ADVANCING LIFE CYCLE ASSESSMENT: PERSPECTIVES FROM THE BUILDING AND HEALTHCARE INDUSTRIES

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University of Pittsburgh, 2015

This research investigates the development of life cycle assessment (LCA) in the building and healthcare industries. The ultimate goal is to advance necessary contributions and provide strategic recommendations on the development of LCA in both industries. Because the building industry has progressed farther in terms of environmental and economic assessments than the healthcare industry, the lessons learned from past implementation and market adoption of building LCAs is essential for the future of healthcare LCAs. To achieve the goal of this dissertation, the evolution of LCA in each industry was studied, followed by recommendations and strategies for future sustainable development.

To understand the building industry, three different studies are presented. The first building LCA study focused on building materials, comparing green building materials to traditional building materials and concluding that there is a quantitative need for LCA integration in the zero-energy building definition. The second LCA study integrated LCA with life cycle cost assessment (LCCA) as a complimentary tool for building owner decision-making. The last LCA study builds on the LCA/LCCA study and developed an integrated pathway linking LCA

with a host of other environmental and economic tools that broaden the scope of building projects.

To understand the healthcare industry, three different studies are presented. The use of LCA in the healthcare industry is relatively new; therefore the first study compared two different birth procedures to determine the high-impact areas within healthcare. The second LCA study focused on disposable products discussing streamlining efforts and strategies that could be applied universally across the healthcare industry. The last healthcare LCA study is a set of organizational techniques that can be applied to any healthcare institution attempting to reduce their environmental impacts; the more advanced green teams integrating LCA for quantitative information.

The final study presented connects the building and healthcare industries, quantifying design decisions of evidence-based design and green building design through a host of metrics such as quality of care, utilities, and staff satisfaction. Both the building and healthcare industries have a tremendous amount of potential to enhance sustainable development utilizing life cycle assessment.

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NOMENCLATURE

ADE	Adverse Drug Event
AEC	Architecture, Engineering, and Construction [industry]
AIA	American Institute of Architects
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating, and Air Conditioning Engineers
BIM	Building Information Modeling
CED	Cumulative Energy Demand
CSL	Center for Sustainable Landscapes
CTU (h or e)	Cumulative Toxicity Unit (human or environment) – number of disease cases per kg of chemical emitted
CUFT	Cubic Feet
DOE	Department of Energy
DLCA	Dynamic Life Cycle Assessment
EBD	Evidence-Based Design
EEB	Energy Efficiency Buildings [Hub]
EIO-LCA	Economic Input-Output Life Cycle Assessment
EOL	End-of-Life
EPA	Environmental Protection Agency

EPD	Environmental Product Declaration
EPDM	Ethylene Propylene Diene Monomer
Eq.	Equivalent
FTE	Full Time Employee
Gal	Gallons
GBI	Green Building Initiative
GBRS	Green Building Rating System
GDP	Gross Domestic Product
GHG	Greenhouse Gas [emissions]
GWP	Global Warming Potential
HCAHPS	Hospital Consumer Assessment of Healthcare Providers and Systems
HDPE	High Density Polyethylene
HVAC	Heating, Ventilation, and Air Conditioning
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
IPD	Integrated Project Delivery
ISO	International Standards Organization
kWh	Kilo-Watt hours
LBC	Living Building Challenge
LBS	Pounds
LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Assessment
LCI	Life Cycle Inventory

LCIA	Life Cycle Impact Assessment
LDPE	Low Density Polyethylene
LDR	Labor and Delivery Room
LEED	Leadership in Energy and Environmental Design
Magee	Magee-Womens Hospital
MSW	Municipal Solid Waste
NIH	National Institute of Health
O&M	Operations and Management
OR	Operating Room
PCTs	Patient Care Technicians
Phipps	Phipps Conservatory and Botanical Garden
PIB	Patient in Bed
PMP	Proactive Maintenance Plan
PP	Polypropylene
PV	Photovoltaic
PVC	Polyvinyl Chloride
Req.	Required
REPA	Resource And Environmental Profile Analysis
RMP	Reactive Maintenance Plan
RMW	Regulated Medical Waste
RN	Registered Nurse
ROI	Return on Investment
SETAC	Society of Toxicology and Chemistry

SMS PP	Spunbound-meltblown-spunbound polypropylene
SUD	Single-Use Device
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
UPMC	University of Pittsburgh Medical Center
USGBC	US Green Building Council
ZEB	Zero-Energy Building

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1.0 INTRODUCTION

1.1 MOTIVATION

Life cycle assessments are permeating a host of diverse sectors in the U.S., from energy to buildings to food. Large corporations, such as ExxonMobile, Bayer, and Walmart, employ a growing number of LCA analysts. Environmental product declarations (EPDs), which reports the environmental life cycle assessment data for a specific product, has become an increasingly popular part of life cycle assessment market transformation (ISO 2006a). As the competitive market prepares for carbon taxes, LCA and its subset, carbon footprinting, will continue to expand (Davenport 2013). Experts in LCA, however, continue to note shortcomings of LCA, such as adequate data sources and impact assessment methods, replicability and standardization of LCA methods, and comprehensible results that motivate decision-makers (Guinee, Heijungs et al. 2010, Baitz, Albrecht et al. 2012). LCA advancement, especially robust intensive studies, is needed in diverse industries. The two industries considered are seemingly diverse, buildings and healthcare, yet represent appropriate benchmarks in the LCA development and future implementation.

United States programs dedicated to the environmental sustainability of the building industry can be dated back to the early 1990's (EPA 2014b). Similarly, the commercialization of LCA also occurred in 1990 (Hunt, Franklin et al. 1996). In contrast, the healthcare industry is still in the infancy of environmental sustainability (PracticeGreenHealth 2008). *This research investigates the building and healthcare industries aiming to advance necessary contributions and provide strategic recommendations on the development of LCA in both sectors.* Because the building industry has progressed farther in terms of environmental and economic assessments than the healthcare industry, as indicated by the search terms found in the ScienceDirect and ProQuest databases in Table 1, the lessons learned from engineering analyses and market adoption of building LCAs will be essential in developing strategies and recommendations for the future of healthcare LCAs.

Table 1: Search terms and returned results in the ScienceDirect and ProQuest databases for peer-reviewed journals 1990-2015

Search Term	ScienceDirect Database	ProQuest Database	Healthcare to Building Ratio SD | PQ
"Buildings" and "life cycle assessment" "Healthcare" and "life cycle assessment"	7,534 276	2,305 268	3.6% | 11.6%
"Building industry" and "life cycle assessment" "Healthcare industry" and "life cycle assessment"	1,041 45	14,704 1,816	4.3% | 12.4%
"Building sustainability" "Healthcare sustainability"	357 23	357 17	6.4% | 4.8%

The United States building industry has significant environmental, economic, and social impacts. In 2013, the building industry accounted for approximately 40% of the total US energy consumption (DOE 2014). The building and construction industries also contribute to an estimated 20% of the US Gross Domestic Product (GDP) (WorldBank 2014b). Additionally, people spend about 90% of their lives indoors, where pollutants may have concentrations 2 to 5 times higher than average outdoor conditions (EPA 2008b). Given the number of environmental impacts of the building industry, many tools, policies, and methods have been developed to track progress, identify improvement areas, and establish best practice strategies for sustainable buildings. The selection of more than one tool, policy, or method presents serious challenges to designers, builders, and owners.

Healthcare is also one the largest industries in the United States. Healthcare consumes 73 billion kWh of electricity annually, accounts for 17.9% of the total US GDP, employs over 5.3 million people, and spends nearly $320 billion on goods and services (CEA 2009, DOE 2012, Vogt and Nunes 2014, WorldBank 2014a). Consequently, the healthcare industry is estimated to produce 8% of the total US carbon dioxide emissions (Chung and Meltzer 2009b). Despite these statistics on consumption and emissions, only 0.03% of the $29 billion US National Institute of Health budget is allocated to research focused on increasing sustainability in healthcare delivery (OSTP 2014). The healthcare industry needs quantitative information to curb excess waste and develop sustainable solutions for maintaining and exceeding the current level of care, expertise, and patient outcomes (Berwick and Hackbarth 2012).

1.2 RESEARCH GOALS & OBJECTIVES

The goal of this research is to provide strategic recommendations on the development of life cycle assessment in both the building and healthcare industries by analyses of past and current contributions. An overview of the objectives is shown in Figure 1. This research has been published in *Science of the Total Environment*, the *Journal of Cleaner Production*, and *energies* (Campion, Thiel et al. 2012, Thiel, Campion et al. 2013, Campion, Thiel et al. 2015).

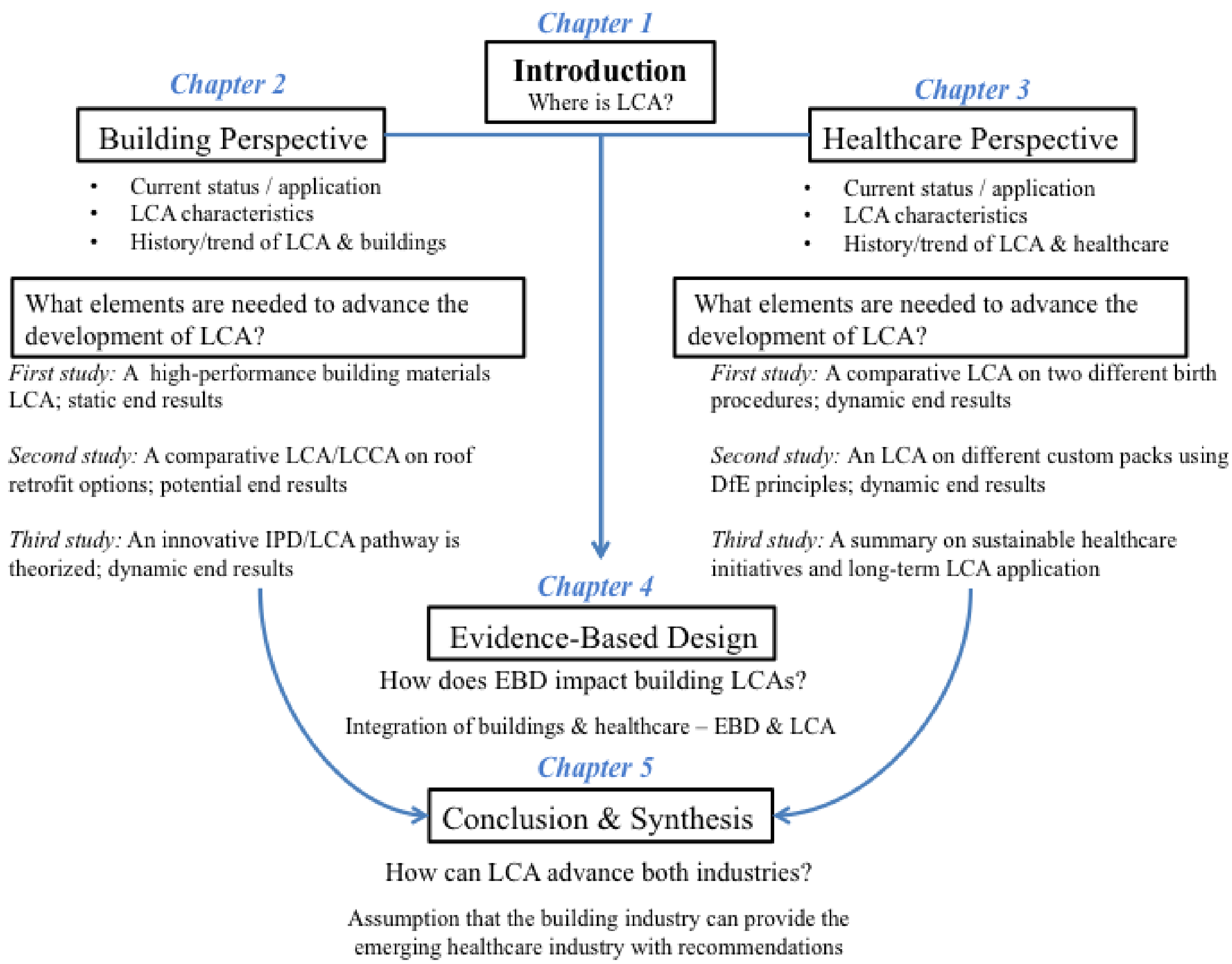


Figure 1: Overview of dissertation research questions and objectives. The numbers relate to the Dissertation Chapters: 1) Introduction, 2) Building Perspective, 3) Healthcare Perspective, 4) Evidence-Based Design, and 5) Conclusion.

The specific research questions and pertaining objectives for this dissertation are as follows:

1) What tools and strategies are needed to advance LCA in the building industry?
2) What tools and strategies are needed to advance LCA in the healthcare industry?
3) How can green buildings and LCA be integrated into EBD to enhance the environmental and occupational impacts of building design?

4) After completing in-depth analyses of the building and healthcare industries, what strategies are needed to advance LCA in those industries, with the assumption that the building industry may be able to provide recommendations to the emerging healthcare industry?

1.3 BROADER IMPACTS

The broader impacts of the research presented attest to the breadth of collaborators and industry scope. The research itself can be applied to a variety of applications beyond those presented such as construction, medicine, operations, and product development. Recommendations developed can be interchangeable and modified to cater to the needs of the client, whether they are a building owner, a physician, or a facilities manager.

The building and healthcare industries represent almost 40% of the US GDP, therefore advancing life cycle assessment science in these sectors has considerable market potential for sustainable development. The work pertaining to the evolution of building LCAs, specifically the integrated project delivery (IPD) and LCA pathway, provides an approach for building projects to create an integrative team that encourages the use of building assessments, such as LCA. Assessing market perception of LCA suggests that incorporating LCA and other quantitative assessments into the green building rating system LEED is an appropriate outlet for LCA growth in the building industry and for market transformation.

The work pertaining to the evolution of healthcare LCAs provides a framework for data driven decision-making. The two studies presented have had an impact on the host hospital as well as providing the healthcare industry with data on high-impact areas, such as disposable products. In addition, the strategies and suggestions for implementing a green team within a hospital institution resonate with traditional hospital hierarchy and can be applied universally. The work pertaining to healthcare buildings focuses on the overlap between traditional healthcare building design, evidence-based design, and green building design and what the outcomes are in relation to social and environmental impacts. Capturing the aspects of EBD and green building design that compliment each other provides healthcare institutions and green building rating systems with information to enhance patient and staff satisfaction with better building performance.

1.4 INTELLECTUAL MERIT

This study will further contribute to the limited scientific understanding of life cycle assessment in the healthcare industry in relation to the more recognized building industry. The novel relationship between the building and healthcare industries provides strategies and recommendations for advancement through integrative approaches, data collection methods, and market transformation. Utilizing an integrative project delivery method compliments the use of LCA in the building industry and suggests a realistic approach for future project applications. The frameworks developed for the healthcare LCA studies encourage healthcare institutions to request more data-driven information on current practices in order to make appropriate and sustainable changes. The relationship between evidence-based design and green building design highlights the differences between healthcare-centric designs and green designs while addressing potential for overlap in future healthcare buildings, marrying patient satisfaction with building performance.

1.5 LIFE CYCLE ASSESSMENT BACKGROUND

Life cycle assessment (LCA) is a universal tool used to analyze the environmental impacts of a product or process from raw material extraction to production, use, and end-of-life (EOL) (ISO 1997a, Baumann and Tillman 2004). Oftentimes, the terms "cradle to gate" or "cradle to cradle" are used to describe LCA, cradle is the production phase or the recycling phase and gate is the use phase.

Life cycle assessment (LCA) can be dated back to 1969, yet its emergence into the market started around 1990. An overview of LCA history is adapted from Robert E. Hunt's article in the first volume of the *International Journal of Life Cycle Assessment* and described in Table 2. The term REPA (resource and environmental profile analysis) was used to describe LCA from 1970 to 1990, when LCA became the official term (Hunt, Franklin et al. 1996).

Table 2: History of Life Cycle Assessment; LCA = life cycle assessment; EOL = end-of-life; MRI = Midwest Research Institute; REPA = resource and environmental profile analysis; EPA = Environmental Protection Agency; EPD = environmental product declarations; ISO = International Standards Organization. (Hunt, Sellers et al. 1992, Curran 1993, Curran 1996, Hunt, Franklin et al. 1996, ISO 1997a, Rice, Clift et al. 1997, ISO 2006b, Finkbeiner 2013)

Date	Description
1969	Coca Cola started first LCA (packaging, plastic bottles, & EOL)
1970-74	REPA/LCA framework developed for impact assessment
1972	First LCA publications appeared, describing methodology & data sets
1973	First computer program funded by MRI client
1974	EPA published report and impact assessment on 9 drink containers
1975	EPA decided REPA/LCA was impractical as a regulatory tool (EPD)
1975	Franklin Associates was established (first LCA company)
1976	Coca Cola published their LCA study (1969) in Science Magazine
1978	Goodyear Tire and Rubber Company LCA on PET drink containers (not published)
1988	Re-awakening of environmental consciousness (garbage barge & pressure from Europe); relook at LCA and solid waste (recycling, landfilling, etc)

Table 2 (continued)

1989	PE International's GaBi software released
1990	International forum by The Conservation Foundation debated role of REPA
1990	Society of Environmental Toxicology and Chemistry (SETAC) first workshop on REPA & the adoption of the term "life cycle analysis"
1990	Pre was established, development of SimaPro
1992	Franklin Associates published first methodology of LCA article
1992	EPA developed guidance manual for conducting and evaluating life cycle inventory
1996	*International Journal of Life Cycle Assessment* launched
1997	ISO developed 14000 Series (environmental management) 14040: life cycle assessment – principles and framework
2006	ISO 14044: life cycle assessment – requirements and guidelines established
2011	World Resource Institute and World Business Council for Sustainable Development's PAS 2050:2011 Specification for the assessment of life cycle greenhouse gas emissions of goods and services
2012	International Reference Life Cycle Data System Handbook released (European Commission Joint Research Centre's Institute for Environment and Sustainability)
2014	ISO 14071 & 14072: Technical Specification – LCA requirements and guidelines for critical review processes and review competencies

Life Cycle Assessment (LCA) analyzes the environmental impacts of a product or process throughout its life cycle, including the production of raw materials, manufacturing, use, disposal, and any transportation between these steps. The Coca-Cola Company first used LCA in 1969 to analyze the environmental impacts of their product packaging. Coca-Cola's life cycle thinking enabled the production of highly recyclable, lightweight, durable, and cheaper packaging material (2011). LCA is used in disparate industries beyond manufacturing from building construction to biofuel production to healthcare to waste management.

