABS	-		0.27	lbs/ea	0.27	lbs	100	assumed
		Concrete anchor	Concrete, 20MPa	0.46	ft3	150.00	lbs/ft3	68.66	lbs	100	assumed
		Iron cover	Cast Iron	-		3.85	lbs/ea	3.85	lbs	100	assumed
	Stormwater piping	2" HDPE	HDPE	330.00	ft	0.64	lbs/ft	211.20	lbs	100	literature
UV treatment system (2x)	Enclosure	12-guage steel	Steel, low-alloyed	88.00	ft2	4.41	lbs/ft2	388.08	lbs	100	assumed
	UV purifier (2x)	Housing	Steel, chromium	-		-		36.00	lbs	50	assumed
		UV lamp	UV lamp	-		-		1.00	lbs	2	reported
	Amiad filter	Housing	Polypropylene	-		-		13.50	lbs	50	assumed
		Filter Mesh	Polypropylene	-		-		2.50	lbs	0.5	reported
		Filter Screen	Steel, chromium	-		-		1.00	lbs	0.5	reported
	Amtrol pressure tank	Shell	Steel, low-alloyed	-		-		7.00	lbs	14	assumed
		Liner	Polypropylene	-		-		1.00	lbs	14	assumed
	Flo-max filter	Housing	Steel, chromium	-		-		56.00	lbs	50	assumed
		Synthetic Fabric Filter	Polyester	-		-		4.00	lbs	0.5	reported
		Plastic Mesh Filter Support	Polypropylene	-		-		1.00	lbs	0.5	reported
	Pump	Pump	Custom pump	-		-		108.00	lbs	20	assumed

Table 17. LCI materials and processes for the NZB and the reference buildings.

Category	Description	Unit process	Source
NZB Materials	Concrete[1]	Concrete, 20 MPa[1]	ecoinvent
	Reinforcing steel	Steel, low-alloyed	ecoinvent
	Gravel	Gravel, round	ecoinvent
	Pea gravel	Gravel, crushed	ecoinvent
	Sand	Sand	ecoinvent
	Plywood	Plywood, for outdoor use	ecoinvent
	HDPE piping, liners & tanks	Polyethylene, high density, granulate	ecoinvent
	Polypropylene liners & tanks	Polypropylene resin	ecoinvent
	Polystyrene insulation	Polystyrene, expandable	ecoinvent
	EPDM membrane	Synthetic rubber	ecoinvent
	ABS piping	Acrylonitrile-butadiene-styrene copolymer	ecoinvent
	RCP piping	Concrete, 20 Mpa & Steel, low-alloyed	ecoinvent
	Manhole & cleanout covers	Cast iron	ecoinvent
	Manhole box	Concrete, 20 MPa	ecoinvent
	Equipment (UV, Filters, Pumps, etc.)	Steel, low-alloyed	ecoinvent
		Steel, chromium steel 18/8	ecoinvent
		Polyester resin, unsaturated	ecoinvent
		Polypropylene, granulate	ecoinvent
		Ultraviolet lamp	ecoinvent
		Water pump[1]	ecoinvent
NZB Direct Emissions to Air	Methane[2]	Emissions to air	Literature
	Carbon dioxide, biogenic[2]	Emissions to air	Literature
	Dinitrogen monoxide[2]	Emissions to air	Literature
NZB Electricity	PV panels	Electricity production, photovoltaic, 3kWp	ecoinvent
Potable water	WTP	Tap water[3]	ecoinvent
Sewage	WWTP	Treatment, sewage, to wastewater treatment[3]	ecoinvent

[1] Unit processes modified to reflect case study specific characteristics.
[2] Septic tank and constructed wetland (CW) emission estimates were obtained from literature or calculated and input as direct emissions to air.
[3] Unit processes were modified to reflect actual electricity use and regional electricity mix. Certain chemical inputs were also added or modified based on actual reporting from local WTP.

Table 18. Constructed wetland (CW) size and emissions.

All values for CO2, CH4, and N2O represent horizontal subsurface flow (HSSF) constructed wetland estimates from literature (Fey et al., 1999; Johansson et al., 2004; Johansson et al., 2003; Søvik et al., 2006). All emission values shown are in mg/m^2/day. (SE = standard error)

NZB CW characteristics	
CW cells:	2
Cell length:	12 ft (3.65 m)
Cell width:	15 ft (4.56 m)

CO_2					# of samples		Summer emissions			Winter emissions		
Test year	Author	Location	Soil Type	Wastewater	Summer	Winter	Mean	±	SE	Mean	±	SE
2001-03	Søvik	Estonia	Sand	Municipal	160	140	3800	±	210	960	±	66
2001-03	Søvik	Estonia	Gravel	Municipal	120	89	2100	±	240	380	±	29
2001	Søvik	Norway	Sand	Municipal	22	6	790	±	170	260	±	53
2002	Søvik	Poland	Sand	Municipal	34	6	3300	±	650	560	±	160

CH_4					# of samples		Summer emissions			Winter emissions		
Test year	Author	Location	Soil Type	Wastewater	Summer	Winter	Mean	±	SE	Mean	±	SE
1998-99	Johansson	Sweden		Municipal	325		180	±	252			
2001-03	Søvik	Estonia	Sand	Municipal	160	140	340	±	240	1.5	±	0.3
2001-03	Søvik	Estonia	Gravel	Municipal	120	89	160	±	38	11	±	4.5
2001	Søvik	Norway	Sand	Municipal	22	6	130	±	43	-1.5	±	6.9
2002	Søvik	Poland	Sand	Municipal	34	6	670	±	220	44	±	34

N_2O					# of samples		Summer emissions			Winter emissions		
Test year	Author	Location	Soil Type	Wastewater	Summer	Winter	Mean	±	SE	Mean	±	SE
1998-99	Johansson	Sweden		Municipal	241		3.12	±	5.28			
1995-96	Fey	Germany	Sand	Dairy farm		168				3.19	±	0.62
2001-03	Søvik	Estonia	Sand	Municipal	160	140	7.1	±	1.2	1.6	±	0.23
2001-03	Søvik	Estonia	Gravel	Municipal	120	89	4.2	±	0.82	1.1	±	0.31
2001	Søvik	Norway	Sand	Municipal	22	6	6.9	±	4.3	36	±	22

Note: Summer samples were taken between May and October which accounts for approximately 214 days out of a year. Winter samples were taken between November and April which accounts for approximately 151 days out of a year. The reported means were weighted by the corresponding number of samples and the number of days representing a corresponding season. The weighted means were then averaged over an entire year and applied to the dimensions of the constructed wetlands at the CSL.

Table 19. Detailed NZB water system impact results.