Process LCA follows guidelines set forth by the International Organization for Standardization (ISO 14040 and 14044) and is conducted in four stages, Table 3 (ISO 1997b, ISO 2006c). Stage one establishes the boundary conditions of the system and defines a functional unit for the system. This stage standardizes the results and enables equivalent comparison with other products or processes. During stage two, Life Cycle Inventory (LCI), all raw data are compiled with respect to system inputs and outputs. The LCI quantifies the materials and energy used as well as the emissions associated with each input and output. Stage three, Life Cycle

Impact Assessment (LCIA), is the stage where the inventory data are translated into impact categories (e.g. ecotoxicity and global warming potential). The fourth and final stage is interpretation, where the inventory and impact assessment results are analyzed for areas within the system that have moderate to high environmental impacts.

Table 3: Summary of Life Cycle Assessment Steps (Baumann and Tillman 2004)

Stage	Description	Major Steps
Goal and Scope Definition	Define the system and its boundaries	1.What processes to be included 2.What environmental impacts to be considered 3.Level of detail and necessary data requirements 4.Define functional unit
Inventory Analysis (LCI)	Build a model according to the goal and scope, including products and processes involved	1.Design a process-flow diagram 2.Collect data on all inputs and outputs involved (raw materials, products, waste) 3.Calculate amount of resources used and pollution associated with regard to the functional unit
Impact Assessment (LCIA)	Describes the environmental impacts calculated from the inventory analysis	Classify the inventory analysis by contribution to environmental impact
Improvement Analysis	Identify the areas in the system that have the highest environmental impact according to the LCIA	Use the system to improve areas

There are several approaches for conducting an LCA. Economic Input-Output LCA (EIO-LCA) uses aggregated data from economic sectors and attributes an environmental loading based on how much each sector purchases from other sectors (Hendrickson, Lave et al. 2006, CMU and Institute 2008). Hybrid LCA combines process-based LCA, as described above, and EIO-LCA and is suitable for use in large systems where production is known for some items but where only financial purchasing is known for others (Suh, Lenzen et al. 2004, Bilec 2007).

1.6 DISSERTATION ORGANIZATION

For this dissertation, there are five chapters. Chapter 1.0 introduces and presents the general background. Chapter 2.0 presents building LCA applications via three building studies. Chapter 3.0 presents healthcare LCA applications via three healthcare studies. Chapter 4.0 presents an evidence-based design healthcare building case study. Chapter 5.0 synthesizes the significant findings in Chapter 2.0 and Chapter 3.0 and concludes with recommendations for future building and healthcare LCA applications.

2.0 BUILDING LCA APPLICATIONS

2.1 INTRODUCTION & BACKGROUND

2.1.1 Chapter 2 Organization

In Chapter 2.0 a building LCA literature review is presented, followed by a building LCA case study that focused on the building materials used to construct a LEED Platinum, net-zero energy building. Second, a retrofit case study is presented that used LCA, energy modeling, and life cycle cost assessment to make an informed decision on product selection. Lastly, a pathway to increase the use of LCA in the building industry through integrated project delivery is explored. The evolution of Chapter 2.0 addresses the first research question "what tools and strategies are needed to advance LCA in the building industry?"

2.1.2 Building LCA Literature Review

Building LCAs emerged into the market around the mid-1990s to understand the impacts of building materials (Hunt, Franklin et al. 1996). Since then, a host of building LCA topics has been published. For example, Haapio et al. analyzed and categorized existing environmental assessment tools for buildings, from LCA to green building rating systems (GBRS), and how each tool fit into the building life cycle from design, material selection, energy, or end-of-life (EOL) (Haapio and Viitaniemi 2008). Finnveden et al. discussed issues with LCA as applied to any industry, specifically scope and definition, data collection, allocation, study boundaries, and impact categories and weightings (Finnveden, Hauschild et al. 2009). To overcome the shortcoming of LCA complexity, Zabalza Bribian et al. and Malmqvist et al. proposed simplification methodologies, highlighting the importance of LCA tool selection and system boundaries (Zabalza Bribián, Aranda Usón et al. 2009, Malmqvist, Glaumann et al. 2011). Khasreen et al. reviewed various LCA tools and the differences in data quality, system boundaries, inventory, impact assessment, and interpretation for LCAs in general while highlighting residential and commercial building case studies (Khasreen, Banfill et al. 2009). Further, Sharma et al. completed a review article of building LCA studies by comparing which building type, life cycle phase, and building location had the highest environmental impact and/or energy consumption (Sharma, Saxena et al. 2011).

To ensure building LCA implementation, both Singh et al. and Saunders et al. discussed the level of LCA knowledge in the architectural, engineering, and construction (AEC) community, highlighting the appropriate tools, methodological applications, benefits, and barriers of building LCAs (Singh, Berghorn et al. 2010, Saunders, Landis et al. 2013). Benefits included the ability to compare products, the use of a scientific approach, and advancement of a project's triple bottom line. Barriers included costs of LCA performance, little client demand, and lack of location specific building data (Saunders, Landis et al. 2013). Although there are limitations, LCA has the potential to impact the design, construction, and operational phases of the building industry.

Because building LCAs encompass such a large system boundary, important aspects of the building may get reduced or eliminated from the analysis, when in fact they have major environmental implications. The terms 'operational energy' and 'embodied energy' are used often in the context of building LCAs, yet are disregarded in some applications. 'Operational energy' is defined by the building energy consumption during the use phase of the building while 'embodied energy' is defined as the energy required to produce and transport building materials/products to the building site (Yohanis and Norton 2002, Thiel, Campion et al. 2013). As buildings move towards low- to zero-energy buildings, the impacts of product embodied energy becomes much more important to the building's life cycle, as evident by many published work (Yohanis and Norton 2002, Scheuer, Keoleian et al. 2003, Torcellini, Pless et al. 2006, Sartori and Hestnes 2007, Hernandez and Kenny 2010, Ramesh, Prakash et al. 2010, Hernandez and Kenny 2011, Passer, Kreiner et al. 2012, Thiel, Campion et al. 2013).

Although a range of findings are prevalent in the LCA and energy building literature, general consensus maintains that the use phase of a standard building represents the largest phase in terms of energy consumption. Studies assuming a 40 to 50 year life span found that the use phase, or operational energy, contributes anywhere from 52% to 82% of the total life cycle energy consumption of a building (Suzuki and Oka 1998, Junnila and Horvath 2003, Junnila, Horvath et al. 2006, Kofoworola and Gheewala 2008, Aktas and Bilec 2012). One study used a 75-year lifetime and another analyzed 73 case studies ranging from 40 to 100 years, resulting in total operational life cycle energy of 94% and 80-90% respectively, highlighting the influence of a building's life span (Scheuer, Keoleian et al. 2003, Ramesh, Prakash et al. 2010). The construction and material phases of traditional buildings account for 2% to 15% of a building's total life cycle energy, from embodied energy to operational energy to demolition energy (Suzuki and Oka 1998, Scheuer, Keoleian et al. 2003, Ramesh, Prakash et al. 2010). However, as the impacts associated with the use phase of buildings starts to decrease with more efficient technologies, it is becoming more important to look at the embodied energy (Venkatarama Reddy and Jagadish 2003).

Building LCAs target operational energy either through energy modeling schemes, extracting the energy consumption and interpreting the environmental impacts of the energy source. However, the recent development of dynamic LCAs (DLCA) has begun to reshape the static response to building assessments. DLCAs track the environmental impacts of the building throughout its use phase, such as energy consumption and indoor environmental quality (IEQ) (Levasseur, Lesage et al. 2010, Collinge, Landis et al. 2013). Incorporating temporal data, either on the minute, hour, day, or month scale, allows building owners and operators to track the building's environmental impact, identifying seasonal and behavioral trends or complications in the system that require immediate attention. Collinge et al. conclude that changes made throughout the building's use phase can influence LCA results to a greater degree than the construction, material, and estimated use phases (Collinge, Landis et al. 2013).

The environmental impacts of building products play a large role in the building LCA, reiterating the need for embodied energy inclusion in analyses. Some studies have concluded that embodied energy for conventional buildings accounts for 10-38% of the total energy in a building's life cycle (Yohanis and Norton 2002, Sartori and Hestnes 2007, Ramesh, Prakash et al. 2010, Aktas and Bilec 2012). Embodied energy has a higher relative percentage in low-energy buildings, one study finding 9-46% of a buildings total life cycle energy, than in conventional buildings, an important realization for moving forward with green building analyses (Sartori and Hestnes 2007, Aktas and Bilec 2012). This is especially important when considering the environmental impacts and embodied energy of renewable energy systems, which is much higher than its energy grid counterpart (Thiel, Campion et al. 2013). Rajagopalan et al. discusses another issue with building products, the potential of greenwashing with building product labels (Rajagopalan, Bilec et al. 2012). Without a universal methodology for labeling, it is easy to be confounded by which product is environmentally preferred (Zabalza Bribián, Valero Capilla et al. 2011). Applying LCA to building products could eliminate greenwashing and estimate product embodied energy.

2.1.3 US Green Building History

A historical review of the LCA and US green building program was conducted. The goal of the historical review was to identify and display how LCA and US green building practices have evolved over the last 25 years. Specifically, the review is attempting to answer the question of when LCA became a key component of the US green building industry.

The United States has had significant growth in the green building industry since the early 1990's, and life cycle assessment has followed a similar growth pattern. Figure 2 identifies milestones in both green building and life cycle assessment advancements. Each milestone is color coded to represent a policy (orange), a green building program (green), or an environmental guide or program (blue).

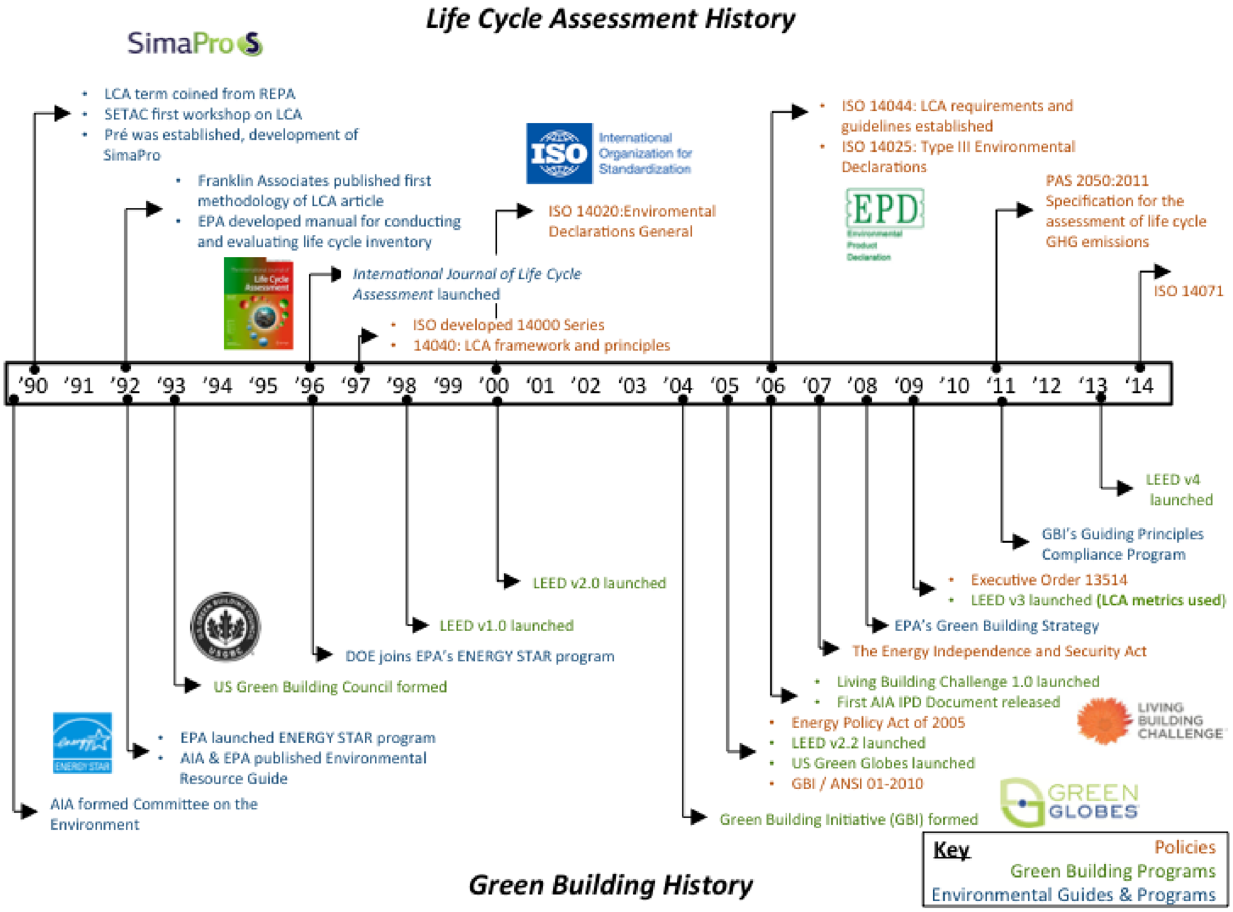


Figure 2: History in LCA and US green buildings (blue = environmental guides and programs, green = green building programs, orange = policies); LCA= life cycle assessment, REPA = resource and environmental profile analysis, EPA = environmental protection agency, ISO = international standards organization, PAS = publically available specification, GHG= greenhouse gases, AIA = American institute of architects, DOE = department of energy, LEED = leadership in energy and environmental design, IPD = integrated project delivery; SETAC – society of environmental toxicology and chemistry (EPA 2014b)

LCA can be dated back to the 1960s when it was termed REPA – resource and environmental profile analysis with – with market emergence in 1990. That same year, the

Society of Toxicology and Chemistry (SETAC) had its first workshop on LCA and Pré was established, the developers of the umbrella LCA program SimaPro (Goedkoop and Oele 2004). Franklin Associates, another LCA company, published the first universal LCA methodology article in 1992, which complimented the EPA's manual for conducting and evaluating life cycle inventory. In 1996, the *International Journal of Life Cycle Assessment* launched, which is the first journal dedicated to LCA practices (Hunt, Franklin et al. 1996). After the initial development of LCA, standards began to emerge, most notably the International Organization of Standardization (ISO) 14000 Series. ISO 14040: LCA framework and principles launched in 1997 and ISO 14044: LCA requirements and guidelines launched in 2006 (ISO 1997a, ISO 2006b). There has been recent development in the ISO 14070 series, including the launch of ISO 14071 in 2014 which standardizes critical reviews of LCAs (Finkbeiner 2013). Beyond ISO, another LCA centric policy was the Publically Available Specification (PAS) 2050:2011 that provides a method for assessing the greenhouse gas emissions of goods and services.

In 1989, the AIA formed the Committee on the Environment, one of the first US building organizations to recognize buildings and the environment. Shortly thereafter in 1992, the AIA and EPA jointly published an Environmental Resource Guide and the EPA launched the ENERGY STAR program under the Clean Air Act, Section 103(g) (EPA 2014b). The ENERGY STAR program, also supported by the US Department of Energy (DOE) since 1996, is an energy efficiency program (EPA 2014a). The ENERGY STAR program encourages energy efficient products, practices, and services through valuable partnerships, measurement tools, and market education. Other environmental programs established include the EPA's Green Building Strategy published in 2008, which facilitates the adoption of effective green practices, and the Green Building Initiative's (GBI) 2011 Guiding Principles Compliance Program (EPA 2008a). The

GBI, modeled after Canada's counterpart, formed in 2004 to promote green building programs within the National Association of Home Builders' (GBI 2014).

There have been four significant policies released that impact the US green building history since 1990. The Energy Policy Act of 2005 attempts to decrease energy problems through programs such as renewable energy sources tax incentives (2009). In 2007, the Energy Independence and Security Act was established to move the US towards energy independence (2007). The Executive Order 13514 was released in 2009, which required each federal agency to submit a 2020 greenhouse gas pollution reduction target (2009). Last, the GBI /ANSI (American National Standard Institute) 01-2010: green building assessment protocol for commercial buildings standard was approved in 2010 (ANSI 2010b). As energy policies continue to advance the minimum standards of efficiency, green building programs and life cycle integration will continue.

The US Green Building Council (USGBC) formed in 1993 as the first non-profit organization dedicated to green building design in the US. The USGBC launched the Leadership in Energy and Environmental Design (LEED) green building rating system pilot version 1.0 in 1998, with an original 45 credits and prerequisites. In 2000, LEED v2.0 was launched and later in 2005, both LEED v2.2 and the US Green Globes launched. Green Globes is a green building rating system that originated in Canada and is modeled after the UK's system BREEAM, Building Research Establishment Environmental Assessment Methodology (GBI 2014). Shortly after, the Living Building Challenge 1.0 launched and the first AIA document on integrated project delivery (IPD), a collaborative building process, was released (Castellanos 2010). The difference between Green Globes, LEED, and LBC can be shown in Table 1. LEED v3, 2009, was the first LEED version to successfully integrate LCA via credit weightings. The latest version of LEED – v4 – has the highest level of LCA integration.