Impact category	Bldg.	Total	NZB Materials	NZB Emissions	NZB PV	WTP	WWTP
Ozone Depletion kg CFC-11 eq	NZB/D. 20	1.57E-04	4.63E-05	0.00E+00	1.04E-04	6.99E-06	2.56E-07
	NZB/D. 50	1.34E-04	2.31E-05	0.00E+00	1.04E-04	6.99E-06	2.56E-07
	NZB/D. 100	1.28E-04	1.65E-05	0.00E+00	1.04E-04	6.99E-06	2.56E-07
	LFRB/C.	4.41E-05	0.00E+00	0.00E+00	0.00E+00	2.98E-05	1.42E-05
	NFRB/C.	1.28E-04	0.00E+00	0.00E+00	0.00E+00	8.69E-05	4.15E-05
Global warming kg CO_2 eq	NZB/D. 20	1.45E+03	6.27E+02	2.80E+02	4.60E+02	8.32E+01	1.03E+00
	NZB/D. 50	1.12E+03	3.00E+02	2.80E+02	4.60E+02	8.32E+01	1.03E+00
	NZB/D. 100	1.03E+03	2.07E+02	2.80E+02	4.60E+02	8.32E+01	1.03E+00
	LFRB/C.	5.12E+02	0.00E+00	0.00E+00	0.00E+00	3.55E+02	1.57E+02
	NFRB/C.	1.49E+03	0.00E+00	0.00E+00	0.00E+00	1.03E+03	4.58E+02
Smog kg O_3 eq	NZB/D. 20	7.08E+01	4.08E+01	1.40E-01	2.66E+01	3.10E+00	1.32E-01
	NZB/D. 50	4.90E+01	1.90E+01	1.40E-01	2.66E+01	3.10E+00	1.32E-01
	NZB/D. 100	4.28E+01	1.28E+01	1.40E-01	2.66E+01	3.10E+00	1.32E-01
	LFRB/C.	2.69E+01	0.00E+00	0.00E+00	0.00E+00	1.32E+01	1.37E+01
	NFRB/C.	7.84E+01	0.00E+00	0.00E+00	0.00E+00	3.85E+01	3.99E+01
Acidification kg SO_2 eq	NZB/D. 20	6.04E+00	2.72E+00	0.00E+00	2.96E+00	3.50E-01	5.34E-03
	NZB/D. 50	4.61E+00	1.29E+00	0.00E+00	2.96E+00	3.50E-01	5.34E-03
	NZB/D. 100	4.21E+00	8.93E-01	0.00E+00	2.96E+00	3.50E-01	5.34E-03
	LFRB/C.	2.66E+00	0.00E+00	0.00E+00	0.00E+00	1.50E+00	1.16E+00
	NFRB/C.	7.74E+00	0.00E+00	0.00E+00	0.00E+00	4.36E+00	3.39E+00
Eutrophication kg N eq	NZB/D. 20	4.90E+00	1.38E+00	0.00E+00	3.25E+00	2.70E-01	1.22E-03
	NZB/D. 50	4.20E+00	6.78E-01	0.00E+00	3.25E+00	2.70E-01	1.22E-03
	NZB/D. 100	4.00E+00	4.85E-01	0.00E+00	3.25E+00	2.70E-01	1.22E-03
	LFRB/C.	1.01E+01	0.00E+00	0.00E+00	0.00E+00	1.15E+00	8.96E+00
	NFRB/C.	2.95E+01	0.00E+00	0.00E+00	0.00E+00	3.36E+00	2.61E+01
Carcinogenics CTUh	NZB/D. 20	2.90E-04	2.18E-04	0.00E+00	5.87E-05	1.26E-05	3.17E-08
	NZB/D. 50	1.74E-04	1.02E-04	0.00E+00	5.87E-05	1.26E-05	3.17E-08
	NZB/D. 100	1.45E-04	7.37E-05	0.00E+00	5.87E-05	1.26E-05	3.17E-08
	LFRB/C.	9.83E-05	0.00E+00	0.00E+00	0.00E+00	5.40E-05	4.43E-05
	NFRB/C.	2.86E-04	0.00E+00	0.00E+00	0.00E+00	1.57E-04	1.29E-04
Non-carcinogenics CTUh	NZB/D. 20	8.93E-04	3.53E-04	0.00E+00	5.16E-04	2.42E-05	2.59E-07
	NZB/D. 50	7.48E-04	2.08E-04	0.00E+00	5.16E-04	2.42E-05	2.59E-07
	NZB/D. 100	7.10E-04	1.69E-04	0.00E+00	5.16E-04	2.42E-05	2.59E-07
	LFRB/C.	5.98E-04	0.00E+00	0.00E+00	0.00E+00	1.03E-04	4.95E-04
	NFRB/C.	1.74E-03	0.00E+00	0.00E+00	0.00E+00	3.01E-04	1.44E-03
Respiratory effects kg PM2.5 eq	NZB/D. 20	1.49E+00	6.87E-01	0.00E+00	7.50E-01	5.20E-02	7.95E-04
	NZB/D. 50	1.14E+00	3.34E-01	0.00E+00	7.50E-01	5.20E-02	7.95E-04
	NZB/D. 100	1.05E+00	2.48E-01	0.00E+00	7.50E-01	5.20E-02	7.95E-04
	LFRB/C.	3.68E-01	0.00E+00	0.00E+00	0.00E+00	2.22E-01	1.46E-01
	NFRB/C.	1.07E+00	0.00E+00	0.00E+00	0.00E+00	6.46E-01	4.25E-01
Ecotoxicity CTU	NZB/D. 20	4.53E+04	6.96E+03	0.00E+00	3.68E+04	1.58E+03	8.52E+00
	NZB/D. 50	4.17E+04	3.30E+03	0.00E+00	3.68E+04	1.58E+03	8.52E+00
	NZB/D. 100	4.07E+04	2.36E+03	0.00E+00	3.68E+04	1.58E+03	8.52E+00
	LFRB/C.	1.09E+04	0.00E+00	0.00E+00	0.00E+00	6.73E+03	4.18E+03
	NFRB/C.	3.18E+04	0.00E+00	0.00E+00	0.00E+00	1.96E+04	1.22E+04
Fossil fuel depletion MJ surplus	NZB/D. 20	1.86E+03	1.36E+03	0.00E+00	4.49E+02	4.43E+01	2.28E+00
	NZB/D. 50	1.13E+03	6.38E+02	0.00E+00	4.49E+02	4.43E+01	2.28E+00
	NZB/D. 100	9.26E+02	4.30E+02	0.00E+00	4.49E+02	4.43E+01	2.28E+00
	LFRB/C.	3.22E+02	0.00E+00	0.00E+00	0.00E+00	1.89E+02	1.33E+02
	NFRB/C.	9.38E+02	0.00E+00	0.00E+00	0.00E+00	5.51E+02	3.86E+02
CED MJ eq	NZB/D. 20	2.17E+04	1.30E+04	0.00E+00	7.56E+03	1.12E+03	1.72E+01
	NZB/D. 50	1.48E+04	6.13E+03	0.00E+00	7.56E+03	1.12E+03	1.72E+01
	NZB/D. 100	1.29E+04	4.15E+03	0.00E+00	7.56E+03	1.12E+03	1.72E+01
	LFRB/C.	6.91E+03	0.00E+00	0.00E+00	0.00E+00	4.78E+03	2.13E+03
	NFRB/C.	2.01E+04	0.00E+00	0.00E+00	0.00E+00	1.39E+04	6.20E+03

Note: Results are per year based on TRACI 2.1 and cumulative energy demand (CED) characterization factors. (LFRB = low-flow reference building, NFRB = normal-flow reference building, CW = constructed wetland, WTP = water treatment plant, WWTP = wastewater treatment plant).

Results shown in Table 19 correspond with results shown in Figure 6 in chapter 3.3.1. The NZB does not send its wastewater to WWTP; however, sludge extracted from the septic tank is transported to the WWTP for processing. Impacts associated with the transport of sludge are shown in the NZB-WWTP cells.

Table 20. Break-even analysis of the NZB water system.

Results specify the minimum number of years the NZB would have to be in service to become environmentally preferable design choice. The NZB would never break even in categories denoted as n/a. (LFRB = low-flow reference building, NFRB = normal-flow reference building)

	Full system (with potable, reuse & rainwater)		Reuse & potable water only (no rainwater)	
Impact category	LFRB	NFRB	LFRB	NFRB
Ozone depletion	n/a	95	n/a	11
Global warming	n/a	19	n/a	12
Smog	n/a	17	83	12
Acidification	n/a	12	53	8
Eutrophication	4	1	3	1
Carcinogenics	274	20	89	14
Non-carcinogenics	292	6	15	4
Respiratory effects	n/a	92	n/a	16
Ecotoxicity	n/a	n/a	n/a	8
Fossil fuel depletion	n/a	97	436	40
Cumulative energy demand	n/a	23	132	15

The "full system" results in Table 20 show the break-even times of the NZB with the as-built system. These results include the rainwater UV treatment system, which was found to account for 56% of the operational energy use of the entire water system even though it functions mostly as a backup system. Treated rainwater is seldom used for the NZB's water service. The "reuse & potable water only" results show the break-even times of the NZB without the mostly redundant rainwater system. The difference in the break-even times demonstrates the potential for impact reductions of the NZB with optimization of the net-zero water system.

APPENDIX B

SUPPORTING INFORMATION FOR REVIEW OF APPROACHES FOR INTEGRATING LOSS ESTIMATION AND LIFE CYCLE ASSESSMENT TO ASSESS IMPACTS OF SEISMIC BUILDING DAMAGE AND REPAIR (CHAPTER 4)

B.1 Building details and quantity estimates

The representative building used for the demonstration figure was originally based on structural information from Gupta and Krawinkler (1999) and non-structural component information was obtained using the PACT normative estimation tool (Federal Emergency Management Agency, 2012b). Additional information about the foundation and floor slabs was obtained from the SOM Environmental Analysis Tool which provides average quantities from real projects.

The results shown represent a 9-story, 20903 gross m^2, office building located in Los Angeles, CA. The building has one substory and the following above ground dimensions: 45.7 m in length, 45.7 m in width, and 40.8 m in height. Figure 33 shows the building's (a) elevation plan, (b) floor plan, and (c) 3D rendering.

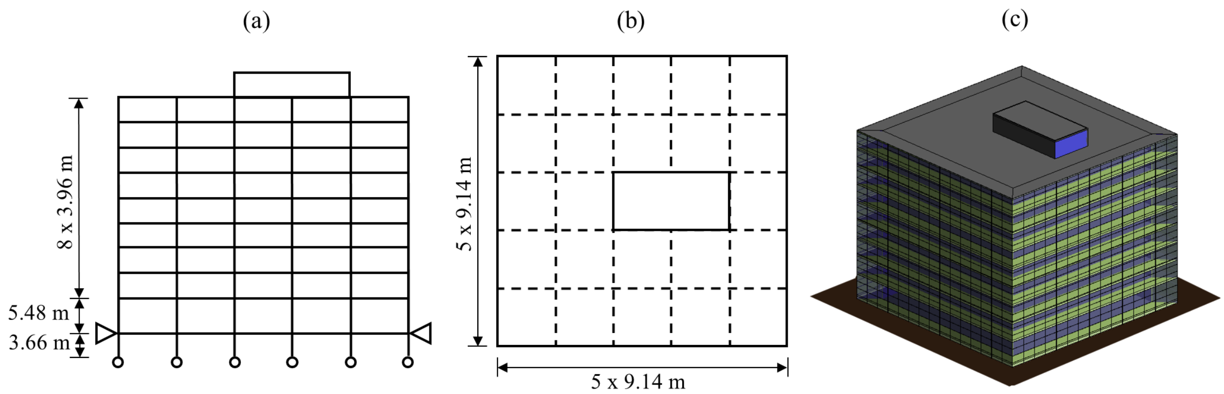

Figure 33. Building details, including (a) elevation plan, (b) floor plan, and (c) 3D model.

Elevation and floor plans were adapted from Gupta and Krawinkler (1999).

Based on the above building dimensions and information, component quantities were generated using the PACT normative estimation tool (Federal Emergency Management Agency, 2012b). RS Means construction cost database (RS Means, 2015) was used to estimate the cost of each of the listed components as well as the total building cost based on building type and total area. The full list of considered components, their material quantities, and estimated economic costs are shown in Table 21. Note that the cost estimates include material costs only (i.e. no labor, equipment, or overhead costs are included). Table A4 shows component and building scale economic cost estimates converted into 2002 US dollars and showing assumptions on representative sectors used for the "Global EIO" and "Component EIO" approaches to using EIO-LCA for environmental impacts assessment. Table A5 shows material assignments for individual components in SimaPro-based process-LCA approach, Athena Impact Estimator process-LCA model, and Tally LCA tool. Finally, Figure A4 shows the input into the SOM Environmental Analysis Tool, with all other settings being kept at default.

Table 21. Quantity schedule and cost estimate for case study building.

Quantities were obtained from Gupta and Krawinkler (Gupta & Krawinkler, 1999), PACT normative estimation tool (Federal Emergency Management Agency, 2012b), and SOM Environmental Analysis Tool (Skidmore Owings & Merill, n.d.). Cost estimate shown is in 2016 US dollars based on cost data from RS Means (RS Means, 2016).

Division			Component	Quantity		Mass		Cost
A	1010	Sub-structure	Standard foundation	2,090	m^2			
			Concrete			353,632	kg	$22,908
			Reinforcement			3,552	kg	$3,758
A	2020	Sub-structure	Basement walls	669	m^2			
			Concrete			530,540	kg	$34,367
			Reinforcement			5,833	kg	$6,172
B	1010	Superstructure	Floor & roof structure	20,903	m^2			
			Concrete			3,825,286	kg	$225,000
			Reinforcement			511,364	kg	$540,000
			Metal deck			204,545	kg	$472,500
B	1030	Superstructure	Steel frame	20,903	m^2			
			Structural steel			1,080,000	kg	$3,718,750
B	2010	Envelope	Glazed curtain wall	6,801	m^2			$5,124,070
			Glazing			255,784	kg	
			Framing			65,676	kg	
			Sealing			1,975	kg	
			Hardware			1,385	kg	
B	3010	Envelope	Roof finish	2,090	m^2			
			Finish			255,682	kg	$75,828
			Membrane			3,170	kg	$33,753
			Insulation			2,508	kg	$11,702
C	1010	Interior	Partition walls	27,174	m^2			
			Wallboard			1,009,851	kg	$96,525
			Framing			3,560	kg	$114,076
			Finish			60,661	kg	$40,950
C	3020	Interior	Flooring	15,677	m^2			$1,687,500
			Panel fill			805,398	kg	
			Panel casing			267,770	kg	
			Hardware			38,352	kg	
C	3030	Interior	Ceilings	18,813	m^2			
			Ceiling tiles			230,114	kg	$370,577
			Framing			184,091	kg	$200,477
Total for all individually estimated components:								$12,778,914
Total for 20,903 m^2 office building in Los Angeles, CA:								$18,980,605

Table 22. Gupta building EIO-LCA sectors and 2002 US dollar cost estimates.

The following data was used for the "Global" and "Component" EIO-LCA assessments.

Component	EIO Sector	Cost (2002 USD)
Standard foundation		
Concrete	Ready-mix concrete manufacturing	$14,229
Reinforcement	Iron and steel mills	$2,334
Basement walls		
Concrete	Ready-mix concrete manufacturing	$21,347
Reinforcement	Iron and steel mills	$3,834
Floor & roof structure		
Concrete	Ready-mix concrete manufacturing	$139,756
Reinforcement	Iron and steel mills	$335,415
Metal deck	Iron and steel mills	$293,488
Steel frame		
Structural steel	Plate work and fabricated structural product manufacturing	$2,309,861
Glazed curtain wall		
Whole system	Flat glass manufacturing + Aluminum product manufacturing (assumed 20% glazing cost, 80% framing cost for EIO-LCA)	$3,182,760
Roof finish		
Finish	Other concrete product manufacturing	$47,100
Membrane	Synthetic rubber manufacturing	$20,965
Insulation	Polystyrene foam product manufacturing	$7,268
Partition walls		
Wallboard	Lime and gypsum product manufacturing	$59,956
Framing	Iron and steel mills	$70,857
Finish	Paint and coating manufacturing	$25,436
Flooring		
Whole system	Iron and steel mills + Other concrete product manufacturing (assumed 50% concrete cost, 50% metal cost for EIO-LCA)	$1,048,172
Ceilings		
Ceiling tiles	Miscellaneous nonmetallic mineral products	$230,180
Framing	Iron and steel mills	$124,524
Total for all individually estimated components:		$7,937,482
Total for 20,903 m^2 office building in Los Angeles, CA:		$11,789,594

Table 23. Input materials for individual components in each LCA tool.