Table 4: LEED, Green Globes, Living Building Challenge (LBC) Comparison (GreenGlobes 2004, USGBC 2011, ILBI 2012b)

	LEED	**Green Globes**	**LBC**
Program Administrators	US Green Building Council	The Green Building Initiative	International Living Building Institute
Year Founded	1998	2005	2006
Point System	LEED Certification, Silver, Gold, or Platinum	1 to 4 "globes" based on points	Only one certification: Living Building Challenge
Application & Documentation	Building project design team is in charge of documentation	A certified Green Globes assessor (3rd party), verifies project against Green Globes questionnaire	Requires one year of building monitoring prior to certification
Number of Certified Buildings	> 45,000	~ 10,000	5 with 160 pending

Cascadia Green Building Council launched the Living Building Challenge (LBC) in 2006 (Cascadia Region Green Building Council 2007). In 2009, Cascadia formed the International Living Building Institute to oversee LBC and in 2011 the Institute was renamed the International Living Future Institute. LBC Version 1.3 is divided into 6 prerequisites or "petals," all must be met to achieve certification. The petals are: beauty and inspiration, site, materials, energy, indoor quality, and water. The materials petal contains 5 of the 16 prerequisites for Living Building certification and includes restrictions in the types of materials that can be used, distance radius from manufacturer to building site for materials and services, carbon footprinting, and construction wastes (Cascadia Region Green Building Council 2007). In order to achieve LBC certification, the building must be in full operation for one year and monitored during this time to ensure it meets operational criteria, including net-zero energy and water consumption.

As of 2014, the International Living Future Institute has 6 buildings with certification: 3 educational buildings have achieved full Living certification, 2 mixed office spaces that have achieved Net-Zero Energy certification, and 1 residential building that has achieved Petal Recognition. Twelve projects are reaching the end of their one-year operational phase and will be submitting for certification in the next 6 months (ILBI 2012a). Net-Zero Energy certification is a partial certification program that focuses on the buildings ability to fulfill net-zero requirements, likewise, petal recognition is a partial certification program that is awarded to projects that satisfy 3 out of the 6 petal categories for the LBC (ILBI 2012b). There are very few life cycle based studies on the environmental effects of net-zero energy buildings or Living Buildings (Fay, Treloar et al. 2000, Blengini and Di Carlo 2010a, Hernandez and Kenny 2010, Aktas and Bilec 2012).

2.2 INITIAL BUILDING LCAS

The work presented in Section 2.2 addresses a building LCA in the context of traditional life cycle assessment study. Understanding the outcomes of a traditional building LCA was fundamental to answering the first research question "what tools and strategies are needed to advance LCA in the building industry?" This work was published in *energies* as "A Materials Life Cycle Assessment of a Net-Zero Energy Building" (Thiel, Campion et al. 2013).

2.2.1 LCA and Building Energy Use

As the number of low-energy buildings increases, the need to consider embodied energy from building materials increases, especially if an overall goal is to reduce the building's life cycle energy use. The life cycle assessment of advanced building materials and systems is paramount to significantly improving overall environmental building performance. Chapter 2.2 focuses on an illustrative case study, a net-zero energy/water building, which aims to achieve significant benchmarks in the United States – the Living Building Challenge (LBC) and Leadership in Energy and Environmental Design (LEED) Platinum. A *materials phase* life cycle assessment was completed on the Center for Sustainable Landscapes (CSL). Focus was on materials not only due to current construction and operation schedules, but also because previous studies have suggested that the materials used to construct green buildings have higher environmental impacts than those of traditional buildings (Venkatarama Reddy and Jagadish 2003, Sartori and Hestnes 2007, Blengini and Di Carlo 2010b).

The following definitions are posed to ensure understanding of the concepts presented: *Embodied Energy:* the energy required to extract, process, manufacture and transport building materials (within the manufacturing stage), associated with the building (Venkatarama Reddy and Jagadish 2003); *Cumulative Energy Demand:* the impact assessment method used to calculate embodied energy and primary energy, developed by ecoinvent (Frischknecht 1996, Frischknecht and Rebitzer 2005); *Carbon Footprint:* a measure of the total amount of greenhouse gas emissions directly and indirectly caused by an activity or is accumulated over the life stages of a product (Wiedmann and Minx 2008); *Embodied Carbon Footprint:* a term used by the International Living Future Institute to describe the carbon footprint associated with the structural materials of a building and used to measure the quantity of carbon offsets needed to be purchased for Living Building Challenge certification (Davies 2010, ILBI 2012b). *Net-Zero Energy:* often defined as the balance between the energy consumed by the use of the building and the energy produced by the building's renewable systems on an annual basis (Hernandez and Kenny 2010). *Material Phase:* the phase related to material extraction and product processing and manufacturing. *Use Phase:* the phase related to a building's operational lifetime, including energy consumption, maintenance, and replacement materials.

Although a range of findings are prevalent in the LCA and energy building literature, general consensus maintains that the use phase of a standard building represents the largest phase in terms of energy consumption. Studies assuming a 40 to 50 year life span found that the use phase, or operational energy, contributes anywhere from 52% to 82% of the total life cycle energy consumption of a building (Suzuki and Oka 1998, Junnila and Horvath 2003, Junnila, Horvath et al. 2006, Kofoworola and Gheewala 2008, Aktas and Bilec 2012). One study used a 75-year lifetime and another analyzed 73 case studies ranging from 40 to 100 years, resulting in total operational life cycle energy of 94% and 80-90% respectively, highlighting the influence of a building's life span (Scheuer, Keoleian et al. 2003, Ramesh, Prakash et al. 2010). The construction and material phases of traditional buildings account for 2% to 15% of a building's total life cycle energy, from embodied energy to operational energy to demolition energy (Suzuki and Oka 1998, Scheuer, Keoleian et al. 2003, Ramesh, Prakash et al. 2010). However, as the impacts associated with the use phase of buildings starts to decrease with more efficient technologies, it is becoming more important to look at the embodied energy (Venkatarama Reddy and Jagadish 2003).

Recent research has found that lower energy houses typically have higher embodied energy compared to traditional houses, and that while environmental sustainability was improved through reduction in energy use, the embodied energy of the materials, particularly those materials comprising the shell of the structure, increases slightly in low-energy buildings (Suzuki and Oka 1998, Junnila and Horvath 2003, Junnila, Horvath et al. 2006, Kofoworola and Gheewala 2008, Blengini and Di Carlo 2010c, Blengini and Di Carlo 2010b). Some studies have concluded that embodied energy for conventional buildings accounts for 10-38% of the total energy in a building's life cycle (Yohanis and Norton 2002, Sartori and Hestnes 2007, Ramesh, Prakash et al. 2010, Aktas and Bilec 2012). Embodied energy has a higher relative percentage in low-energy buildings, one study finding 9-46% of a buildings total life cycle energy, than in conventional buildings, an important realization for moving forward with green building analyses (Sartori and Hestnes 2007, Aktas and Bilec 2012).

2.2.2 Phipps Case Study

Phipps Conservatory and Botanical Gardens was built in 1893 as a gift to the city of Pittsburgh, Pennsylvania (Phipps 2012a). The mission of Phipps, "to inspire and educate visitors with the beauty and importance of plants; to advance sustainability and worldwide biodiversity through action and research; and to celebrate its historic glass house" is complemented by a three-part green capital plan (Phipps 2012a). The green capital plan, which started at the beginning of the new millennium, includes a LEED Silver Welcome Center integrated into a historical landmark, production greenhouses with state-of-the-art energy and water efficiency, and the new Center for Sustainable Landscapes (CSL) building. The CSL is a 24,350 square foot educational, research, and administrative office attempting to meet the high green standards of the Living Building Challenge v1.3, LEED Platinum, and SITES certification for landscapes

(Phipps 2012b). The CSL is an integral part of the existing Phipps Conservatory and Botanical overall plan.

Using an integrated project delivery (IPD) system, the owner, architects, engineers, and contractors designed the CSL to be a facility that combines passive solar design, geothermal wells, photovoltaics, solar hot water collectors, a constructed lagoon and wetland system, permeable paving, and a green roof. The CSL is 3 stories with cast-in-place concrete and steel framing for the structure and aluminum/glass curtain wall and wood cladding for the envelope while the roof is a combination of a green roof, paver patio, and thermoplastic polyolefin white roof. Construction on the facility began in winter 2010 with completion in 2012.

2.2.2.1 Phipps Case Study Methodology

This LCA focuses on the environmental impacts of CSL's building materials. The boundaries for this study include material extraction and product processing and manufacturing (defined herein as "materials phase") of the CSL. Transportation of the building materials to the construction site, construction wastage, and materials used for construction itself are not included. The building material phase is becoming increasingly important as the impacts associated with the use phase of low-energy buildings decreases. The functional unit of this study is defined as the entire CSL building.

Figure 3 details the major components of the analysis, ranging from structural elements to interior flooring as well as ductwork for the Heating, Ventilation and Air Conditioning (HVAC) system and piping for plumbing. This LCA also includes the production phase of the photovoltaic (PV) panels as well as the geothermal heat wells. It is important to note that the PV panels do not include the mounting system or the monitoring system and the associated materials with those PV system parts, as they account for approximately 18% of the total primary energy for the PV system (Kannan, Leong et al. 2006). Not included in the study were landscaping elements; interior finishes such as carpet tiling and paints were also not included in this study as they represent a small quantity of the building's total mass. Paint and interior finished represented only 2-4% of energy and global warming impacts in previous building LCA studies (Junnila, Horvath et al. 2006). The analysis takes a closer look at the initial materials involved with the CSL and does not account for replacement materials, which would be deemed in the "use phase" and therefore, out of the boundary definition.

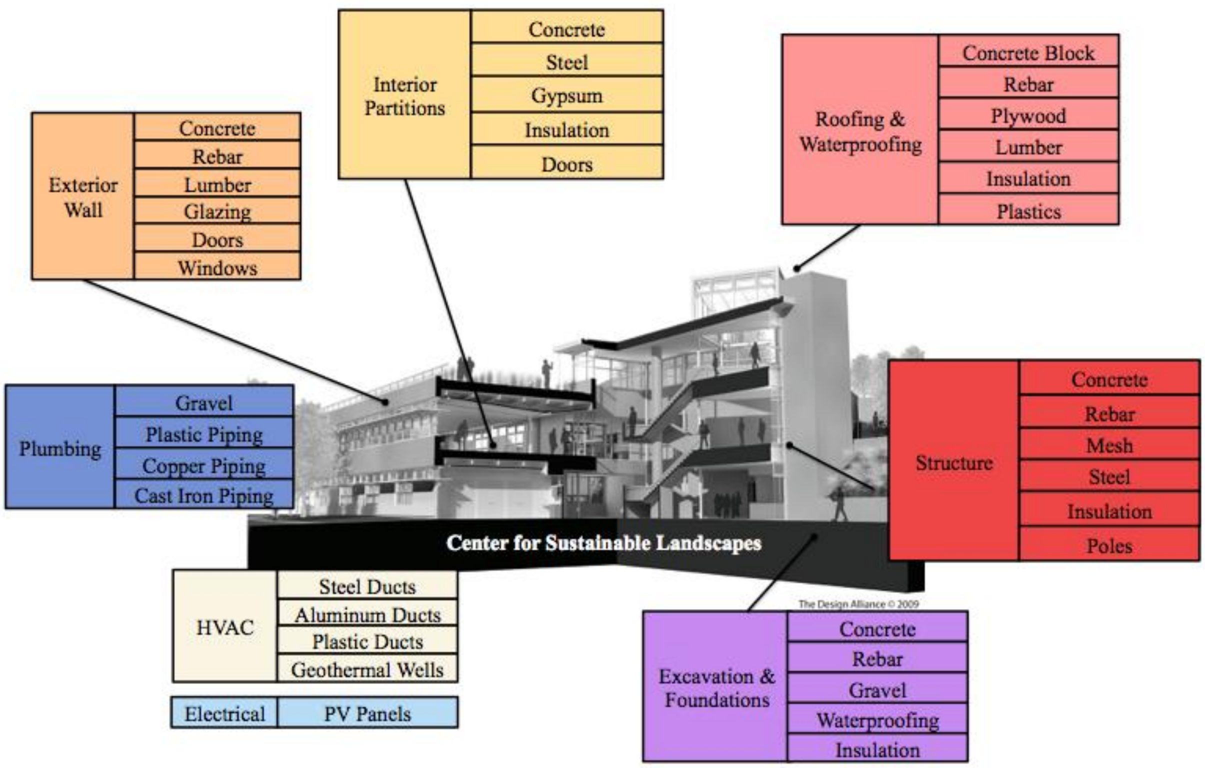


Figure 3: System boundary: Material phase for Phipps Case Study (Phipps 2014)

Material inventory data was obtained through CSL's project documents, including estimates, plans, and specifications provided by the architects and the pre-construction management company. Materials were allocated to a representative LCI unit processes within an environmental impacts database, with preference first given to the US based material process database Franklin USA 98 (Franklin Associates 1998). When Franklin USA 98 was insufficient to represent the material, ecoinvent was used (Frischknecht, Jungbluth et al. 2005). If a unit process was not available in either Franklin USA 98 or ecoinvent, another database was selected based on the best possible information of the unit process description, boundary considerations, and installed product use. Table 5 provides a description of building material and associated LCA unit process.

Table 5: LCI Databases for Building Materials. CH = Switzerland geographical code; RER = Europe geographical code; U = unit process; FAL = Franklin Associates code; ecoinvent Unit Process (Frischknecht and Rebitzer 2005); ETH-ESU 96 U (Frischknecht 1996); Franklin USA 98 (FranklinAssociates 1998); Industry Data 2.0 (PlasticsEurope 2003); IDEMAT 2001 (IDEMAT); * Concrete and concrete block unit processes were modified to adjust for fly ash incorporation based on published results (Flower and Sanjayan 2007b)

Building Category	Building Material	Database	Unit Process Name
Exterior Walls	Glazing	ecoinvent Unit Process	Glazing / ecoinvent Unit Process
	Concrete*	ETH-ESU 96 U	Concrete not reinforced ETH U
	Rebar	Franklin USA 98	Steel cold rolled, EAF FAL / Franklin USA 98
	Lumber	ecoinvent Unit Process	Reclaimed lumber / ecoinvent UP used
	Door	ecoinvent Unit Process	Door, outer, wood-aluminum, at plant/RER U / ecoinvent Unit Process
	Windows	ecoinvent Unit Process	Window frame, aluminum, U=1.6 W/m2K, at plant/RER U / ecoinvent Unit Process
Interior Partitions	Concrete*	ETH-ESU 96 U	Concrete not reinforced ETH U
	Steel	Franklin USA 98	Steel cold rolled, EAF FAL / Franklin USA 98
	Insulation	ecoinvent Unit Process	Rock wool, at plant/CH U
	Doors	ecoinvent Unit Process	Door, inner, wood, at plant/RER U / ecoinvent Unit Process
	Gypsum	ecoinvent Unit Process	Gypsum plaster board, at plant/CH U / ecoinvent Unit Process

Table 5 (continued)

Roofing and Water-proofing	Concrete Block*	ecoinvent Unit Process	Concrete block, at plant/DE U / ecoinvent Unit Process
	Rebar	Franklin USA 98	Steel cold rolled, EAF FAL / Franklin USA 98
	Plywood	ecoinvent Unit Process	Plywood, outdoor use, at plant/RER U / ecoinvent Unit Process
	Lumber	ecoinvent Unit Process	Reclaimed lumber / ecoinvent UP used
	Insulation	ecoinvent Unit Process	Polystyrene, extruded (XPS), at plant/RER U / ecoinvent Unit Process
	HDPE	Franklin USA 98	HDPE bottles FAL / Franklin USA 98
	Recycled Polymer	IDEMAT 2001	Recycling mixed polymer I' / IDEMAT 2001
	LDPE	Franklin USA 98	LDPE film FAL / Franklin USA 98
	Recycled LDPE	Franklin USA 98	LDPE film recycled FAL / Franklin USA 98
Structure	Concrete*	ETH-ESU 96 U	Concrete not reinforced ETH U
	Rebar/Steel/ Mesh	Franklin USA 98	Steel cold rolled, EAF FAL / Franklin USA 98
	Insulation	ecoinvent Unit Process	Rock wool, at plant/CH U
	Poles	ecoinvent Unit Process	Cladding, crossbar-pole, aluminum, at plant/RER U / ecoinvent Unit P
Excavation and Found-ations	Concrete*	ETH-ESU 96 U	Concrete not reinforced ETH U
	Rebar	Franklin USA 98	Steel cold rolled, EAF FAL / Franklin USA 98
	Gravel	ecoinvent Unit Process	Gravel, crushed, at mine/CH U / ecoinvent Unit Process
	Waterproofing	ecoinvent Unit Process	Bitumen sealing Alu80, at plant/RER U / ecoinvent Unit Process
	Insulation	ecoinvent Unit Process	Polystyrene, extruded (XPS), at plant/RER U / ecoinvent Unit Process
Electrical	PV Panels	ecoinvent Unit Process	Photovoltaic panel, single-Si, at plant/RER/I U
	Inverter	ecoinvent Unit Process	Inverter, 2500W, at plant/RER/I U
HVAC	Steel Ducts	ecoinvent Unit Process	Ventilation duct, steel, 100x50 mm, at plant/RER U / ecoinvent Unit Process
	Aluminum Ducts	ecoinvent Unit Process	Flexible duct, aluminum/PET, DN of 125, at plant/RER U / ecoinvent Unit Process
	Plastic Ducts	ecoinvent Unit Process	Ventilation duct, PE corrugated tube, DN 75, at plant/RER U / ecoinvent Unit Process
	Geothermal Wells	ecoinvent Unit Process	Heat geothermal probe 10kW U - edited (no HCFC-22)
Plumbing	Gravel	ecoinvent Unit Process	Gravel, crushed, at mine/CH U / ecoinvent Unit Process
	Plastic Piping	Industry Data	HDPE pipes E / industry data 2.0
	Copper Piping	ecoinvent Unit Process	Copper, primary, at refinery/RER U / ecoinvent Unit Process
	Cast Iron Piping	ecoinvent Unit Process	Cast iron, at plant/RER U / ecoinvent Unit Process

The LCIA phase was conducted using two impact assessment methods. First, embodied energy of the materials was calculated using a Cumulative Energy Demand (CED) method developed by ecoinvent (Frischknecht R. 2003, Frischknecht, Jungbluth et al. 2007a). The remaining environmental impacts were calculated using TRACI 2 v3.01. TRACI, or Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts, was developed by the Environmental Protection Agency (EPA) as a US-based impact assessment method (Bare 2002).

The impact assessment categories reported from TRACI include global warming, acidification, human health cancer, human health noncancer, human health criteria air pollutants, eutrophication, ecotoxicity, smog, natural resource depletion, water intake, and ozone depletion.

2.2.2.2 Phipps Case Study Results and Discussion

Two sets of results were considered with the goal of providing information related to building systems/components (e.g., electrical, plumbing, etc. in Figure 4) and materials (e.g., gravel, steel, etc. in Figure 5). In general, either the *foundations and excavation* or *structure* categories of the CSL represented the highest environmental impact in nearly every impact category analyzed shown in Figure 4. Concrete contributes an average of 73% of the environmental impacts for the excavation and foundation of the building, and steel contributes an average of 59% of the environmental impacts for the structural system of the CSL. The electrical system (PV panels and inverters), along with the plumbing system, also represents high environmental impacts, specifically in the human health cancer, human health non-cancer, eutrophication, and water intake categories. To further understand the source of the environmental impacts, the building materials were analyzed separate from their building system, shown in Figure 3. As concrete and steel represent a large portion of the CSL materials by weight, reducing the impacts associated with concrete and steel would have high-yield results for the building's overall LCA.

Although researchers have identified concrete and steel as significant sources of global warming potential and embodied energy, alternative materials are often not used. Long-term solutions and material replacements may need to be considered (Jonsson, Bjorklund et al. 1998, Guggemos and Horvath 2005, Flower and Sanjayan 2007a). Short-term solutions include continued improvements to the manufacturing process of steel or continued research on additives to concrete to reduce the environmental impacts (Venkatarama Reddy and Jagadish 2003). Instead of using 100% Portland cement for concrete, incorporating 25% fly ash or 40% ground granulated blast furnace slag into the concrete mixture has the potential to reduce greenhouse gas emissions up to 14% and 22% respectively (Flower and Sanjayan 2007a).

To meet the standards set forth by the LBC, the CSL did use a minimum of 40% fly ash for cement replacement, one report found that 12% of cement replacement by mass, attributed to 92% of the embodied energy of the concrete (Zapata and Gambatese 2005). Extrapolating this data in relation to the 40% fly ash incorporation results in a 37% reduction in embodied energy contribution, within an overall 25% reduction in energy consumption for the production of the concrete. According to published reports, embodied and consumption energies associated with the increase of fly ash percentage in cement does not need to not account for the production of fly ash because it is considered a waste by-product (Zapata and Gambatese 2005, Reiner and Rens 2006, Huntzinger and Eatmon 2009, O'Brien, Ménaché et al. 2009). Another report analyzed the GWP of fly ash replacement in cement and found emission factors for cement to be 0.82 t CO_2/ton and for fly ash to be 0.027 t CO_3/ ton (Flower and Sanjayan 2007b). Applying the emission factors to the CSL concrete data found that compared to using 100% Portland cement, the use of 40% fly ash for cement replacement reduced concrete's overall GWP contribution by 39%.

Another study concludes that the incorporation of engineered cementitious composites instead of conventional steel expansion joints can reduce life cycle energy consumption by 40%, waste generation by 50%, and raw material consumption by 38% (Keoleian, Kendall et al. 2005). Although the engineered cementitious composites can extend the life span of the structure and may require less maintenance than conventional infrastructure, the cost is approximately two to three times higher per unit volume (Keoleian, Kendall et al. 2005). Externalities such as cost and resource availability are important in terms of the future of sustainable design. Steel process recycling is also another way to address the environmental impacts associated with the product. Currently, stainless steel production incorporates the use of 33% of recycled steel, which accounts for 3.6 kg of carbon dioxide emissions per 1 kg of stainless steel produced (Johnson, Reck et al. 2008). Johnson and Reck et. al. have theorized that the use of 100% recycled content in the production of stainless steel would result in 1.6 kg of carbon dioxide released for every 1 kg produced, or a 44% overall carbon dioxide reduction (Johnson, Reck et al. 2008). Applied to the CSL, the 100% recycling process would reduce carbon dioxide by 85000 kg and the total global warming potential for the CSL building by 8%.

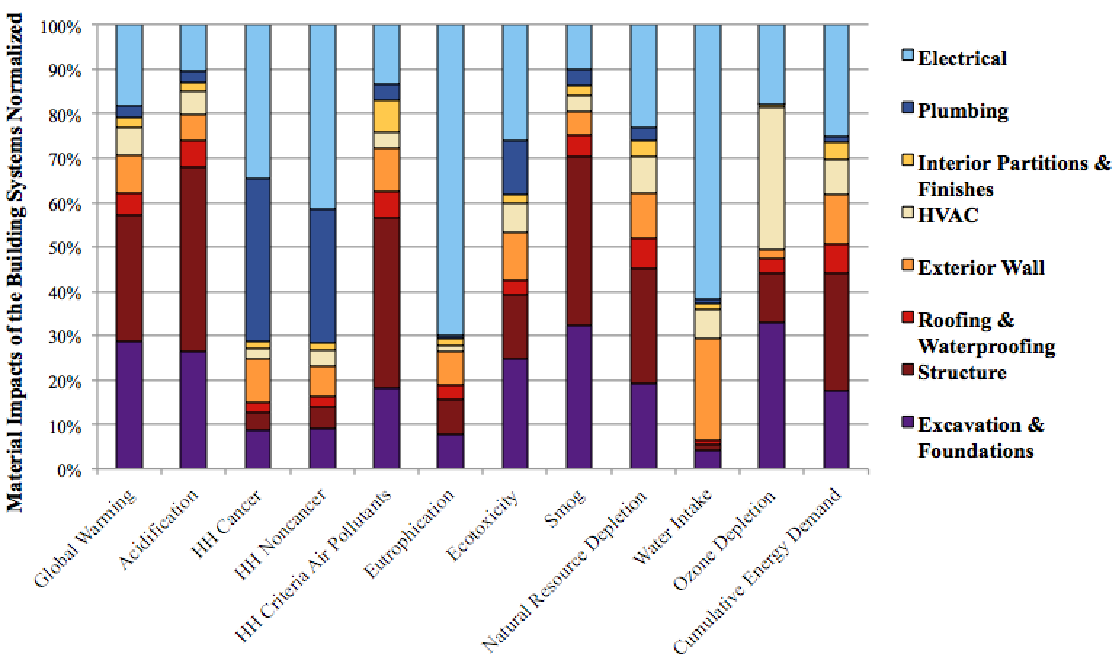


Figure 4: Life Cycle Impact of Building Materials by Building System for Net-Zero Energy Building. (HH= human health)

Other significant materials include gravel, crystalline silicone associated with the PV panels, and electronic components associated with the inverters. Due to the intense process of mining gravel, including machinery, electricity, and hazardous waste disposal, in conjunction with the release of particulate matter, gravel has high human health impacts in both cancer and non-cancer categories (Al-Awadhi 2001, Edvardsson and Magnusson 2009, Jakucionyte and Mikalajune 2011). For PV panels, the high water intake category is a result of heat recovery units within the PV system and prevention of dust accumulation, which inhibits solar efficiency (Tripanagnostopoulos, Souliotis et al. 2005, Chakravarty 2012). Inverters required to utilize the PV panels contain many electronic components, which are associated with a high level of toxicity risk (Alsema and de Wild-Scholten 2004). Components such as the integrated circuit, wiring board, and inductor contribute to global warming potential, while the copper wiring contribute to categories such as acidification, eutrophication, and human health impacts. Standard structures do not generally include PV panels in the material phase as they utilize the grid or natural gas as primary energy sources for the use phase. However, PV panels as a renewable, non-fossil based fuel source reduce the impacts during the use phase of the building's life cycle and reduce the total environmental impacts of the CSL when allocated over the building's lifespan. In other words, PV panels have high impacts in the material phase, but low impacts in the use phase, while traditional non-renewable sources have low impacts in the material phase and high impacts in the use phase.

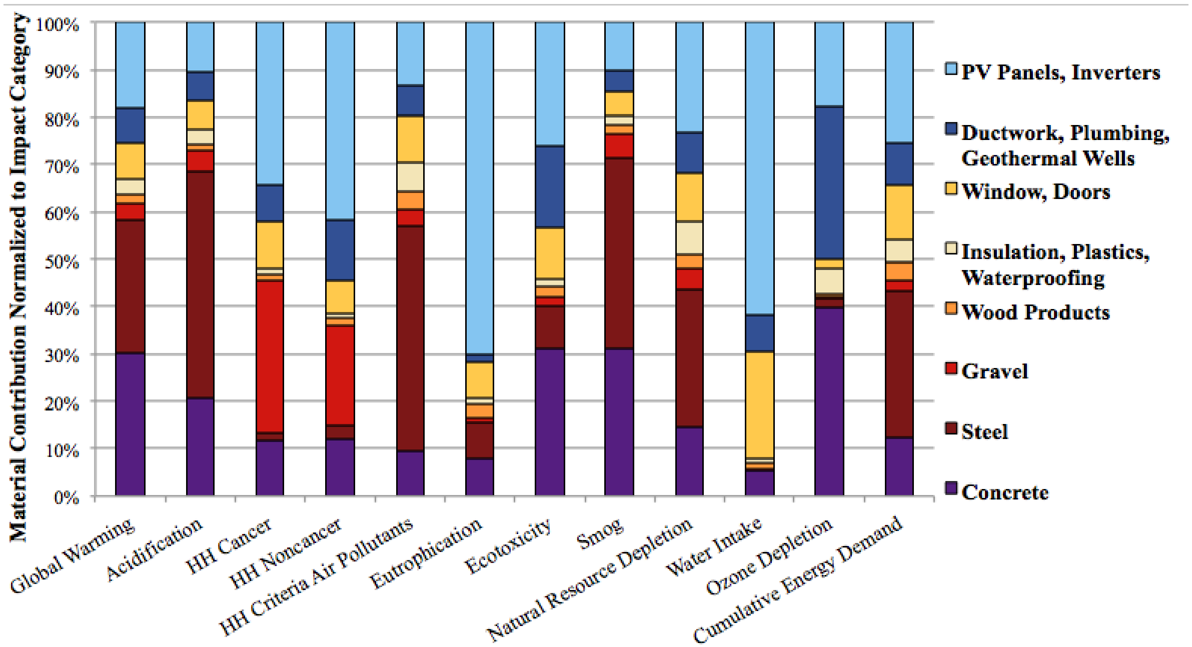


Figure 5: Life Cycle Environmental Impacts of Building Materials by Material Type for Net-Zero Energy Building. PV = Photovoltaic; HH = human health

The differences between environmental impacts of this net-zero energy building and a standard structure largely result from unique design components such as passive solar, natural ventilation, and a green roof. Previous LCA studies of five buildings show that steel, concrete, and glass have significant environmental impacts relative to other building materials. Similarly, the LCA of the CSL identified concrete and steel as materials with the largest relative impacts. This study compares the CSL to other building LCAs based only on the initial building materials and *not* materials required for maintenance nor energy required during the use phase. Material quantity and impact data from these previous studies were extrapolated to include the initial building materials *only*. The analyses of replacement materials in the compared reports were removed to have a more accurate comparison with the CSL study. The results shown are categorized by the initial material total to the m^2 area of each building, not by the lifespan of the materials.

Global warming potential (GWP) was compared between the CSL and the published results (Figure 6). The CSL was compared with and without the inclusion of the PV panels, inverters, and the geothermal wells, due to the fact that they are not a common material across all the published studies examined. The results show that PV panels and inverters account for approximately 16% of the total GWP, while the geothermal wells account for 5% of the total GWP for the CSL. For all structures, concrete and steel accounted for a large range of results, 11% to 65% and 17% to 38% of the buildings' total GWP.

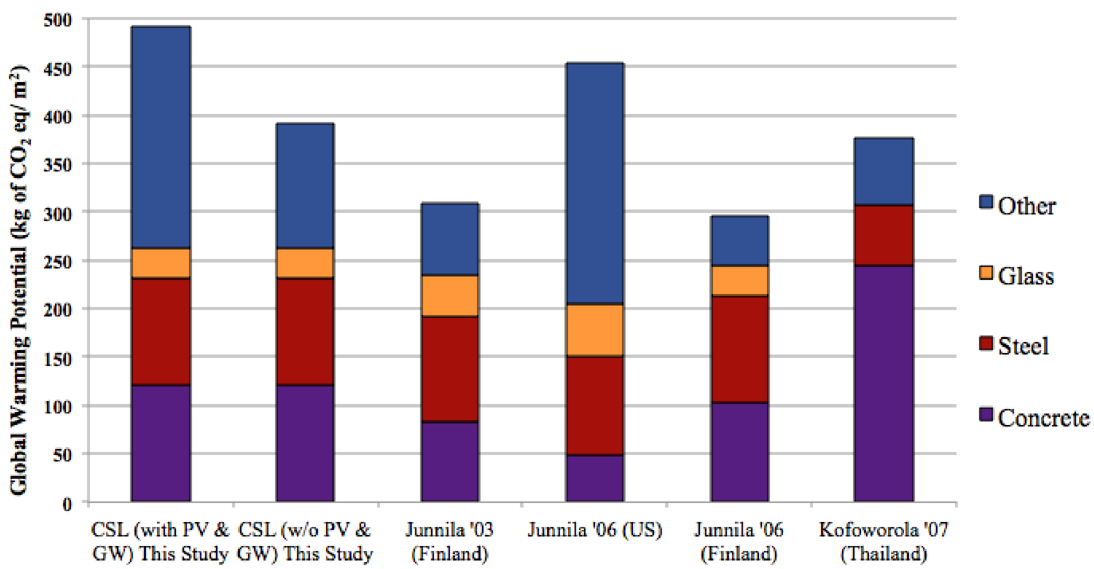


Figure 6: Global warming potential of the Center for Sustainable Landscapes compared to the published results. PV= Photovoltaic & Inverters; GW= Geothermal Wells; Note: The Kofoworola '07 study did not report glass separately from other materials; it is therefore represented in the "other" category

The second parameter compared between the CSL and the published reports was embodied energy. Embodied energy is the energy required to extract, process, manufacture and transport building materials, associated with the building (Venkatarama Reddy and Jagadish 2003). The PV panels and inverters represent 49% of the total embodied energy and the geothermal wells account for approximately 4% of the total embodied energy of the CSL. High levels of energy are required for the production of the PV panels and inverters, contributing to the high levels of embodied energy (Fthenakis 2003). For all structures, concrete and steel contributed 7% to 28% and 12% to 42% of the total embodied energy, respectively.

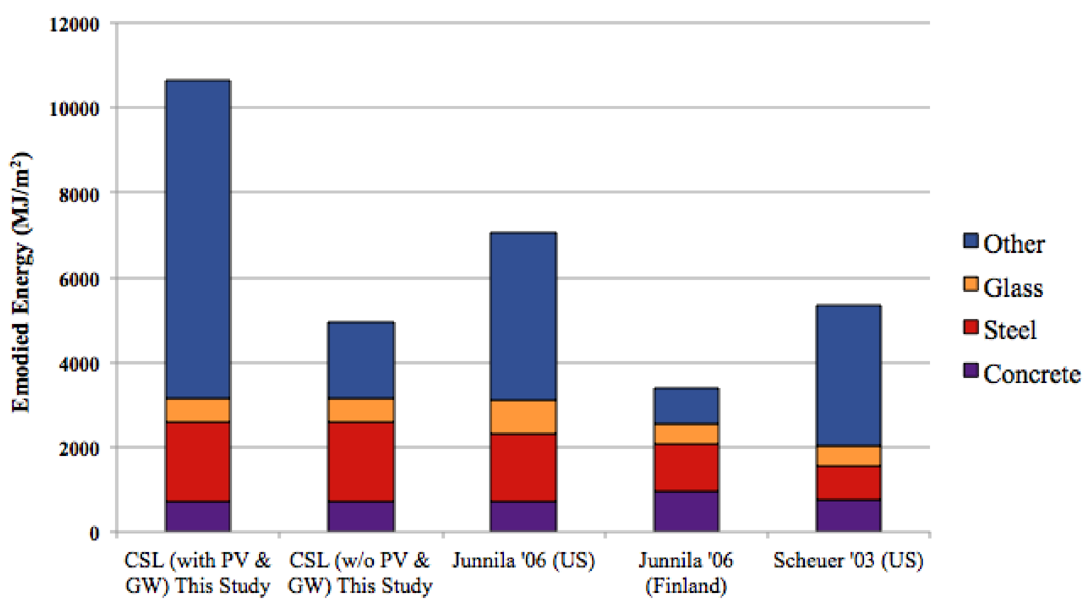


Figure 7: Embodied energy comparison between the Net-Zero Energy, Center for Sustainable Landscapes building and published LCA building studies. *PV= Photovoltaic & Inverters; *GW= Geothermal Wells; Note: Junnila ’03 and Kofoworola ’07 did not report on embodied energy

The contributions of concrete, steel, and glass to GWP and embodied energy are comparable between the CSL and standard commercial structures, as seen in Figures 4 and 5. The addition of green energy features such as the PV system and geothermal wells increases the CSL's global warming potential and embodied energy by nearly 30% and 50% respectively. Yet despite this increase, the GWP for all of the CSL's materials is only 10% higher than Junnila's US-based commercial structure, and the embodied energy remains slightly less than Junnila's US structure. Due to previous literature, it was assumed the CSL's materials would have a higher embodied energy when compared to standard buildings (Venkatarama Reddy and Jagadish 2003, Sartori and Hestnes 2007, Blengini and Di Carlo 2010a).

2.2.2.3 Phipps Case Study Conclusion

This study analyzed the environmental impacts of the materials phase of a net-zero energy building. Concrete and steel, the majority represented by the excavation and foundations and structural building systems, represent the highest environmental impacts in most categories. Gravel makes up a noticeable impact in the human health cancerous and non-cancerous categories of the CSL, while the production of PV panels and inverters makes up over 50% of water intake and eutrophication impacts. It is important to identify those materials within the building system that have the greatest effect on a building's environmental impacts in order to target specific areas for minimizing environmental impacts in future construction. Comparing LCA results of the CSL to standard commercial structures reveals that the addition of the CSL's energy reduction systems, such as PV and geothermal wells, result in a 10% higher global warming potential and nearly equal embodied energy per square foot relative to standard commercial buildings.