Component	SimaPro Inputs	Athena Inputs	Tally Inputs
Standard foundation			
Concrete	Concrete 35 Mpa	Concrete 35 Mpa	Structural concrete; 35 Mpa, generic
Reinforcement	Reinforcing steel	Rebar, rod, light sections	Steel; reinforcing rod
Basement walls			
Concrete	Concrete 35 Mpa	Concrete 35 Mpa	Structural concrete; 35 Mpa, generic
Reinforcement	Reinforcing steel	Rebar, rod, light sections	Steel; reinforcing rod
Floor & roof structure			
Concrete	Concrete 35 Mpa	Concrete 35 Mpa	Structural concrete; 35 Mpa, generic
Reinforcement	Reinforcing steel	Rebar, rod, light sections	Steel; reinforcing rod
Metal deck	Steel, low-alloyed	Galvanized decking	Galvanized steel form deck
Steel frame			
Structural steel	Steel, low-alloyed, hot rolled	Wide flange sections	Hot rolled structural steel
Glazed curtain wall			
Glazing	Flat glass, coated	Glazing panel	Glazing; double; insulated (air)
Framing	Aluminium alloy, AlMg3	Aluminum extrusion	Aluminum; extruded
Sealing	Synthetic rubber	EPDM membrane (black 60 mil)	
Hardware	Steel, chromium steel 18/8	Screws, nuts & bolts	
Roof finish			
Finish	Concrete 35 Mpa	Concrete tile	Structural concrete, 35 MPa, generic
Membrane	Synthetic rubber	EPDM membrane (black 60 mil)	EPDM; roofing membrane
Insulation	Polystyrene, expandable	Expanded polystyrene	Expanded polystyrene (EPS); board
Partition walls			
Wallboard	Gypsum plasterboard	Regular gypsum board	Wall board; gypsum; natural
Framing	Steel, low-alloyed	Galvanized stud	Galvanized steel
Finish	Alkyd paint, white	Solvent based alkyd paint	Paint; interior acrylic latex
Flooring			
Panel fill	Concrete 35 Mpa	Concrete 35 Mpa	Structural concrete, 35 MPa, generic
Panel casing	Steel, low-alloyed	Galvanized sheet	Steel, sheet
Hardware	Steel, low-alloyed	Hollow structural steel	Cold formed structural steel
Ceilings			
Ceiling tiles	Gypsum plasterboard	Regular gypsum board	Wall board; gypsum; natural
Framing	Steel, low-alloyed	Cold rolled sheet	Cold formed structural steel

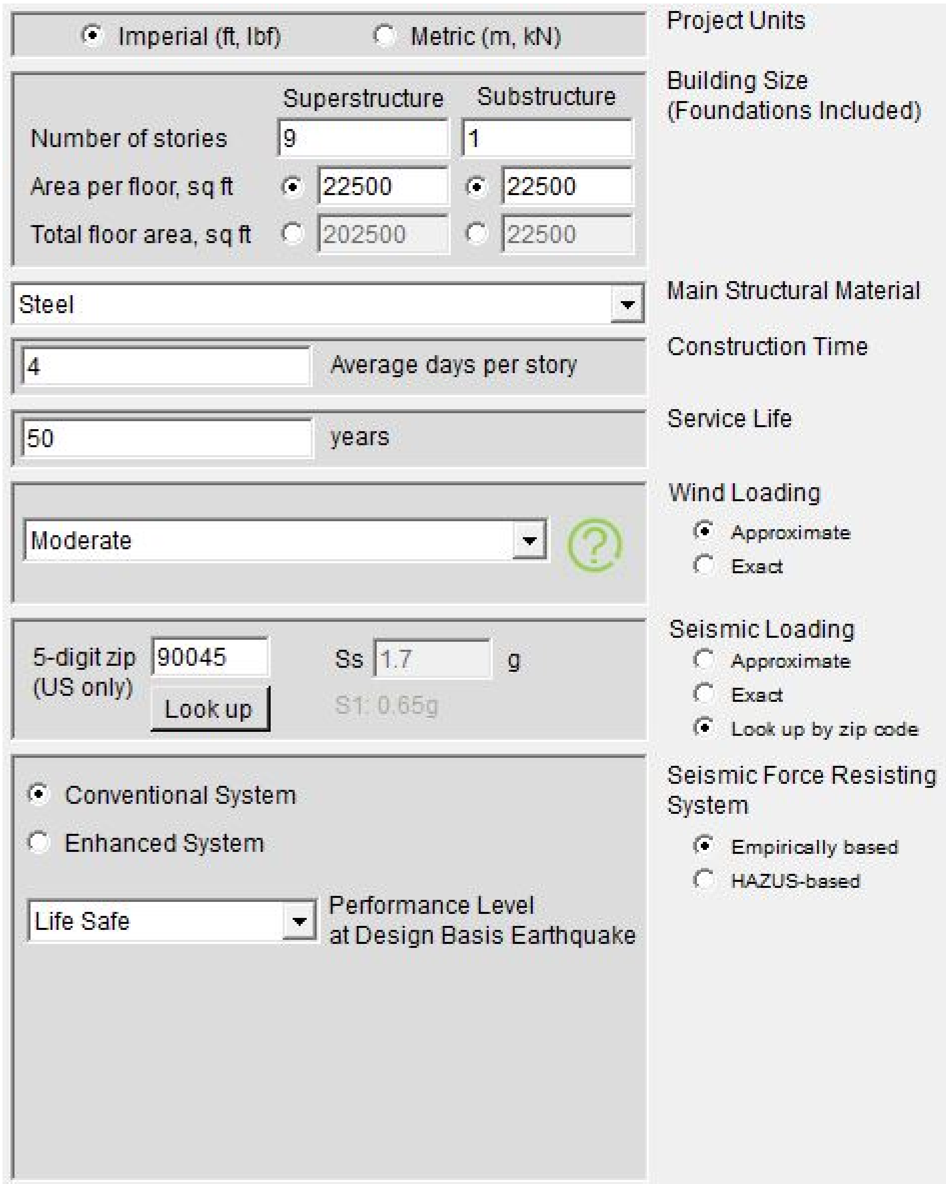

Figure 34. Input into the SOM Environmental Analysis Tool.

APPENDIX C

SUPPORTING INFORMATION FOR PROBABILISTIC ASSESSMENT OF THE LIFECYCLE ENVIRONMENTAL PERFORMANCE AND FUNCTIONAL LIFE OF BUILDINGS DUE TO SEISMIC EVENTS (CHAPTER 5)

C.1 LCI quantity estimates and repair assumptions

This Appendix includes details about the material estimates for individual building components (shown in Table 24), as well as repair assumptions for each component's damage states (shown in Table 25). Additionally, elevator material takeoff and associated repairs are provided in Table 26 and Table 27, respectively. It is important to note that not all data was available for the elevator material estimates to fully follow the damage and repair descriptions provided in the PACT fragility database and is shown in Table 27 accordingly.

Table 24. Building quantity estimates and component material estimates.