This study looked at the both the GWP and the embodied energy for the CSL building materials and it is important to note that for LBC certification, only the Embodied Carbon Footprint (ECF) is needed. As mentioned in the Introduction, the International Living Future Institute defines the ECF as the carbon footprint associated with the materials of a building's structure (Davies 2010, ILBI 2012b). However, this prerequisite is still a work in progress in terms of accuracy, process, and performance (Connelly 2012). The LBC certification is unique as a green building rating system due to its requirement to be net-zero energy and water during the use phase. To accommodate for the fact that energy is used during the manufacturing of the building structure materials, the ECF prerequisite uses a carbon footprint calculator to determine how many carbon-offsets need to be purchased to fulfill the prerequisite. The carbon-offsets are justification for the carbon emissions in the manufacturing process. For future versions of the LBC, more robust embodied energy calculators would be more accurate in understanding the life cycle energy of a building and truly bringing it closer to net-zero.

As more building are designed to meet net-zero energy goals, the embodied energy of the materials plays an increasingly important role. Many studies in the past have focused on use phase energy, as that building life cycle phase typically dominated analyses. One study in particular analyzed the life cycle energy versus the embodied energy of technologies between a traditional building and net-zero energy building. The results found that the traditional building consumed almost 23,000 kWh/m^2 throughout its life cycle with 2,000 kWh/m^2 of embodied energy (total 2,5000 kWh/m^2) while the net-zero energy building consumed about 8,000 kWh/m^2 of life cycle energy but 8,500 kWh/m^2 of embodied energy (total 16,500 kWh/m^2) (Ramesh, Prakash et al. 2010). Current buildings now need to reconsider the important interplay between building materials and use phase performance to truly design and operate net-zero energy buildings (Aktas and Bilec 2012, Rajagopalan, Bilec et al. 2012).

An important and necessary aspect of "net-zero energy" designation is the quantification of embodied energy, illustrated via this case study and using life cycle assessment. Life cycle assessment is a necessary aspect to net-zero energy buildings to understand how the embodied energy of materials is allocated during a building's use phase. With more quantitative data that accurately depict more sustainable processes, such as the incorporation of fly ash into the concrete production, the connection between materials, embodied energy, operational energy, and total life cycle energy will become clearer. Since the impacts of CSL's materials were comparable to standard buildings, future criteria specifically aim to reduce the material impacts below that of a standard building should be further considered.

2.3 ENHANCED BUILDING LCAS

The work presented in Section 2.3 builds off of the results found in Section 2.2. After completing the materials LCA of a net-zero energy building, the results produced were informative, yet static in the context of making any substantial changes to the net-zero energy building or influencing the design of future buildings. As such, it was important to link building LCAs to the needs of a building owner, applying environmental assessments to building decision-making. Environmental assessments are not necessarily at the forefront of building owner decision-making (yet), therefore coupling LCA with other building assessment methods, such as life cycle cost assessment, increases LCA use, encourages a holistic understanding of building decisions, and begins to shift the building industry towards a more sustainable market.

Thus, the work presented in Section 2.3 addresses the applicability of building LCAs and the influence that LCA had on the building owner. Understanding how building owners perceive and apply LCA to building projects was fundamental to answering the first research question "what tools and strategies are needed to advance LCA in the building industry?"

This section first defines different building methods or tools that could compliment LCA: life cycle cost assessment (LCCA), dynamic life cycle assessment (DLCA), environmental product declarations (EPDs), evidence-based design (EBD), and integrated project delivery (IPD). A case study of LCA and one other building tool, life cycle cost assessment, is presented next to illustrate the goals set forth by a building owner and how to integrate LCA and cost together.

2.3.1 Sustainable Building Tools

The building industry has utilized LCA in a variety of aspects from material selection to construction methods to design opportunities (Fay, Treloar et al. 2000, Scheuer, Keoleian et al. 2003, Guggemos and Horvath 2005, Cooper, Fava et al. 2008, Castells, Ortiz et al. 2009, Gustavsson, Joelsson et al. 2010, Aktas and Bilec 2012, Thiel, Campion et al. 2013). However, the incorporation of LCA into building studies has become stagnant in terms of future application – as in how do the results of LCA affect the design process, material selection, or building decisions. LCA would be better practiced in the building industry if coupled with other building tools or methods that address a broader range of building owner's goals, such as occupancy satisfaction or budget limitations.

Life cycle cost assessment (LCCA) is a tool to understand the costs incurred throughout the life of a building or a building system (Asiedu and Gu 1998, Durairaj, Ong et al. 2002b, Dunk 2004, Fuller 2010). This includes the cost to produce and transport materials, construct, maintain, and end-of-life (EOL). LCCA can assist in decision-making by identifying and breaking down the costs for initial purchase versus perceived maintenance costs versus removal costs. Because cost is a significant factor in the decision-making process for a large purchase, such as a roof, the separation of product phases allows the building owner to understand how alternative products will respond to costs over time. A review of LCCA methodologies was conducted (Norris 2001, Durairaj, Ong et al. 2002a, Gluch and Baumann 2004, Ballensky 2006, Cash 2006, Worth 2007, Coffelt and Hendrickson 2010). A simple LCCA calculates the direct costs in net-present value (NPV), represented in Equation 1 (Durairaj, Ong et al. 2002a, Dunk 2004, Russell 2009).

$$\mathbf{NPVTC}(t) = \sum_{i=1}^{t} \frac{[UC(i) + M\&R(i)]}{(1+r)^{t-1}} + \frac{\textit{Replacement Cost}}{(1+r)^{t-1}} + \sum_{i=t+1}^{t} \frac{[UC(i-t) + M\&R(i-t)]}{(1+r)^{t}}$$

Equation 1: Net Present Value of Total Cost for a Life Cycle Cost Assessment. t = replacement year, r = discount rate, i = evaluation year, UC = user cost, M&R = maintenance and repair cost, replacement cost = estimated replacement cost (Coffelt and Hendrickson 2010)

Traditionally, building LCAs have been linked to the physical structure, estimated use phase calculations, and assumed end-of-life scenarios. With the development of dynamic LCA (DLCA), defined as "an approach to LCA which explicitly incorporated dynamic process modeling in the context of temporal and spatial variations in the surrounding industrial and environmental systems", the use phase can be better understood and managed from an operations perspective (Collinge, Landis et al. 2013). Traditional LCAs estimate the energy use, and environmental impacts associated with energy production, during a building's use phase, however, real-time monitoring and analysis throughout the use phase can have varied results (Collinge, Landis et al. 2013). Adaptation of DLCA in the context of whole building LCAs will improve the validity of the results while enhancing the usefulness of building LCAs.

Environmental product declarations (EPDs) are emerging in the market place more than ever (USGBC 2012a, USGBC 2012c). An EPD is a standardized approach for explicitly stating the environmental impacts of a product, third party verified (Fet and Skaar 2006). EPDs are in accordance with ISO 14025 and entail the following information: environmental impacts of raw material extraction, production energy use, product contents (materials and chemical substances), waste and end-of-life, and emissions to air, soil, and water; Figure 8 is an EPD example (Fet and Skaar 2006). The International EPD System assists organizations in obtaining EPDs and other environmental declaration programs and supports standards ISO 14025, EN 15804 (European Standard for construction materials), and ISO 14067 (carbon footprints of products) (Marino 2015).

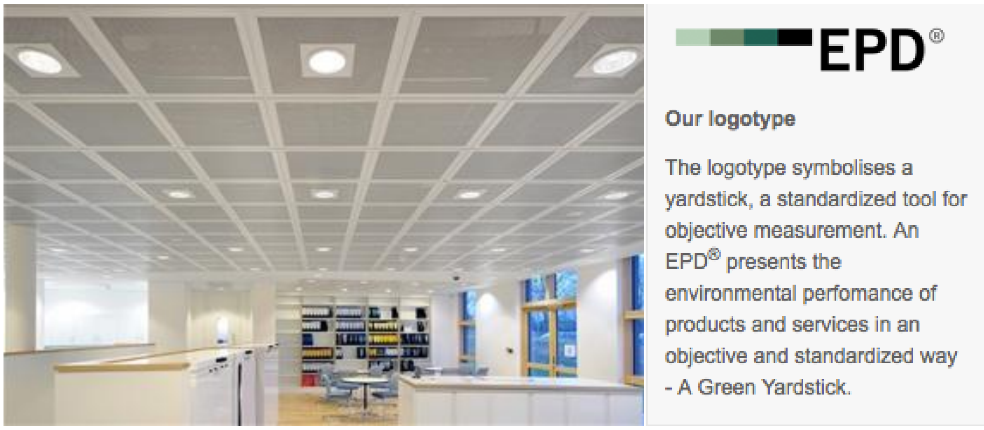


Figure 8: Environmental Product Declaration Example: A SAS System 130 Metal Ceiling (left) and the EPD label (right) (International 2014, Marino 2015)

With the increase in EPDs in the marketplace and encouraged by building certification programs, building designs will continue to incorporate these environmentally preferred products. However, the potential for greenwashing is also increasing (Dahl 2010, Marquis and Toffel 2011, Parguel, Benoît-Moreau et al. 2011). LCA can be used to quantitatively evaluate the greenness of a product and provide validity to green claims, assisting EPDs.

Evidence-based design (EBD) is a scientific approach to understand building design decisions and incorporate those effective designs into future buildings. Studies based on this method have shown green hospital design can increase personnel productivity and increase patient recovery rates (Ulrich 2001, Bilec, Geary et al. 2010). EBD studies can analyze different hospital spaces through various metrics and compare the results. The outcomes of the comparison are aimed to aid in the design process of future healthcare spaces. Although EBD is not as standardized as LCA, it can be complementary to LCA studies focusing on similar objectives.

Integrated project delivery (IPD) is defined as "a project delivery approach that integrates people, systems, business structures and practices into a process that collaboratively utilizes the talents and insights of all participants to optimize project results, increasing value to the Owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction" (AIA 2014). IPD fosters a collaborative foundation essential for achieving sustainability goals within the building industry.

2.3.2 LCA and LCCA Integration

To demonstrate that LCA could be utilized more throughout the building industry if coupled with a widely recognized assessment tool, a study on LCA and LCCA integration is presented. There were two motivating factors for this study. First, the shift towards energy-efficient buildings constructed with environmentally preferred products has increased over the last 20 years, primarily in new construction. However, existing buildings have a significant portfolio in the United States; in the Northeast region alone 85% commercial buildings, approximately 750,000, were built prior to 1990 (EIA 2003). The majority of products and materials within the building have a shorter life span than the building itself, contributing to increased retrofit and renovation applications. Second, for many building owners, initial cost remains the key factor influencing their design decisions or product selections. The goal of this study was to understand the leading factors in the building owner's decision in the context of the results from available data, including environmental impacts, life cycle costs, and retrofit design considerations.

The design of the LCA/LCCA integration study came to fruition under the Energy Efficient Building's (EEB) Hub, a DOE Innovation Hub, located in the Philadelphia Navy Yard.

DOE Innovation Hubs create a collaborative environment to advance areas of energy science and engineering throughout the technology scale, from research and development to commercialization (DOE 2010). The EEB Hub specifically focuses on energy efficient strategies that are scalable, repeatable, and cost effective for retrofit and new construction of small- to medium-sized commercial buildings (DOE 2010). During the study period, 2013 to 2014, there were ten different task groups (management, modeling and design, building energy informatics, intelligent building operations, building energy systems, markets and behavior, education and training, catalyzing the advanced energy retrofit sector, stakeholder engagement, and reporting) within the EEB Hub. The LCA/LCCA integration study nested under Task 5: Building Energy Systems, specifically Subtask 5.3: Integrated Roof Replacements, and was a derivative from the original study performed on the same demonstration site the previous year.

The demonstration site, Building 669, is also located in the Philadelphia Navy Yard and close proximity to the EEB Head Quarters, shown in Figure 9. Built in 1942, Building 669 is currently occupied by Rhoades Industries, a maritime company that has an 11-year lease on the building. Building 669 has two floors; the first floor is used as a mechanical workspace and connects to the dry dock while the second floor is used as the maritime offices for the company. The original study was a whole building analysis that occurred from 2012 to 2013 and encompassed all of Task 5 members, including HVAC, envelope, lighting, glazing, and roof retrofits. During this original building analysis, it was evident from on-site visits that the roof system needed immediate attention; examples of deterioration are found in Figure 10. After the completion of the whole-building analysis, it was decided that a detailed study on roof systems would benefit the owner of Building 669, thus establishing the LCA/LCCA integration study.

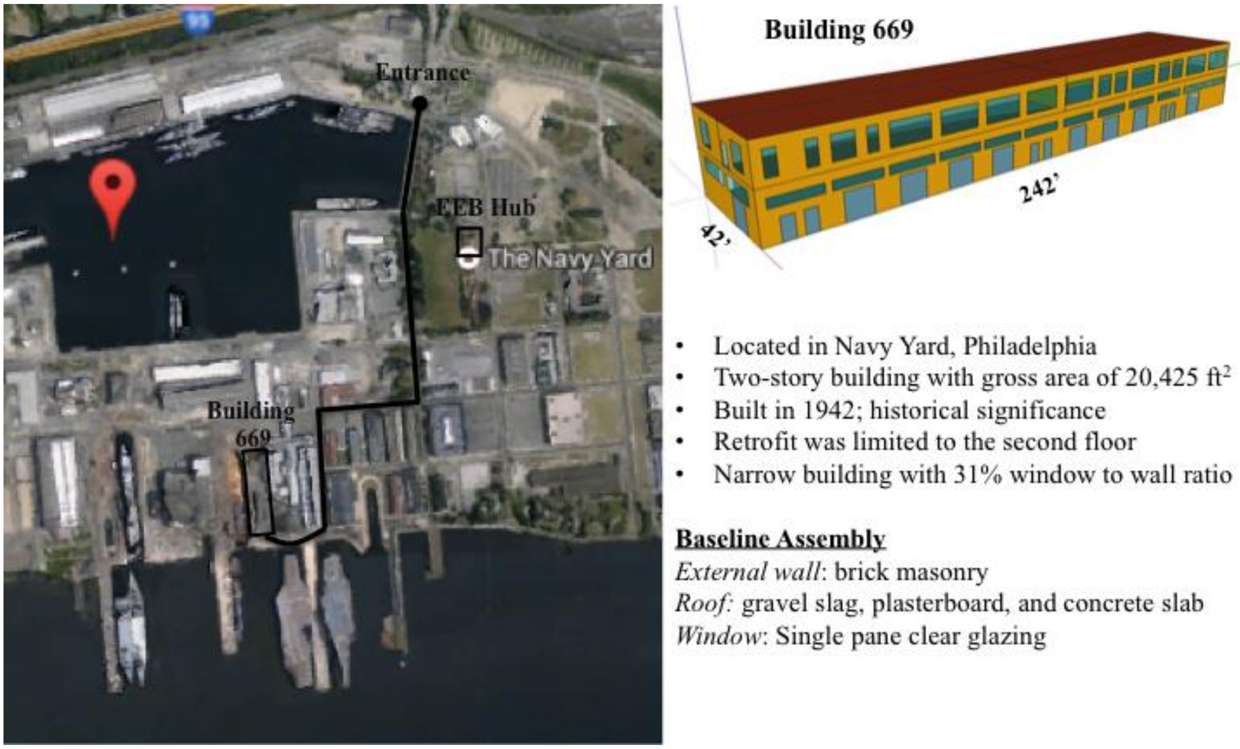


Figure 9: Building 669 Located in the Philadelphia Navy Yard

Figure 10: Pictures from Inside Building 669 (August 2012)

The Building 669 owner requested a roof capable of supporting PV (photovoltaic panels) and a cool roof option; the options selected for the LCA/LCCA study included a black EPDM (ethylene propylene diene monomer) membrane system and a white, PVC (polyvinyl chloride) membrane system, shown in Figure 11. Approximately 25% of roofs in the Northeast region are composed of plastic, rubber, or synthetic sheeting and while EPDM is the most popular single-ply roof membrane in the US, PVC is a growing roof membrane option (EIA 2003, Smith 2014). Both membrane options used a roof section consisting of 4.72" concrete, a vapor barrier, R-30 polyisocyanurate rigid board insulation, and 0.5" Dens Deck roof board with the membrane applied on top. The EPDM membrane required a Kraft paper backing between the Dens Deck and the membrane.

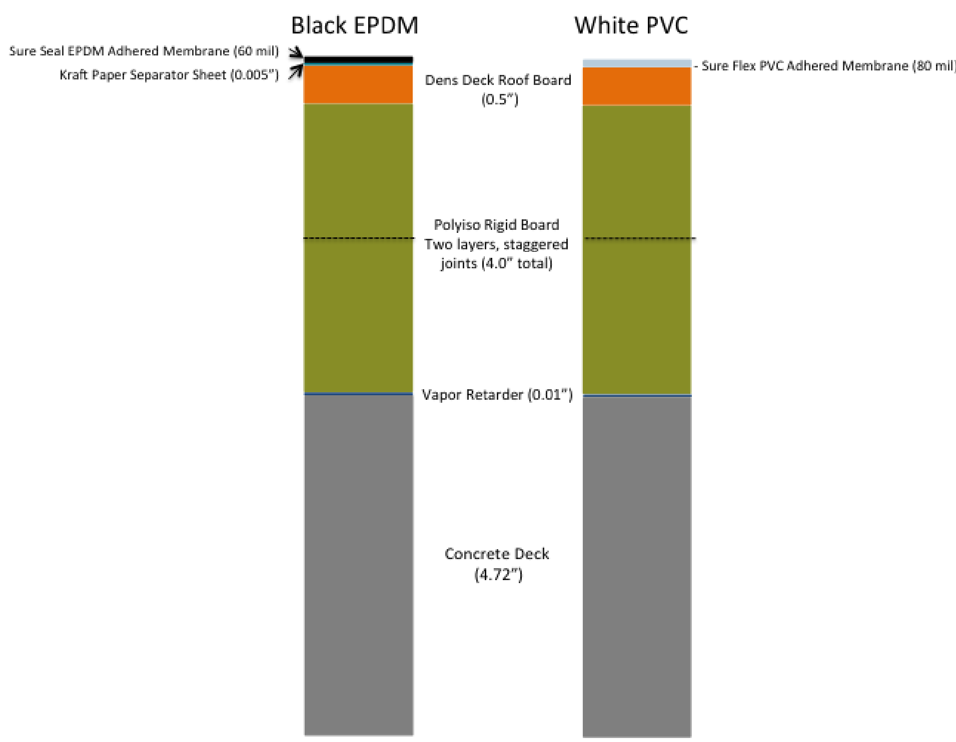


Figure 11: Cross-Section of Roof Material Alternatives

Any major building system, such as a roof, that needs to be replaced or retrofitted includes many options that have different price points, environmental impacts, maintenance requirements, and performance valuations. As building owners continue to experience the need to replace and retrofit major building systems it is apparent that a better framework or platform is necessary to assist in the decision-making process.

2.3.2.1 LCA and LCCA Study Methodology and Results

LCA Methodology and Results. This LCA was a direct comparison between the two different roof systems suggested for an existing building. The system boundary is cradle to gate; therefore the assessment only takes a look at the raw material extraction, product manufacturing, installation of the roof layers, and building energy use; an overview of the study system boundary is shown in Figure 12. End-of-life is not included in the analysis. The functional unit for this assessment is the entire area of Building 669's roof, which is 10,212 ft^2.

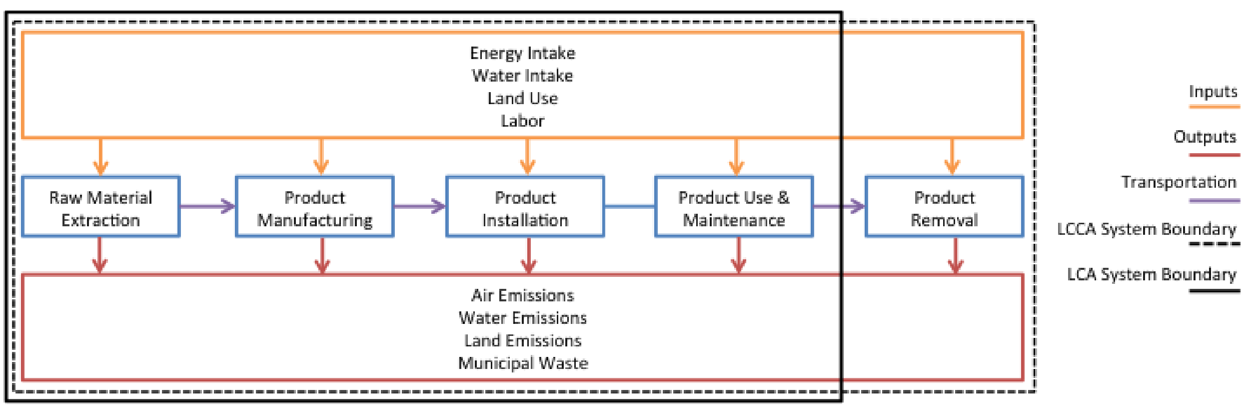


Figure 12: System Boundary of LCA/LCCA Roof Systems

For the life cycle inventory of this comparative LCA, the Athena program was used. Athena creates a platform to calculate the environmental impacts specific to building systems, where a majority of their database inventory comes from industry-specific data (Bowick, O'Connor et al. 2014). Utilizing Athena made it possible to get US material information that was likely more accurate than other LCA programs and/or databases; for example, the polyiso rigid board material found in Athena was from an internal Bayer MaterialScience study, the company product used for both the EPDM and PVC roof systems (ASMI 2012). Because there are set values assigned to most of the data points in Athena, a weighting system was applied to accurately represent the roof material layers in each system according to the roof design, Table 6. For example, the PVC membrane in the roof design is 80 mil while the largest PVC roof membrane in Athena is 48 mil, therefore the LCA results for the PVC membrane were multiplied by a factor of 1.67 to represent the study roof design. Athena uses TRACI v2.1 as the impact assessment method.

Table 6: Life Cycle Inventory for the Roof Materials via Athena

Roof Description	Athena Unit Process	Factor
EPDM Membrane (60 mil)	EPDM Black 60 mil	1
PVC Membrane (80 mil)	PVC 48 mil	1.67
Kraft Paper (0.005")	PP Scrim Kraft Vapor Retarder Cloth	1
Dens Deck (0.5")	Moisture Resistant Gypsum Board (0.5")	1
Polyiso Rigid Board (4")	Polyiso Foam Board (unfaced) 1"	4
Vapor Retarder (0.01")	3 mil PE (0.03")	0.34

An overview of the LCA results can be found in Figure 13. The results show that the PVC membrane has significantly higher environmental impacts compared to the EPDM membrane. The manufacturing of PVC includes chlorine, cancer causing vinyl chloride monomer, and toxic additives (SPI 2009, APME 2013, North and Halden 2013, Rochman, Browne et al. 2013). Additionally, PVC generates large quantities of waste. However, in one category, fossil fuel consumptions, EPDM and PVC are similar, which infers that both of these materials require large amounts of energy to produce and manufacture.

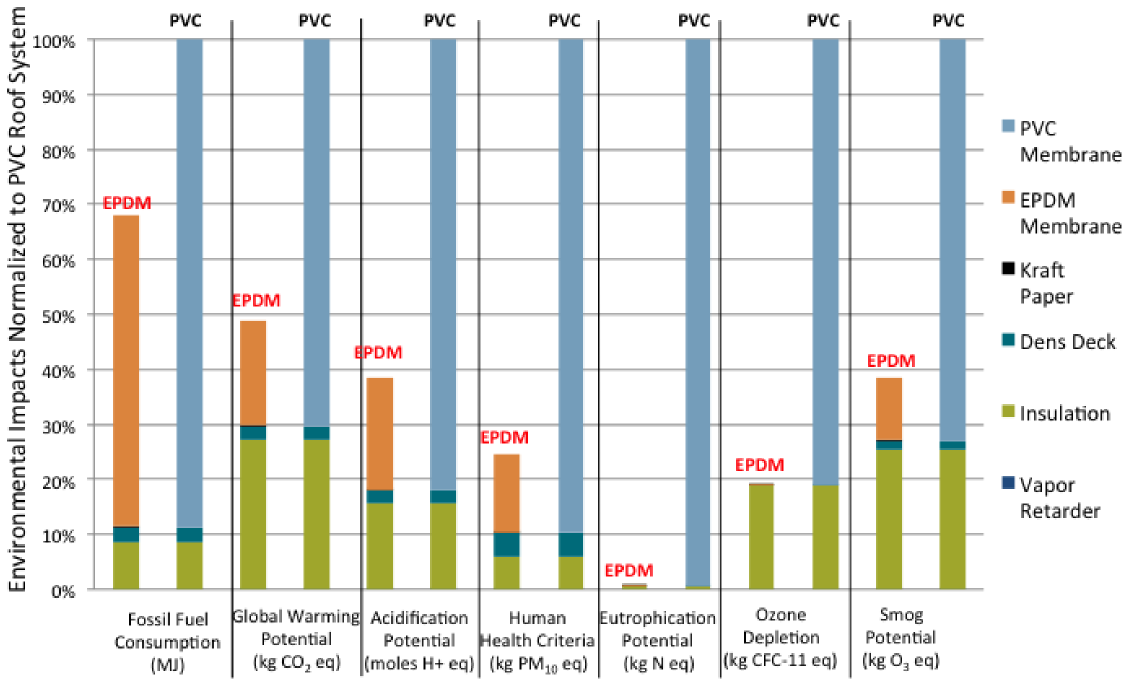


Figure 13: LCA results of roof scenario materials. PVC = polyvinyl chloride; EPDM = ethylene propylene diene monomer

Taking into consideration the use phase of Building 669, an LCA of the energy consumption was also analyzed. The environmental impacts for the building's energy consumption was also included. eQuest v3.64 was used to analyze the energy consumption of the study building. Separate files were created within eQuest to specify the reflection, absorptance, and emittance for the black EPDM and white PVC membranes. The energy consumption was divided into cooling and heating loads; the cooling load adjusted for electric window units with a 3.4 coefficient of performance and the heating load is natural gas. Considering the 20-year life span of the roof materials, the energy consumption for the building also accounted for 20 years. The LCA results show that the energy consumption, especially the cooling loads, dominated all environmental impact categories Figure 14. Utilizing a PVC membrane resulted in a lower cooling load by approximately 1% over the EPDM membrane, while heating loads were about equal.

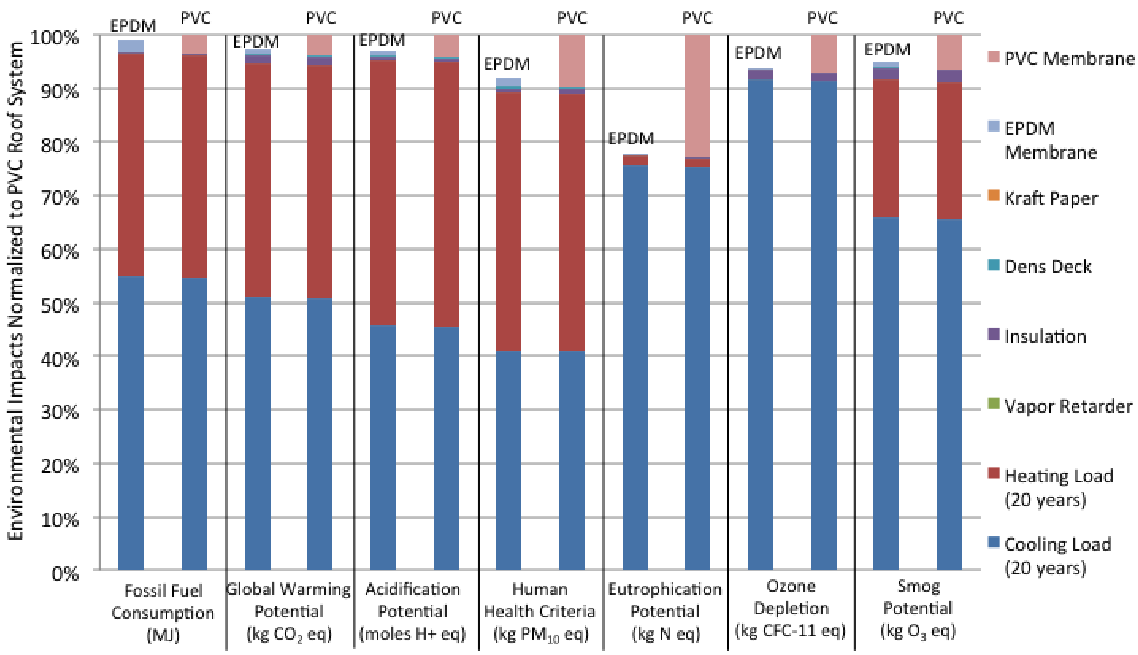


Figure 14: LCA of roof options including material production and building use energy consumption. PVC = polyvinyl chloride; EPDM = ethylene propylene diene monomer

LCCA Methodology and Results. The LCCA encompassed the entire life cycle of the roof from material production to installation to maintenance and product material. Data collection for the LCCA included the sources of Carlisle SynTec, the Center for Environmental Innovation in Roofing, and CP Rankin; shown in Table 7. For the cost assumptions, an industry standard of 20-year lifespan (2013-2033) was assigned to the study (Cash 2006, Hoff 2007, Coffelt and Hendrickson 2010, DPR 2013). An inflation rate of 3% was included in the net-present value of all the calculations. An installation cost estimate was determined in February 2013 by a local

Philadelphia estimating company for the two roof options and included the removal of the current roof system down to the concrete deck, any necessary plumbing, materials and labor of the new roof, and a 20-year built-in warranty that guarantees material replacement and repairs if necessary. The future replacement and removal costs were projected from the February 2013 roof estimate.

Table 7: Life Cycle Cost Assessment Data Collection

Roof Description	Data Collection
EPDM System Installation	CP Rankin
PVC System Installation	CP Rankin
Maintenance Plan	CEIR and Carlisle Syntec
Removal Cost	CP Rankin
Building Energy Cost	eQuest data & CBEC data

One area for concern in regards to a roof's life cycle cost is the decision to have a maintenance plan (Hoff 2007, Coffelt and Hendrickson 2010, Vross 2012, DPR 2013). This analysis examined two different maintenance plans, a reactive plan and a proactive plan. A reactive maintenance plan only responds to major roof situations, such as a leak or a material malfunction. A proactive maintenance plan is a more active approach, including quarterly inspections by professionals who check the roof seams, clear any drains, and test for moisture infiltrations among other things. A 15-year industry study found that the average building owner with a reactive maintenance plan pays approximately $0.25/ft^2/year over a roofs life span with an average roof replacement at year 13 while a building owner with a proactive maintenance plans pays approximately $0.14/ft^2/year with an average replacement at year 21 (Vross 2012, DPR

2013). Having a proactive maintenance plan has a considerable impact on the life cycle cost of a roof system.

In order to understand Building 669's potential in energy saving costs due to a new roof, an energy modeling simulation was conducted, as previously described. Building 669 was modeled as is, with no changes; the roof was then replaced with the two options proposed and the energy model recalculated. For both the black EPDM and the white PVC membrane options, there was approximately 17% energy saved in the cooling season and approximately 28% energy saved in heating season. In the LCCA, an average of 20% reduction in energy consumption as applied for the use phase.

The LCCA results are shown in Figure 15. The life cycle costs articulate the importance of a roof maintenance plan and its effect on what year a replacement roof is needed (either year 13 or year 21) (Vross 2012, DPR 2013).

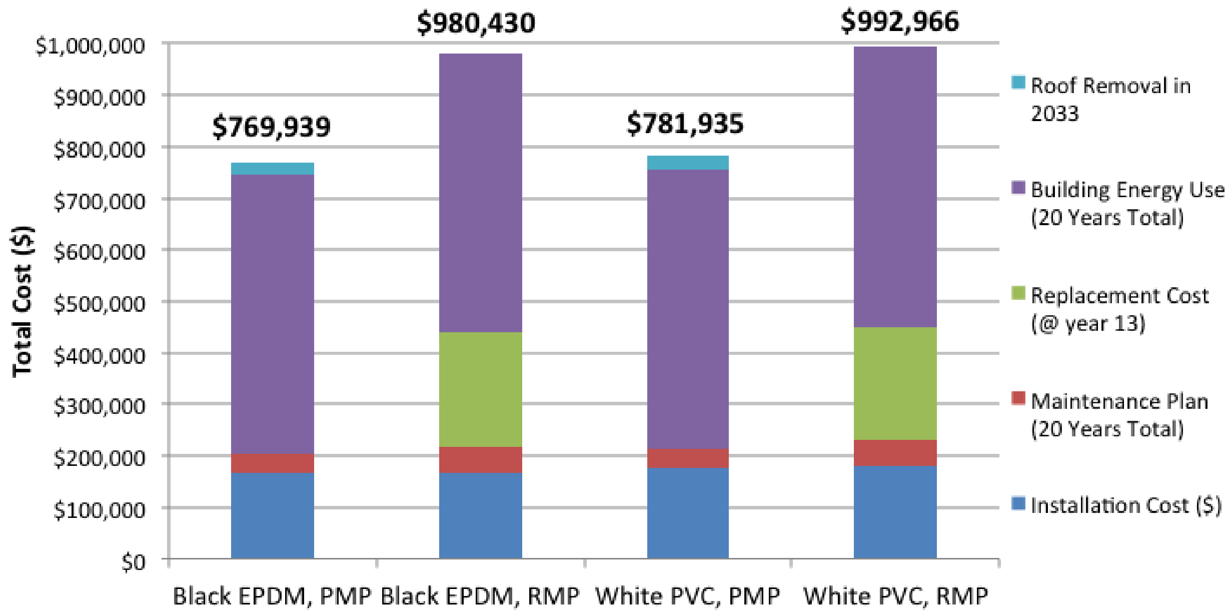


Figure 15: Life Cycle Cost Assessment of Roof Options for Building 669; RMP = Reactive Maintenance Plan; PMP = Proactive Maintenance Plan; PVC = polyvinyl chloride; EPDM = ethylene propylene diene monomer

2.3.2.2 LCA and LCCA Case Study Discussion and Conclusion

Based on the LCCA and LCA results of the two different options, it is recommended that Building 669 use a black EPDM roof with a proactive maintenance plan for their retrofit option. For this specific case study, both the LCCA and LCA results had the black EPDM roof system as the more viable option compared to the white PVC roof system. It was important to present and interview the Building 669 owner on the LCCA/LCA process to gather feedback on realistic applications for future retrofit projects (Stutman and Gorgone 2014).

The LCCA analysis proved to be more of interest to the Building 669 owner as well as other members of the EEB Hub and PIDC (Philadelphia Industrial Development Corporation), building management company for most of the Philadelphia Navy Yard. Specifically, installation cost, operating costs, periodic replacements & repairs, and end-of-life disposal/salvage value were of more value than knowing or understanding the material and production costs found in the beginning of a product life cycle. One key takeaway from the interview with the Building 669 owner, the director of sustainability for PIDC, and the Demonstration Project Manager for the EEB Hub was that a typical bank loan for a small- to medium-sized company is about $20/sf for retrofits and renovations (Stutman and Gorgone 2014). The building owner is going to look at initial costs first, maintainability second, and potentially other life cycle costs and/or energy considerations.

The LCA results were challenging to valuate for the Building 669 roof retrofit. The PVC membrane was the largest contributor in environmental impact categories, followed by the EPDM membrane and the polyiso-rigid board insulation. Due to the nature of Rhoades Industries, the most important environmental impact to the building owner is air permitting, specifically the Pennsylvania Title V permit. Any analyses that provide an opportunity for credit reductions would be more appropriate than a full LCA. However, it was made apparent that a larger corporation, which may invest in more than one property, may benefit from LCA, especially in relation to green building rating systems, such as LEED.

The feedback gathered from the Building 669 owner and members of the EEB Hub and PIDC have helped develop lessons and strategies for future LCCA/LCA application: (1) Budget requirements are extremely important; (2) Client goals and/or programs should be known (i.e., LEED certification, environmental permitting requirements, company mission); (3) Companies (typically larger) with more available capital are more likely to invest in LCCA and/or LCA analyses.