			Building		Material	
Item	**Details**	**LCI unit process**	**Qty.**	**Unit**	**Qty.**	**Unit**
Floor & roof suspended slab [b]	Concrete	Concrete, 20 MPa	225,000	SF	48.00	cu in/SF
	Deck	Steel, low-alloyed			1.61	lbs/SF
	Rebar	Reinforcing steel			3.42	lbs/SF
Columns & beams [b]	WF Sections	Steel, low-alloyed, hot rolled	1,190	ST		
Bolted shear tab gravity connections [b]	Plates, nuts and bolts	Steel, low-alloyed, hot rolled	800	EA	280.86	lbs/EA
Column Base Plates (150 plf < W < 300 plf) [b]	Plates	Steel, low-alloyed, hot rolled	16	EA	706.02	lbs/EA
	Welds	Welding, arc, steel			90.00	in/EA
Column Base Plates (W > 300 plf) [b]	Plates	Steel, low-alloyed, hot rolled	20	EA	2,075.69	lbs/EA
	Welds	Welding, arc, steel			105.00	in/EA

Welded column splices (W < 150 plf) [b]	Plates	Steel, low-alloyed, hot rolled	38	EA	267.58	lbs/EA
	Welds	Welding, arc, steel			250.00	in/EA
Welded column splices (150 plf < W < 300 plf) [b]	Plates	Steel, low-alloyed, hot rolled	50	EA	254.16	lbs/EA
	Welds	Welding, arc, steel			240.00	in/EA
Welded column splices (W > 300 plf) [b]	Plates	Steel, low-alloyed, hot rolled	56	EA	250.64	lbs/EA
	Welds	Welding, arc, steel			240.00	in/EA
Welded moment connection, one side (≤ W27) [b]	Plates	Steel, low-alloyed, hot rolled	24	EA	1,434.60	lbs/EA
	Welds	Welding, arc, steel			108.00	in/EA
Welded moment connection, one side (≥ W30) [b]	Plates	Steel, low-alloyed, hot rolled	56	EA	2,300.38	lbs/EA
	Welds	Welding, arc, steel			257.50	in/EA
Welded moment connection, two sides (≤ W27) [b]	Plates	Steel, low-alloyed, hot rolled	36	EA	2,869.20	lbs/EA
	Welds	Welding, arc, steel			216.00	in/EA
Welded moment connection, two sides (≥ W30) [b]	Plates	Steel, low-alloyed, hot rolled	84	EA	4,600.76	lbs/EA
	Welds	Welding, arc, steel			515.00	in/EA
Curtain Wall [a]	Glazing panel	Flat glass, coated	67,500	SF	6.56	lbs/SF
	Aluminum frame	Aluminium, wrought alloy			3.84	lbs/SF
	Rubber seal	Synthetic rubber			0.14	lbs/SF
	Hardware	Steel, chromium steel 18/8			0.12	lbs/SF
Concrete tile roof [c]	Tiles	Concrete roof tile	60,750	SF	9.30	lbs/SF
Wall Partition, Gypsum with metal studs [a]	Wallboard	Gypsum plasterboard	292,500	SF	8.00	lbs/SF
	Metal stud, hardware	Steel, low-alloyed			0.30	lbs/SF
	Joint compound	Joint compound			0.07	lbs/SF
	Paint	Alkyd paint, white			0.08	lbs/SF
	Tape	Drywall tape			0.02	oz/SF
Prefabricated steel stair[a]	Stair	Steel, low-alloyed	30	EA	1,486.00	lbs/EA
	Paint	Alkyd paint, white			13.90	lbs/EA
Raised Access Floor	Base, stringers, hardware	Steel, low-alloyed	168,750	SF	6.50	lbs/SF
	Fill	Concrete, 20 MPa			0.73	lbs/SF
	Paint	Alkyd paint, white			0.03	lbs/SF
Suspended Ceiling	Tile	Gypsum plasterboard	202,500	SF	1.10	lbs/SF
	Tile coating	Polyvinyl chloride			0.06	lbs/SF
	Grid, hardware, wire	Steel, low-alloyed			0.11	lbs/SF
	Hook	Steel, chromium steel 18/8			0.01	oz/SF
Recessed lighting	Body	Steel, low-alloyed, hot-rolled	3,375	EA	3.15	lbs/EA
Independent Pendant Lighting	Diffuser	Flat glass, coated	3,375	EA	1.50	lbs/EA
	Body	Steel, low-alloyed			0.50	lbs/EA
Traction Elevator[d]		Cast iron	7	EA	2,355.00	lbs/EA
		Steel, chromium steel 18/8			131.00	lbs/EA
		Steel, low-alloyed			2,155.00	lbs/EA
		Steel, unalloyed			1,240.00	lbs/EA
		Flat glass, coated			63.00	lbs/EA
		Copper			56.00	lbs/EA
		Polycarbonate			50.00	lbs/EA
		Aluminium, wrought alloy			38.00	lbs/EA
		Electronics, for control units			300.00	lbs/EA

Cold Water Piping (diameter > 2.5 in)	Pipe	Polyvinylchloride, suspension polymerised	3,375	LF	2.71	lbs/LF
Hot Water Piping (diameter < 2.5 in) [a]	Pipe	Steel, low-alloyed	18,900	LF	2.99	lbs/LF
	Insulation	Polyurethane, flexible foam			0.33	lbs/LF
	Casing	Polyethylene, high density, granulate			1.57	lbs/LF
Hot Water Piping (diameter > 2.5 in) [a]	Pipe	Steel, low-alloyed	6,750	LF	9.99	lbs/LF
	Insulation	Polyurethane, flexible foam			0.64	lbs/LF
	Casing	Polyethylene, high density, granulate			2.57	lbs/LF
Sanitary Waste Piping	Pipe	Cast iron	12,825	LF	6.35	lbs/EA
	Supports	Steel, chromium steel 18/8			0.09	lbs/EA
Chiller - Capacity: 75 Ton[c]	Chiller	Absorption chiller, 100 kW	9	EA		
Cooling Tower - Capacity: 75 Ton	Structure	Glass fibre reinforced plastic, polyester resin	9	EA	426.98	lbs/EA
	Base platform	Steel, low-alloyed			296.40	lbs/EA
	Fill pack, drift eliminator, louvers	Polyvinylchloride, suspension polymerised			97.80	lbs/EA
	Pipe and spray nozzles, fan blades	Acrylonitrile-butadiene-styrene copolymer			14.55	lbs/EA
	Motor	Cast iron			72.98	lbs/EA
HVAC Metal Ducting <6 sq. ft x-area[a]	Duct	Steel, low-alloyed	16,875	LF	5.56	lbs/LF
HVAC Metal Ducting >6 sq. ft x-area[a]	Duct	Steel, low-alloyed	4,500	LF	9.93	lbs/LF
HVAC Drops / Diffusers	Diffusers	Steel, low-alloyed	2,025	EA	8.53	lbs/EA
Variable Air Volume box[a]	Box, coil, chassis, fan	Steel, low-alloyed	1,125	EA	89.78	lbs/EA
	Insulation	Glass fibre			1.04	lbs/EA
	Coil	Copper			15.87	lbs/EA
	Electronics	Electronics, for control units			2.00	lbs/EA
Air Handling Unit - Capacity: 4000 CFM[a]	Structure, inlet, discharge, coils, drive, fan	Steel, low-alloyed	40	EA	308.00	lbs/EA
	Filter	Glass fibre			0.50	lbs/EA
	Filter	Corrugated board box			0.50	lbs/EA
	Coils	Copper			64.00	lbs/EA
	Drive	Cast iron			72.00	lbs/EA
	Drive	Synthetic rubber			1.00	lbs/EA
Fire Sprinkler Water Piping[a]	Pipe, joints	Steel, low-alloyed	45,000	LF	2.77	lbs/LF
Fire Sprinkler Drop[a]	Body	Brass	2,025	EA	0.49	lbs/EA
	Seal	Tetrafluoroethylene			0.08	oz/EA
	Bulb	Glass tube, borosilicate			0.08	oz/EA

[a] Estimate based on manufacturers' brochures, details, submittals, and specification sheets (Anvil International LLC 2015; Insul-Tek Piping Systems ; JMC Steel Group ; Johnson Controls 2008; Nailor Industries Inc. ; Steel Flooring Products Co ; Steel Stud Solutions LLC ; Sunpak Inc. ; TAMBE Metal Products ; The Viking Corporation 2014; Tubelite Inc. 2016)
[b] Estimate based on specifications in Gupta and Krawinkler (1999)
[c] Estimate based on ecoinvent 3.0 model
[d] Material weights were obtained from an Environmental Product Declaration (KONE) and assigned to best representative unit processes in the Ecoinvent 3.0 database. This information was used only for the environmental impact estimate of the whole elevator and for comparison with the individually modeled elevator components shown in Tables 7 and 8.

Table 25. Damage descriptions, repair assumptions and associated impact data.

Damage descriptions are adopted from FEMA (2012) and its PACT fragility database, which contains additional information. Global Warming Potentials (GWP) for the 100-year horizon were calculated based on modeled repairs, using ecoinvent 3.0 database and TRACI 2.1 impact assessment method.

Component	Damage Description	Repair Assumption	Damage State	EDP	GWP_{100} (kg CO_2 eq.)	
					Median	β
Bolted shear tab gravity connections	Yielding of shear tab and elongation of bolt holes, possible crack initiation around bolt holes or at shear tab weld.	2x 20x30x0.75 inch steel plates	DS_1	IDR	212.96	0.12
	Partial tearing of shear tab and possibility of bolt shear failure (6-bolt or deeper connections).	2x 20x30x0.75 inch steel plates + 6 bolts	DS_2	IDR	220.85	0.12
	Complete separation of shear tab, close to complete loss of vertical load resistance.	2x 20x30x0.75 inch steel plates + 6 bolts	DS_3	IDR	220.85	0.12
Base Plates, Column 150 plf < W < 300 plf	Initiation of crack at the fusion line between the column flange and the base plate weld.	35 in weld	DS_1	IDR	0.15	0.17
	Propagation of brittle crack into column and/or base plate.	90 in weld, 25x25x4 in plate	DS_2	IDR	586.60	0.12
	Complete fracture of the column (or column weld) and dislocation of column relative to the base.	90 in weld, 25x25x4 in plate, 13 ft W14X257 section	DS_3	IDR	3677.90	0.20
Base Plates, Column W > 300 plf	Initiation of crack at the fusion line between the column flange and the base plate weld.	35 in weld	DS_1	IDR	0.15	0.16
	Propagation of brittle crack into column and/or base plate.	105 in weld, 35x35x6 in plate	DS_2	IDR	1728.75	0.12
	Complete fracture of the column (or column weld) and dislocation of column relative to the base.	105 in weld, 35x35x6 in plate, 13 ft W14X500 section	DS_3	IDR	7965.50	0.15
Welded column splices, Column 150 plf < W < 300 plf	Cracking of the groove welded flange splice.	2x 15x15x1 in plates, 2x 60 in welds	DS_1	IDR	120.35	0.19
	DS 1 followed by complete failure of the web splice plate and dislocation of the two column segments on either side of the splice.	4x 15x15x1 in plates, 4x 60 in welds	DS_2	IDR	240.44	0.18
	Complete fracture of the column (or column weld) and dislocation of column relative to the column below plate. (More severe case of type DS2)	4x 15x15x1 in plates, 4x 60 in welds, 13 ft W14X283 section	DS_3	IDR	3791.54	0.19
Welded column splices, Column W > 300 plf	Cracking of the groove welded flange splice.	2x 12x12x1 in plates, 2x50 in welds	DS_1	IDR	77.84	0.19
	DS1 followed by complete failure of the web splice plate and dislocation of the two column segments on either side of the splice.	2x 12x12x1 in plates, 2x 25x12x1 in plates, 2x 50 in welds, 2x 70 in welds	DS_2	IDR	242.29	0.19

	Complete fracture of the column (or column weld) and dislocation of column relative to the column below plate. (More severe case of type DS2)	2x 12x12x1 in plates, 2x 25x12x1 in plates, 2x 50 in welds, 2x 70 in welds, 13 ft W24X335 section	DS_3	IDR	4369.00	0.18
Welded moment connection, beam one side, beam ≤ W27	Local beam flange and web buckling.	Heat straightning*	DS_1	IDR	0.00	0.00
	DS1 plus lateral-torsional distortion of beam in hinge region.	15 ft W27X84 section, 1 moment resisting connection	DS_2	IDR	1342.74	0.19
	Low-cycle fatigue fracture in buckled region	15 ft W27X84 section, 1 moment resisting connection	DS_3	IDR	1342.74	0.19
Welded moment connection, beam one side, beam ≥ W30	Local beam flange and web buckling.	Heat straightening*	DS_1	IDR	0.00	0.00
	DS1 plus lateral-torsional distortion of beam in hinge region.	15 ft W33X141 section, 1 moment resisting connection	DS_2	IDR	2195.94	0.18
	Low-cycle fatigue fracture in buckled region	15 ft W33X141 section, 1 moment resisting connection	DS_3	IDR	2195.94	0.18
Welded moment connection, beams both sides, beam ≤ W27	Local beam flange and web buckling.	Heat straightening*	DS_1	IDR	0.00	0.00
	DS1 plus lateral-torsional distortion of beam in hinge region.	30 ft W27X84 section, 2 moment resisting connections	DS_2	IDR	2587.27	0.18
	Low-cycle fatigue fracture in buckled region	30 ft W27X84 section, 2 moment resisting connections	DS_3	IDR	2587.27	0.18
Welded moment connection, beams both sides, beam ≥ W30	Local beam flange and web buckling.	Heat straightening*	DS_1	IDR	0.00	0.00
	DS1 plus lateral-torsional distortion of beam in hinge region.	30 ft W33X141 section, 2 moment resisting connections	DS_2	IDR	4395.65	0.18
	Low-cycle fatigue fracture in buckled region of RBS.	30 ft W33X141 section, 2 moment resisting connections	DS_3	IDR	4395.65	0.18
Curtain Wall	Glass cracking.	100% glass replacement (for 30 SF panel)	DS_1	IDR	108.69	0.18
	Glass falls from frame.	100% glass replacement (for 30 SF panel)	DS_2	IDR	924.00	0.08
Concrete tile roof	Minor damage; tiles dislodged.	30% new tiles needed (over 100 SF section)	DS_1	IDR	39.75	0.21
	Major portion of tile dislodged.	60% new tiles needed (over 100 SF section)	DS_2	IDR	79.51	0.21
Wall Partition, Gypsum with metal studs	Screws pop-out, minor cracking of wall board, warping or cracking of tape.	5% new tape, paste, paint (13x100 ft panels)	DS_1	IDR	10.73	1.00
	Moderate cracking or crushing of gypsum wall boards (typically in corners and in corners of openings).	50% new tape, paste, paint; 25% new wallboard (13x100 ft panels)	DS_{2a}	IDR	631.67	0.27
		100% new wallboard, tape, paste, paint (13x100 ft panels)	DS_{2b}	IDR	2258.70	0.18
	Significant cracking and/or crushing of gypsum wall boards- buckling of studs and tearing of tracks.	25% complete replacement (13x100 ft panels)	DS_{3a}	IDR	833.80	0.13