In conclusion, the LCCA and LCA results were appreciated by the building owner, but not entirely realistic for a small- to medium-size company looking to do a roof retrofit. The breadth of the LCCA and LCA was too detailed for a restricted budget experienced by Building 669.

2.4 ADVANCED BUILDING LCAS

The work presented in Section 2.4 builds off of the results found in Section 2.2 and 2.3. After completing the materials LCA and the retrofit LCA/LCCA, it was evident that there is no clear path for integrating environmental assessments with current building project practice. Without a standard practice for buildings projects that adapt to various assessments, such as LCA or LCCA, the process of developing a sustainable built environment is challenging. Additionally, gaining market recognition for the use of building assessments is a hurdle. Thus, the work presented in Section 2.4 first describes a progressive pathway that encompasses life cycle assessment with a whole suite of building tools for future building assessments. Second, the impact of LEED on market transformation and integration of LCA and other building assessments is discussed. Developing an integrated building project pathway and understanding the building market's perspective on LCA was essential and the answer to the first research question "what tools and strategies are needed to advance LCA in the building industry?"

2.4.1 Integrated Project Delivery and Life Cycle Assessment

The green building movement continues to grow in relation to the demand for a sustainable built environment. However, green buildings are not as prevalent as they could be, mainly due to perceptions in cost, value, and building performance (Newsham, Mancini et al. 2009, Denzer and Hedges 2011). One way to dispel some of the green building limitations is by addressing the project delivery method for a building project; green buildings require a high level of interdisciplinary collaboration and design analyses (Lapinski, Horman et al. 2006). The necessary traits for an effective sustainable building project delivery method can be found in integrated project delivery.

Integrated project delivery (IPD) is defined as "a project delivery approach that integrates people, systems, business structures and practices into a process that collaboratively utilizes the talents and insights of all participants to optimize project results, increasing value to the Owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction" (AIA 2014). The IPD approach requires more coordination from project onset than traditional building methods like design-bid-build or design-build, however IPD allows for seamless integration of a project's sustainability goals to accommodate for the growing demand for a sustainable built environment.

The current state of the United States building industry has significant environmental, economic, and social impacts. In 2013, the building industry accounted for approximately 40% of the total US energy consumption (DOE 2014). The building and construction industries also contribute to an estimated 20% of the US GDP (WorldBank 2014b). Additionally, people spend about 90% of their lives indoors, where pollutants tend to have concentrations 2 to 5 times higher than average outdoor conditions (EPA 2008b). Given the number of environmental impacts of the building industry, many tools, policies, and methods have been developed to track progress, identify improvement areas, and establish best practice strategies for sustainable buildings. The selection of more than one tool, policy, or method presents serious challenges to designers, builders, and owners, therefore this paper focuses on the IPD process as an outlet for various sustainable tools to converge, creating an effective and efficient platform for all building project parties.

One promising sustainability tool is life cycle assessment (LCA), a scientific approach to evaluate the environmental impacts of a product or process from raw material extraction to production to use and end-of-life; LCA is delineated in ISO 14040/44 (ISO 1997a, Baumann and Tillman 2004). Although LCA is utilized in many industries, such as product development and manufacturing, the use of LCA in the United States is neither consistent across the building industry nor used to its fullest potential. LCA suffers from use in the US because its use is often fragmented and not well integrated in the building project.

The holistic understanding of the building process, rendered by both IPD and LCA, can influence the use of cost assessments, product decisions, and appropriate building operations and management strategies. From a process standpoint, IPD, is grounded in design, construction, building use phases, and decision-makers. From a tool standpoint, life cycle assessment (LCA) also spans all of the building phases. It is rational that the process and tool have the potential to be complimentary.

A pathway to harmonize life cycle assessment and integrated project delivery is proposed. The LCA/IPD partnership is twofold: 1) enhances the environmental performance goals of a building project, and 2) enables additional analyses, such as life cycle cost assessment, to easily integrate into the project. Key to this integration is developing a strong program and commitment from all stakeholders and this is further explored through the lens of triple bottom line – people, profit, planet – accounting.

2.4.1.1 IPD/LCA Pathway Methodology

First, a pathway for LCA and IPD integration was developed. Though there has been extensive work on building LCAs or IPD and building projects, little research has synthesized both methods. The AIA published standards on LCA (AIA Guide to Building Life Cycle Assessment in Practice) and IPD (Integrated Project Delivery: A Guide) were first reviewed to assimilate language preferences and identify recommended processes (Bayer, Gamble et al. 2010, AIA 2014). Both the LCA and IPD processes defined by the AIA were then compared against a traditional building process. A traditional building process is considered either design-bid-build or design-build (Mohsini and Davidson 1992, Ling, Chan et al. 2004, Hale, Shrestha et al. 2009). Both design-bid-build and design-build have a contractual separation between owner and contractors (designers or engineers), while IPD is an integrated approach across all parties. The life cycle of a building project was illustrated using IPD language preference and overlaying LCA potential. Because both LCA and IPD require a similar organizational structure – participants, data collection and documentation, results – their building services compliment each other.

Second, the IPD/LCA pathway is theoretically examined. The goal of the pathway is to enable additional building analyses to be integrated and utilized for data driven decision-making. The building analyses addressed include life cycle cost assessment (LCCA), building information modeling (BIM), energy modeling, dynamic life cycle assessment (DLCA), and green building rating certification, specifically Leadership in Energy and Environmental Design (LEED). LCCA is a concept that can resonates with building owners, as initial costs, return-on-investments (ROI), and operational costs are leading factors in a building project (Durairaj, Ong et al. 2002b, Gluch and Baumann 2004). BIM is a model-based software program that allows design and construction documents to overlap, creating a virtual space to collaborate (Jalaei and Jrade 2014). Energy models theoretically optimize the energy consumption of a building; the results and consumption value can be integrated into the BIM models. DLCA is a new concept that continues to model the environmental impacts of a building throughout its use (or operational) phase, such as energy consumption or indoor environmental quality (Levasseur, Lesage et al. 2010, Collinge, Landis et al. 2013). Many green buildings strive for certification to market their sustainability efforts. The IPD/LCA pathway has the potential to reduce errors, double accounting, and redundant documentation for the LEED certification process.

Building projects have an array of goals; therefore achieving these goals with the appropriate tool can expedite decision-making. The proposed IPD/LCA pathway assists building projects in defining project goals and developing a collaborative team, which creates an environment from the onset that supports the addition of other decision-making tools. The recommendations and suggestions found in literature and case studies that supports the use of IPD/LCA with LCCA, BIM, DLCA, or LEED were summarized and presented in the results.

2.4.1.2 IPD/LCA Pathway Outcomes and Discussion

IPD/LCA Pathway. Integrated project delivery and life cycle assessment are both directed towards optimization, either of the project itself or the associated environmental impacts. First, the decision to use integrated project delivery as the delivery method over traditional building methods such as design/bid/build or design/building should be established. For sustainable buildings, IPD is the favorable approach due to its collaborative foundation and shared risk and reward (Lapinski, Horman et al. 2006, Castellanos 2010, Kent and Becerik-Gerber 2010).

Second, the building owner and lead designer need to disclose limitations and define goals. Examples include budget and return-on-investment constraints, site or building code restrictions, green building rating system (GBRS) certification, energy efficiency goals, waste management programs, social and educational objectives, and building use or purpose. Clear value definition at the onset of a project can reduce long-term costs and help allocate funds over the project lifetime to accommodate for system investments (AIA 2014). Pertinent documentation can also be uncovered and completed throughout project progression as opposed to final closeout phases (AIA 2014). Developing transparent goals fosters an efficient and collaborative environment, which leads to the third part of the IDP/LCA pathway.

Third, a collaborative, multidisciplinary team needs to be established. Spearheaded by the building owner, project teams may include regulatory agencies, construction managers, contractors, architects, engineers, and building managers. Defining the role and responsibility of each team member from the onset can have three significant outcomes: (1) *project flexibility* when design challenges occur, such as technology updates, due to collaborative understanding established; (2) *project pace* is smooth and quick due to early coordination and flush out of potential misunderstandings; (3) *project litigation* problems are diminished due to shared risk and reward among team members (AIA 2014). Respect and trust should be guiding principles among team member to encourage a safe and transparent working environment to integrate, collaborate, and share information, which differs from traditional building process silos or top-down responsibility distributions (Kent and Becerik-Gerber 2010, AIA 2014). The collaborative team is further developed by technology, such as building information modeling (BIM). These key team members can help conceptualize and design the building project.

When the building project is conceptualized with the help of the project team and the design criteria becomes a realization, initial building goals are reevaluated. Project scope is explicitly defined including building system selections, target costs, sustainability goals, building component quality, and scheduling overview. It is necessary for building owners to identify their needs of building assessments – *what are they looking to answer with the results?* An overview of typical building strategies can be found in Table 8. Explicit building assessment needs help define the assessment scope and boundary, including which building and life cycle phase the assessment corresponds to, which LCA program and/or tool is most appropriate, and an ideal timeline for crucial decision-making. In turn, the data essential to the building assessment, such as material alternatives, product vendors, and energy analyses, is outlined via the scope and definition. The use of LCA throughout the building design can provide the team with data to inform environmentally preferred decision-making.

Table 8: Typical building assessment needs modified from (Bayer, Gamble et al. 2010)

IPD Phase	*Building Assessment Strategy*	*Building Assessment Strategy Results*
Conceptual Design	Choose structural system	Measures downstream and upstream impacts (environmental or cost) of different structural systems
Criteria & Detailed Design	Choose building materials and products	Measures downstream and upstream impacts (environmental or cost) and embodied energy of different building materials and products
Detailed Design	Choose HVAC and lighting systems	Measures downstream and upstream impacts (environmental or cost), conducts energy models, and model occupancy patterns of different HVAC and lighting systems
Implementation Documents	Green building rating system certifications	Allocate budget, identify goals, and commission certification documentation

Table 8 (continued)

Construction	Set and manage construction goals	Collect data on material flows and waste management for green building certification or to verify impact (environmental or cost) reduction strategies
Building Occupancy	Building performance	Measures indoor environmental quality and carbon footprint of building use; energy model verification and comparison; post-occupancy productivity and performance

Many IPDs utilize building information modeling (BIM) to facilitate seamless collaboration among building project stakeholders. There are more published articles on BIM and LCA (Russell-Smith and Lepech 2011, Stadel, Eboli et al. 2011, Bynum, Issa et al. 2013, Díaz and Antön 2014, Inyim, Rivera et al. 2014, Jalaei and Jrade 2014, Senescu, Haymaker et al. 2014), indicating the popularity of the tool over the IPD process. However, when IPD and BIM are used in concert with LCA, the design process is optimized and there is an increase in building efficiency (Kent and Becerik-Gerber 2010, Díaz and Antön 2014, Jalaei and Jrade 2014). BIM models also integrate into building automation systems, detailing out building systems for the building operator to manage efficiently. Life cycle thinking enhances both IPD and BIM by bringing the triple bottom line – people, profit, planet – to the forefront of decision-making. Figure 16 describes the necessary components for the IPD and LCA pathway (Bayer, Gamble et al. 2010, AIA 2014).

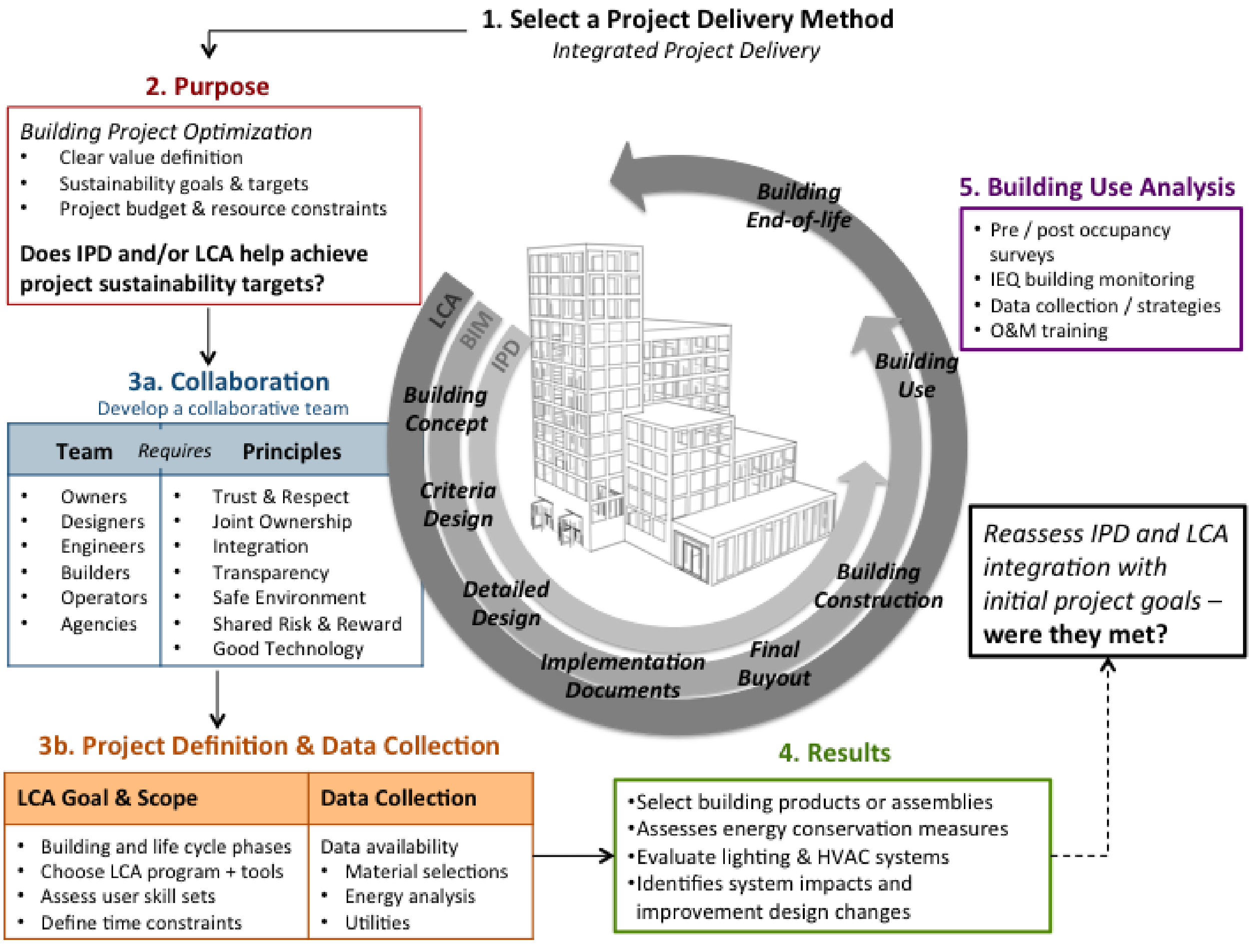


Figure 16: IDP and LCA Framework; LCA = life cycle assessment, IPD = integrated project delivery, BIM = building information modeling, HVAC = heating, ventilation, and air conditioning, IEQ = indoor environmental quality, O&M = operators and management

IPD/LCA Pathway Exploration. When life cycle thinking is established at the beginning of the building project, a holistic understanding of the process is used throughout the project. One limitation with LCA is that the assessment does not garner results that address all of the decision-making issues that a building owner is faced with, such as budget constraints or building codes. Expanding the role of traditional LCAs, by incorporating other tools and strategies, can broaden the LCA application market base, especially in the building industry. A decision tree was developed as an interdisciplinary approach, guiding users to an appropriate LCA improvement method for their project, as shown in Figure 17 (Guinee, Heijungs et al. 2010).

The first two steps of the LCA decision tree coincide with the second step of the IPD/LCA pathway to define the project purpose. The project purpose includes an outline of all limitations and goals, such as environmental achievements, economic constraints, and occupant productivity. The beginning of the project should also recognize what and how the results – of any assessment – will impact the project and what to expect from any outcomes. Consequential LCA captures how the environmental impact of a product or process change in response to different inputs and output of the set system and should be used for decision-making (Finnveden, Hauschild et al. 2009). Attributional LCA delves further into understanding all of the physical flows in and out of the set system and should be used when there is only one selection, but the environmental impacts of the system are unknown (Finnveden, Hauschild et al. 2009). The majority of building project LCAs should consider consequential LCAs, however attributional LCAs could benefit whole project LCAs and broader insight to the environmental impacts of the entire building.

There are three major types of building LCAs – "LCA Scope" – that a building owner could request: (1) a whole building LCA; (2) a partial building selection or material comparison; or (3) building use phase and building performance. For a whole building LCA (1), the owner may be attempting to get a GBRS certification, so the assessment is a requirement or the building project is a test bed for institutional studies. Evaluating the cost of a whole building throughout its life cycle may uncover more efficient design strategies, product choice, or end-of-life options than the initial building estimation. A whole building LCA also indicates that the building owner may be trying to introduce evidence-based design (EBD) into the building to quantify the impact design choice has on building occupants (Ulrich, Zimring et al. 2008). Environmental impact, cost considerations, and design choices are reasons a whole building LCA may be conducted, spanning all phases of the building and requiring many levels of data collection.

A partial building LCA (2) is typically geared towards building material or system selection, either addressing the attributional effects (what is the environmental impact of the building products, including embodied energy?) or the consequential effects (which building material is environmentally preferred for this project?) (Finnveden, Hauschild et al. 2009). Environmental product declarations (EPDs) have emerged into the building industry, where third-party vendors verify a product's LCA. Although there are not many EPDs available, the market trend towards full product LCAs is promising. The partial building LCA also allows end users to understand the embodied energy of their building products and how they play into the whole building life cycle. This is important for net-zero energy buildings (ZEB) and identifies a large flaw in the definition of ZEB – that net-zero does not include the energy used to produce renewable energy technologies (Thiel, Campion et al. 2013). When LCCA is considered with LCA, the results may find that different building phases such as maintenance and replacement have significant cost and environmental implications compared to the initial installation cost or product manufacturing. Specifically using LCA with EPDs or LCCA can influence product and system choices by providing the IPD team with quantitative information.