		100% complete replacement (13x100 ft panels)	DS_{3b}	IDR	3299.04	0.13
Prefabricated steel stair	Non structural damage, local steel yielding.	Paint 10% of staircase	DS_1	IDR	0.00	0.00
	Buckling of steel, weld cracking.	Replace 5% of staircase	DS_2	IDR	63.72	0.12
	Loss of live load capacity. Connection and or weld fracture.	Replace 100% of staircase	DS_3	IDR	1274.39	0.12
Raised Access Floor	Minor damage to the flooring system. Damage to the equipment of the flooring system.	Replace 5% of floor area (over 100 SF section)	DS_1	PFA	24.77	0.13
Suspended Ceiling	5 % of tiles dislodge and fall.	Replace tiles in 5% of ceiling area (over 250 SF section)	DS_1	PFA	4.41	0.08
	30% of tiles dislodge and fall and t-bar grid damaged.	Replace 30% of ceiling area (over 250 SF section)	DS_2	PFA	33.46	0.08
	Total ceiling and grid collapse.	Replace 100% of ceiling (over 250 SF section)	DS_3	PFA	111.52	0.07
Independent Pendant Lighting	Disassembly of rod system at connections with horizontal light fixture, low cycle fatigue failure of the threaded rod, pullout of rods from ceiling assembly.	Replace unit	DS_1	PFA	1.31	0.13
Traction Elevator	Controller anchorage failed, and or machine anchorage failed, and or motor generator anchorage failed, and or governor anchorage failed, and or rope guard failures.	**See elevator repair estimate on Tables 7 and 8.	DS_{1a}	PFA	259.17	0.18
	Rail distortion, and or intermediate bracket separate and spread, and or counterweight bracket break or bend, and or car bracket break or bend, and or car guide shoes damaged, and or counterweight guide shoes damaged, and or counterweight frame distortion, and or tail sheave dislodged and/or twisted.	**See elevator repair estimate on Tables 7 and 8.	DS_{1b}	PFA	2947.46	0.12
	Cab stabilizers bent, or cab walls damaged, or cab doors damaged.	**See elevator repair estimate Tables 7 and 8.	DS_{1c}	PFA	69.65	0.08
	Cab ceiling damaged.	**See elevator repair estimate Tables 7 and 8	DS_{1d}	PFA	121.97	0.08
Cold Water Piping (diameter > 2.5 inches)	Minor leakage at flange connections - 1 leak per 1000 feet of pipe	Replace 2 ft of pipe per 1000 ft run	DS_1	PFA	5.15	0.01
	Pipe Break - 1 break per 1000 feet of pipe	Replace 10 ft of pipe per 1000 ft run	DS_2	PFA	25.76	0.01
Hot Water Piping (diameter < 2.5 inches)	Small Leakage at joints - 1 leak per 1000 feet of pipe	Apply sealant at leak*	DS_1	PFA	0.00	0.00
	Large Leakage w/ major repair - 1 leak per 1000 feet of pipe	Replace 10ft length of pipe per 1000 ft run	DS_2	PFA	24.15	0.12
Hot Water Piping (diameter > 2.5 inches)	Minor leakage at flange connections - 1 leak per 1000 feet of pipe	Apply sealant at leak*	DS_1	PFA	0.00	0.00

	Pipe Break - 1 break per 1000 feet of pipe	Replace 10ft length of pipe per 1000 ft run	DS_2	PFA	75.60	0.12
Sanitary Waste Piping	Isolated support failure w/o leakage - 0.5 supports fail per 1000 feet of pipe (assuming supports every 20 feet)	Replace 25 supports per 1000ft of pipe	DS_1	PFA	169.67	0.09
Chiller - Capacity: 75 Ton	Damaged, inoperative	Repair impacts 10% of initial	DS_1	PFA	84.19	0.12
Cooling Tower - Capacity: 75 Ton	Damaged equipment and attached piping.	Repair impacts 10% of initial	DS_1	PFA	84.12	0.12
HVAC Metal Ducting less than 6 sq. ft x-area	Individual supports fail and duct sags - 1 failed support per 1000 feet of ducting	Replace support, replace 1ft of duct per 1000 ft run	DS_1	PFA	8.42	0.12
	Several adjacent supports fail and sections of ducting fall - 60 feet of ducting fail and fall per 1000 foot of ducting	Replace supports for 60ft (8ft spacing), replace 60ft of duct per 1000 ft run	DS_2	PFA	505.12	0.12
HVAC Metal Ducting - 6 sq. ft x-area	Individual supports fail and duct sags - 1 failed support per 1000 feet of ducting	Replace support, replace 1ft of duct per 1000 ft run	DS_1	PFA	8.42	0.12
	Several adjacent supports fail and sections of ducting fall - 60 feet of ducting fail and fall per 1000 foot of ducting	Replace supports for 60ft (8ft spacing), replace 60ft of duct per 1000 ft run	DS_2	PFA	505.12	0.12
HVAC Drops / Diffusers	HVAC Drops or Diffusers Dislodges and Falls	Replace entire diffuser	DS_1	PFA	71.46	0.12
Variable Air Volume box	Coil damages connection to plumbing. Leakage of hot water	Replace coil	DS_1	PFA	1404.38	0.08
Air Handling Unit - Capacity: 4000 CFM	Equipment does not function. Damage to attached ducting or piping.	Replace 10ft of ducting, replace 5% of unit	DS_1	PFA	84.19	0.12
	Equipment does not function Equipment damaged beyond repair.	Replace 10ft of ducting, replace entire unit	DS_2	PFA	499.09	0.08
Fire Sprinkler Water Piping	Spraying & Dripping Leakage at joints - 0.02 leaks per 20 ft section of pipe	Replace 5% of all joints per 1000 ft run	DS_1	PFA	0.43	0.12
	Joints Break - Major Leakage - 0.02 breaks per 20 ft section of pipe	Replace 2% of pipe per 1000 ft run	DS_2	PFA	47.13	0.12
Fire Sprinkler Drop	Spraying & Dripping Leakage at drop joints - 0.01 leaks per drop	Replace drop	DS_1	PFA	190.42	0.20

IDR=Inter-story Drift Ratio, PFA=Peak Floor Acceleration, $EI_{0.5}$=Median values of environmental impacts, β=Standard deviation of ln EI_r
* Starred items were not modelled due to lack of available data.
** Elevator repairs are included in Tables 7 and 8 due to additional complexity in the material and repair estimations. Material weights from Table 5 were not used in this case.

Table 26. Elevator quantity estimates.

Component	Subcomponent	Material	Count	Dimension		Multiplier		Total	
Motor Generator	Generator	Generator	1	-		-		1.00	ea
Governor	Mechanism	Steel	1	-				90.00	lbs
Cab Guide Rail	Rail	Steel	2	134.00	ft	11.00	lbs/ft	2,948.00	lbs
	Brackets	Steel	24	-		8.00	lbs/ea	192.00	lbs
	Intermediate Brackets	Steel	24	-		8.00	lbs/ea	192.00	lbs
Guide Shoes	Housing	Steel	4	-		30.00	lbs/ea	120.00	lbs
	Wheel	Steel	12	-		1.25	lbs/ea	15.00	lbs
	Tire	Urethane	12	-		1.25	lbs/ea	15.00	lbs
Counterweight Guide Rail	Rail	Steel	2	134.00	ft	8.00	lbs/ft	2,144.00	lbs
	Brackets	Steel	24	-		10.00	lbs/ea	240.00	lbs
Counterweight	Filler	Steel	10	-		25.00	lbs/ea	5,328.00	lbs
	Frame	Steel	1	-		-		525.00	lbs
Cab Ceiling	Canopy	Plywood	2	37.22	sf	0.75	in	4.65	cf
	Ceiling Frame	Aluminum	1	28.67	ft	0.21	lbs/ft	6.12	lbs
	Ceiling Tiles	Polycarbonate	1	25.33	sf	0.31	lbs/sf	7.79	lbs
Cab Walls	Structural Panel	Particle board	1	156.28	sf	1.00	in	13.02	cf
		Paint	1	156.28	sf	0.06	lbs/sf	10.00	lbs
	Wall Finish	Stainless steel	1	156.28	sf	0.81	lbs/sf	126.98	lbs
	Handrail	Stainless steel	1	16.17	ft	0.65	lbs/ft	10.51	lbs
Cab Floor	Structural Panel	Plywood	1	37.22	sf	0.75	in	2.33	cf
	Floor Finish	Vinyl	1	0.33	cf	86.00	lbs/cf	28.37	lbs
Cab Doors	Shell/finish	Steel	2	32.875	sf	2.5	lbs/sf	164.38	lbs
Cab Sling	Sling Frame	Steel	1	-		-		1,183.00	lbs

Note: ea = units

Table 27. Elevator repair estimates.

Percent change based on FEMA (2012) PACT fragility descriptions. n/a in unit process means the corresponding items were excluded due to lack of available data.

DS	Elevator repairs	Change	Description	Unit Process	Quantity	
DS1	Controller	4%		n/a		
	Motor generator	63%	1 electric generator	Generator	0.0646	p
	New generator and anchors	23%		n/a		
	New governor	7%	1 governor	Steel, low-alloyed	6.30	lbs
	Rope guards	15%		n/a		
DS2	Rail	62%	2 car rails, 2 counterweight rails	Steel, low-alloyed	3,157.04	lbs
	Bracket/Tie rod	28%	24 brackets	Steel, low-alloyed	53.76	lbs
	Counterweight bracket	14%	24 brackets	Steel, low-alloyed	33.60	lbs
	Intermediate bracket	28%	24 brackets	Steel, low-alloyed	53.76	lbs
	Car guide shoes	35%	4 shoes	Steel, low-alloyed	57.00	lbs
				Polyurethane, rigid foam	5.25	lbs
	Counterweight guide shoe	28%	4 shoes	Steel, low-alloyed	48.60	lbs
				Polyurethane, rigid foam	4.20	lbs
	Counterweight frame	28%	1 frame	Steel, low-alloyed	147.00	lbs
	Tail sheave	1%		n/a		
DS3	Cab walls	3%	all walls	Steel, chromium	3.81	lbs
				Plywood	0.39	cf
				Paint, alkyd	0.30	lbs
	Cab doors	17%	1 door	Steel, chromium	27.94	lbs
	Cab stabilizers	92%		n/a		
DS4	Cab ceiling	100%	complete ceiling	Plywood	4.65	cf
				Aluminum	6.12	lbs
				Polycarbonate	7.79	lbs

Note: DS = damage state

APPENDIX D

SUPPORTING INFORMATION FOR SENSITIVITY OF LIFE CYCLE ENVIRONMENTAL IMPACTS AND COSTS OF BUILDINGS TO DESIGN AND SERVICE DECISIONS (CHAPTER 6)

D.1 Additional material, construction, and service information

Table 28. Sensitivity study construction types and materials.

Construction	Material layers
Roof R15 XPS	Concrete RF slab 6in XPS 60psi 3in R15
Roof R40 XPS	Concrete RF slab 6in XPS 60psi 4in R20 XPS 60psi 4in R20
Roof R15 PIR	Concrete RF slab 6in PIR 2-1/2in unfaced R14.40
Roof R40 PIR	Concrete RF slab 6in PIR 3-1/2in unfaced R20.16 PIR 3-1/2in unfaced R20.16
Slab	Concrete RF slab 6in Concrete RF slab 6in Carpet 1/4in
Floor	Concrete RF slab 6in Carpet 1/4in
Interior Wall	Gypsum board 1/2in Gypsum board 1/2in
Exterior Wall A	Plaster 1/2in Brick 8in Plaster 1/2in
Exterior Wall B	Brick 4in EPS 2in CMU 4in Plaster 1/2in
Single glazing	Single 1/4in clear
Double glazing	Double 1/4in clear
Ceiling	Gypsum board 1/2in

Table 29. Sensitivity study water and wastewater treatment data.

Treatment type	Ecoinvent data	Treatment energy [a]	Aerator energy [b]	One time cost [c]	Recurring cost [d]
Centralized Conventional	Tap water, production, conventional treatment	4.27	0	0	0
Centralized Direct Filtration	Tap water, production, direct filtration	2.86	0	0	0
Centralized Wastewater	Wastewater, treatment of, capacity 1.1E10l/year	0.22	0	0	0
On-Site, Septic, Aerobic	-	4.65	4.47	8,924	1,344
On-Site, Septic, Anaerobic	-	4.65	0	8,924	1,344

[a] Amount of electricity needed to treat a volume of water. [kWh/m^3]
[b] Only applicable to on-site systems. [kWh/day]
[c] Only applicable to on-site systems. [$]
[d] Only applicable to on-site systems. [$/year]

Table 30. Glazing subcomponent quantities and links to LCI data.

Name	Subcomponent	LCI Name*	Amount per glazing area		Material density		Service life	
Single 1/4in clear	Glazing	Flat glass, coated, 6mm	15.6	kg/m^2	2600	kg/m^3	40	years
	Framing	Aluminium alloy, AlMg3	4.83	kg/m^2	2700	kg/m^3	40	years
	Sealing	Synthetic rubber	0.29	kg/m^2	860	kg/m^3	40	years
	Hardware	Steel, chromium steel 18/8	0.20	kg/m^2	7800	kg/m^3	40	years
Double 1/4in clear	Glazing	Flat glass, coated, 6mm	15.6	kg/m^2	2600	kg/m^3	40	years
	Glazing	Flat glass, coated, 6mm	15.6	kg/m^2	2600	kg/m^3	40	years
	Framing	Aluminium alloy, AlMg3	4.83	kg/m^2	2700	kg/m^3	40	years
	Sealing	Synthetic rubber	0.29	kg/m^2	860	kg/m^3	40	years
	Hardware	Steel, chromium steel 18/8	0.20	kg/m^2	7800	kg/m^3	40	years

* Based on ecoinvent database

Table 31. Glazing unit properties and links to LCI and cost data.

Name	U-Value	SHGC	Visible Transmittance	Glass Thickness	LCI Name	Cost Name	Service Life
	[W/m^2·K]	-	-	[m]			[Years]
Single 1/4in clear	5.78	0.819	0.881	0.006	Single 1/4in clear	Single glazed, average	40
Double 1/4in clear	2.67	0.703	0.781	0.013	Double 1/4in clear	Double glazed, average	40

Table 32. Material properties and links to LCI and cost data.

Name	Thickness	Conductivity	Density	Specific Heat	Thermal Absorp.	Solar Absorp.	Visible Absorp.	LCI Name	Cost Name	Service Life
	[m]	[W/m·K]	[kg/m^3]	[J/kg·K]	-	-	-			[Years]
Brick 4in	0.105	0.720	1920	840	0.90	0.70	0.70	Clay brick	Brick 4x4x8in	100
Brick 8in	0.200	0.720	1920	840	0.90	0.70	0.70	Clay brick	Brick 4x4x8in	100
Carpet 1/4in	0.006	0.060	288	1380	0.90	0.75	0.75	Carpet, Mohawk, EPD	Carpet tile	15
CMU 4in	0.100	0.190	600	1000	0.90	0.70	0.70	Concrete block	CMU 8x16x8in	100
Concrete LW 4in	0.102	0.890	1920	790	0.90	0.70	0.70	Concrete, 30-32MPa	Concrete Lightweight Slab	100
Concrete RF 8in	0.200	1.900	2300	840	0.90	0.70	0.70	Concrete, 30-32MPa, reinforced	Concrete Reinforced Slab	100
EPS 2in	0.050	0.035	25	1400	0.90	0.75	0.75	Polystyrene, expandable	EPS 2in	60
Plaster 1/2in	0.013	0.500	1300	1000	0.90	0.92	0.92	Clay plaster	Plaster 1/2in	60
Gypsum 1/2in	0.013	0.160	800	1090	0.90	0.70	0.70	Gypsum plasterboard	Gypsum board, standard	40
XPS 60psi R15	0.076	0.029	29	1210	0.90	0.70	0.70	Polystyrene, extruded	XPS R15	60
XPS 60psi R20	0.102	0.029	29	1210	0.90	0.70	0.70	Polystyrene, extruded	XPS R20	60
PIR 2-1/2in R14.4	0.064	0.025	24	1590	0.90	0.70	0.70	Polyurethane, rigid foam	PIR 2-1/2in R14.4	60
PIR 3-1/2in R20.2	0.089	0.025	24	1590	0.90	0.70	0.70	Polyurethane, rigid foam	PIR 3-1/2in R20.2	60
EPDM 60 mil	0.002	0.200	1371	2000	0.90	0.70	0.70	Synthetic rubber	EPDM roofing 60 mil	40

Note: Name and Cost Name columns include names with IP units based on the naming convention of the sources (RS Means for Cost Names). Physical properties and LCI Name include SI units based on the convention of the data sources (i.e., EnergyPlus for physical properties and ecoinvent database for LCI Name).

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