A use phase specific LCA study (3) attempts to address how a building is performing. This may be the most progressive application of LCA, where LCA is moving away from a static set of recommendations to continuous adaptation of how the building is performing, also known as dynamic LCA (DLCA). DLCA provides owners and operators with data and metrics for monitoring building changes throughout the building's use phase (Collinge, Landis et al. 2013). DLCA can also incorporate energy consumption information, utilizing utility bills to assess trends in consumption or identify errors in the HVAC system, while monetizing energy efficiency. Revisiting how the EBD layout of the building is affecting building occupant productivity also contributes to the impact of the use phase. Because people spend up to 90% of their lives indoors, quantifying the impacts of building use can continue to encourage the use of low-emitting products, efficient design layouts, and reduction in environmental footprint (EPA 2008b).

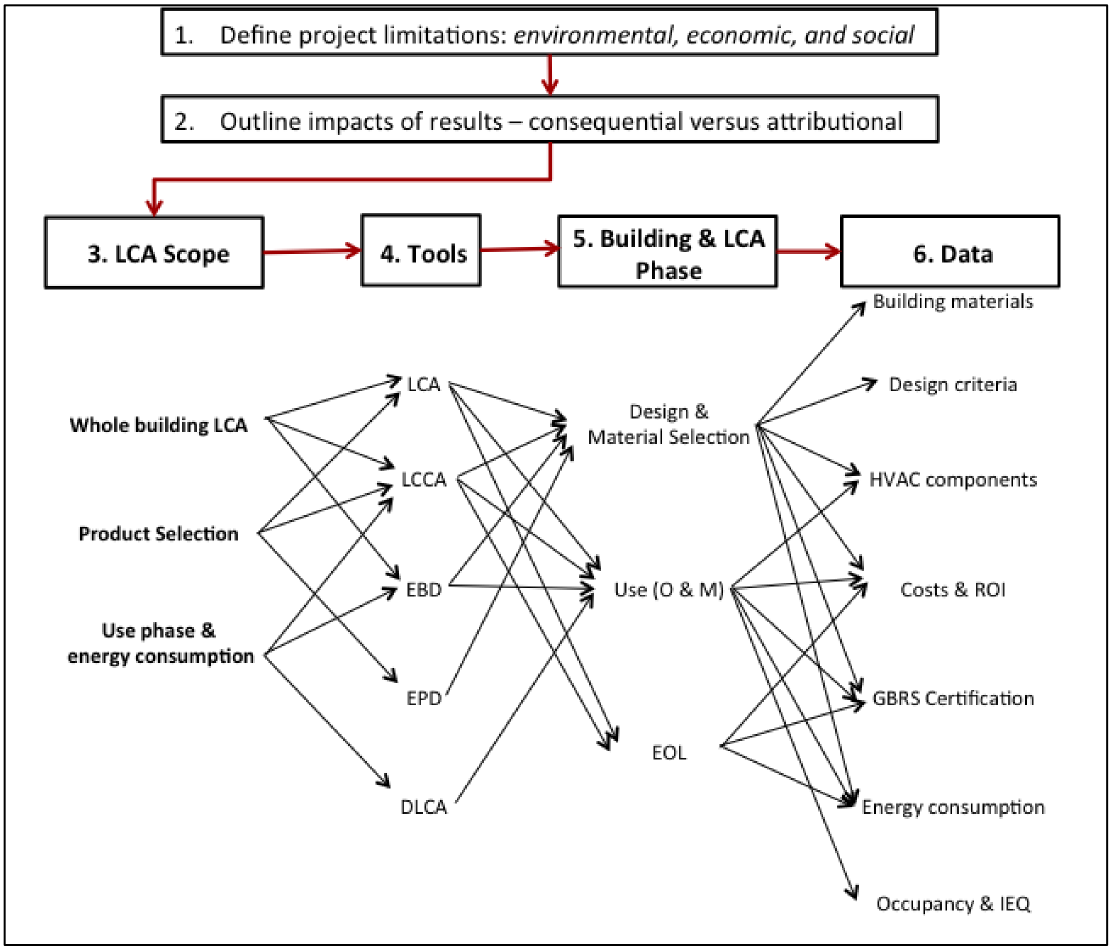


Figure 17: LCA improvement tool decision tree; LCA = life cycle assessment; LCCA = life cycle cost assessment; EBD = evidence-based design; EPD = environmental product declarations; DLCA = dynamic LCA; O&M = operations and management; EOL = end-of-life; HVAC= heating ventilation and air conditioning; ROI = return-on-investment; GBRS = green building rating system; IEQ = indoor environmental quality

By selecting the appropriate LCA improvement pathway via the decision tree in Figure 17 the IPD team will continue to increase project life cycle thinking and awareness of building impacts. The purpose of the decision tree is to visually link how different LCA tools can be integrated for a specific goal, such as product selection or energy consumption. Furthermore, when IPD is established and BIM is used to collect building information, the resources, data, and collaboration for LCA is already vested.

2.4.1.3 IPD/LCA Pathway Conclusion

The United States green building movement continues to grow in relation to the demand for a sustainable built environment. Many tools, policies, and methods have been developed to track progress, identify improvement areas, and establish best practice strategies for sustainable buildings. However, the selection of more than one tool, policy, or method presents serious challenges to designers, builders, and owners. To address this challenge, *a pathway to harmonize life cycle assessment and integrated project delivery* was proposed.

The holistic understanding of the building process, rendered by both IPD and LCA, can influence the use of cost assessments, product decisions, and appropriate building operations and management strategies. Further developing LCA in the design programs, such as IPD and BIM, will encourage future LCA use. Transparency in EPDs and market encouragement will continue to shift the building and construction materials industries towards more sustainable practice, increasing the awareness of suppliers and producers. As automated building monitoring systems become more commonplace in managing buildings during the use phase, the addition of DLCA could be a commercial tactic to tracking environmental impacts of a building throughout its use phase. Continuing to grow the body of building LCA knowledge will increase the need for green building validation, the use of environmentally preferred products, and the understanding of human consumption.

2.4.2 Green Building Rating Systems and Market Transformation

Understanding the building market is essential for increasing the use and development of sustainable building assessments. Without market support of LCA, the building industry will remain the same, lacking the tools necessary to advance building projects. Recognizing how the building market is responding towards sustainable building assessments and utilizing these tools throughout their projects is important for future development. The integration of LCA throughout the familiar green building rating system, LEED, is presented, followed by the impact that that LEED has had on market transformation.

2.4.2.1 LEED and LCA

One way that LCA is infiltrating the building market is through the GBRS, Leadership in Energy and Environmental Design (LEED). Literature suggests that LEED should evolve to incorporate LCA into the credit rating systems (Humbert, Abeck et al. 2007, Optis and Wild 2010, Denzer and Hedges 2011, Malmqvist, Glaumann et al. 2011, Suh, Tomar et al. 2014, Al-Ghamdi and Bilec 2015). The suggestion comes from studies that have evaluated LEED projects and found that LEED credits fail to account for a building's performance over its life cycle, certain credits do not accurately depict the environmental merit suggested, and the idea that as buildings become more energy efficient, the subsequent actions of the building (materials used, maintenance, disposal) become more important in the total building life cycle (Humbert, Abeck et al. 2007, Optis 2008, Denzer and Hedges 2011, Hernandez and Kenny 2011). To better measure the issues described above, conducting a life cycle assessment on a LEED building will yield life cycle energy results among other environmental impacts. The following studies highlight the importance of increasing scientific merit into LEED as a long-term direction.

One study found that there is a large disparity among LEED credits and how beneficial they are in relation to each other (Humbert, Abeck et al. 2007). Credits related to physical reductions such as reduced energy consumption, reduced commute, reduced waste, and reuse of materials proved to have the most environmental benefits of all the credits (Humbert, Abeck et al. 2007). The authors of this study suggest a higher point system so that each credit can have more realistic weighting according to the environmental impacts. It is important to note that this study was published in 2007, relating to an earlier version of LEED. LEED has since then undergone a change in the credit weightings based on LCA.

Other studies highlight the importance of assessing life cycle energy of a building as opposed to just the operational energy (Sartori and Hestnes 2007, Ortiz, Castells et al. 2009, Hernandez and Kenny 2011). A review of 60 buildings shows that embodied energy (the energy associated with building manufacturing, construction, maintenance, and disposal) accounts for 2-38% of a conventional building life cycle and 9-46% of a low-energy building life cycle (Sartori and Hestnes 2007, Hernandez and Kenny 2011). LEED buildings are considered "low-energy"; therefore emphasizing the importance of calculating the embodied energy *and* incorporating it into the LEED rating system. Embodied energy has been disregarded in the past because of its low percentage in a conventional building life cycles, but is much more apparent as new energy efficient technologies are implemented in conjunction with the low operational energy usage (Sartori and Hestnes 2007, Zabalza Bribián, Aranda Usón et al. 2009, Hernandez and Kenny 2011, Thiel, Campion et al. 2013).

To better understand a building's performance, one study suggests the implementation of LCA to support optimal building design solutions from the project's inception (Malmqvist, Glaumann et al. 2011). The LCA results in a more robust understanding of the building potential from a life cycle perspective as opposed to a more narrow approach of only the building materials used or projected energy use. This study offered a solution for a simplified LCA, outlining the method within the report and designing excel templates to accompany the method (Malmqvist, Glaumann et al. 2011). The simplified LCA is used to gauge the results of, for example, CO_2 emissions or embodied energy only and how they incorporate into the rating system before implementing a full scale LCA (Malmqvist, Glaumann et al. 2011).

As LEED has progressed from the first version, specific credits, requirements, and point distribution has become more sophisticated, explanatory, and indicative of the way the market is changing. The latest version of LEED, LEED v4, was released in November 2013. LEED v4 is different from previous versions as it encompasses more life-cycle thinking than before. First, the impact categories for category weightings have been reduced from 13 (LEED 2009) to 7 (LEED v4), incorporating a more robust perspective of the triple bottom line (people, planet, profit), including climate change, human health, water resources, green economy, community, natural resources, and biodiversity (USGBC 2009, USGBC 2012a). LEED v4 also aims to have the highest reduction of carbon dioxide emissions of any LEED versions to date (USGBC 2012a).

The Materials and Resources category has seen the largest integration of LCA. There is a larger scope for raw materials, products require more detailed information, and there is a complete building assessment credit (USGBC 2012b). Specifically, there is a building life-cycle impact reduction credit, which incorporates historic building reuse, renovation of abandoned or blighted building, building and material reuse, or whole-building life-cycle assessment depending on which LEED Rating System is being achieved (USGBC 2012c). The three building product disclosure and optimization credits for environmental product declarations, sourcing of raw materials, and material ingredients incorporate a higher set of standards for documentation of building materials and products in order to achieve the credit points. These standards include ISO 14025, 14040, 14044, 21930, 26000 for third party verification and cradle to gate scope, USGBC approved programs for criteria optimization, and the Global Reporting Initiative (GRI) Sustainability Report (ISO 1997a, ISO 2006b, ISO 2006a, ISO 2010, USGBC 2012c, GRI 2013). The Indoor Environmental Quality category has one credit option for low-emitting interiors, as opposed to 4 credits in LEED 2009. The low-emitting interiors credit requires documentation and adherence set forth by the major organizations mentioned above in the LEED 2009 section (USGBC 2012c). LCA can also be incorporated in the Innovation and Design category through either the pilot credit option or the exemplary performance option.

Further developing LCA in design programs, such as IPD (integrated project delivery) and BIM (building information modeling), will encourage future LCA use. Transparency in EPDs (environmental product declarations) and market encouragement will continue to shift the building and construction materials sector, increasing the awareness of suppliers and producers. As automated building monitoring systems become more commonplace in managing buildings during the use phase, the addition of DLCA could be a commercial tactic to tracking environmental impacts of a building throughout its use phase. Continuing to grow the body of building LCA knowledge will increase the need for green building validation, the use of environmentally preferred products, and the understanding of human consumption.

2.4.2.2 Market Transformation

LEED is a consensus-based program that evolves in response to market considerations and USGBC leadership. The USGBC's critical decision to make LEED market-based and consensus driven in the 1998 inception of the rating system has been an important factor for how

LEED has been shaped in the last 15 years. As the construction, architecture, design, and material industries have adjusted their products or services to accommodate for LEED-based requirements and credits, the social market, acceptance and knowledge, has grown. For example, when the first version of LEED was released, the availability of low-VOC paint and products was low and expensive, while today paint manufactures have made low-VOC paint mainstream and affordable; there was a 14% increase in low-emitting credits from 2009 to 2012 (Todd, Pyke et al. 2013). LEED has also been successful in market transformation with the inclusion of established programs like ENERGY STAR or EPDs and relating baseline energy consumption to ASHRAE 90.1 (Todd, Pyke et al. 2013). LEED currently does a good job of adjusting LEED to the scientific level that the market is ready for, but maybe taking greater strides between each version will push LEED farther ahead of the market instead of waiting for it to catch up and then move forward.

The long-term direction of LEED must become scientific-based in order to maintain its significance in the sustainable development world. As technologies become more efficient, data more accessible, policies stricter, and social awareness deeper, the current state of LEED will also have to adapt. Novel green building policies and educational programs via projects and case studies, professional contact hours, academic laboratory hours, and technology development will help increase a building owners' or designers' knowledge on efficient building processes and products (Mellross and Fraser 2012, Van Den Wymelenberg, Brown et al. 2013). Future LEED versions could explicitly have carbon footprint values associated with different building design options. Incorporating more use phase or performance based credits could alleviate design-only focus and increase life cycle thinking of buildings. Taking into account the trend of current projects should be also be considered, evaluating the "easy" credits and making them prerequisites or a lesser point value, upping the anti on the level it takes to reach LEED Certification each version cycle.

As the market has evolved in response to LEED, there is enough momentum behind the green building force to commit to a scientific-based rating system. Although LEED v4 is not fully scientific based, it is showing positive movement within the market and industry towards a more technical LEED rating system. LEED should aim to become 100% scientific-based by evaluating lessons learned for LEED v4 and incorporating LCA across all LEED categories, not just Materials and Resources.

3.0 HEALTHCARE LCA APPLICATIONS

3.1 INTRODUCTION AND BACKGROUND

3.1.1 Chapter 3 Organization

In Chapter 3.0 a healthcare LCA literature review is presented, followed by a healthcare LCA that focused on the disposable materials, reusable instruments, energy consumption, and end-of-life of two different birthing procedures (Campion, Thiel et al. 2012). Second, and building off of the first birth study, LCAs of 15 different disposable custom packs for the same birth procedure were completed to develop streamlining recommendations using design for the environment (DfE) strategies (Campion, Thiel et al. 2015). Lastly, a pathway to increase the use of LCA in the healthcare industry through increased personnel education and data driven decision-making. The pathway represents an advanced application of LCA. The evolution of Chapter 3.0 addresses the second research question "what tools and strategies are needed to advance LCA in the healthcare industry?"

3.1.2 Healthcare LCA Literature Review

Understanding the environmental impacts associated with the healthcare system supports the necessary transition to more sustainable healthcare practices (Daschner and Dettenkofer

1997, Karlsson and Pigretti-Ohman 2005, Kreisberg 2007, Shanks 2009, Sherman and Ryan 2010). There is an overall contradiction that plagues the healthcare system: it is a service designed to make people healthier, yet the negative environmental impacts from the hospital service cause long-term, negative health affects (Shanks 2009). Unfortunately, many doctors and hospital personnel do not fully understand the magnitude of environmental impacts associated with an operational hospital (Sherman and Ryan 2010). It is imperative that hospitals incorporate educational tools on sustainability, waste management, and material use for all hospital personnel in order to create a hospital atmosphere that is conscious of its environmental impacts. One way to quantify the environmental impacts of the healthcare industry is through life cycle assessment.

The healthcare industry has begun estimating environmental impacts with studies analyzing the carbon footprint of hospitals (Maverick Lloyd Foundation 2009, Subaiya, Hogg et al. 2011) and the entire industry (Chung and Meltzer 2009a). England's National Health Services, NHS, found their 2004 carbon footprint to be about 25% of England's total public sector emissions at 18.6 thousand kilograms of carbon dioxide equivalent (CO_2 eq) (Sustainable Development Commission 2008). A recent study calculated the total global warming potential (GWP) directly caused by the US healthcare sector to be 254 billion kilograms of CO_2 eq. Approximately 80% of the GWP in the healthcare sector is attributed to carbon dioxide (CO_2), which is one-tenth of the total CO_2 emissions in the US (Chung and Meltzer 2009a, Patrick 2011a). Although estimating GWP is important, expanding the scope of environmental impacts to include other negative environmental effects will create a more comprehensive understanding of the healthcare industry.

An increasing number of LCA and healthcare studies is emerging (Karlsson and Pigretti-Ohman 2005, Eberle, Lange et al. 2007, Chung and Meltzer 2009b, McGain, Hendel et al. 2009, Kwakye, Pronovost et al. 2010, Kwakye, Brat et al. 2011, Patrick 2011b, Brown, Buettner et al. 2012, Campion, Thiel et al. 2012, Eckelman, Mosher et al. 2012, Power, Silberstein et al. 2012). A recent waste audit of general anesthesia used in typical operating rooms concluded that 58% of the total anesthesia waste could be considered recyclable (McGain, Hendel et al. 2009). The waste produced by general anesthesia makes up approximately 25% of total operating room waste (McGain, Hendel et al. 2009). The success of hospital recycling is dependent on the knowledge and education that hospital personnel have in regards to waste segregation.

Many hospitals use disposable gowns as opposed to reusable gowns for a variety of reasons that may include ease, infection control, and cost. However, a recent cradle-to-gate LCA study resulted in reusable gowns consuming fewer raw materials, using less energy, and having lower emissions (Ponder 2009). The study was based on 1,000 reusable gowns, made out of 55% cotton and 45% polyester, used 75 times and the use of 75,000 disposable gowns, made out of SMS (spun-bound, melt-blown, spun-bound) polypropylene (Ponder 2009). Including the use and laundry needs, each reusable gown required 2,336 kg of raw materials, while each disposable gown required 12,607 kg of raw materials and a reusable gown only needs to be used 10.7 times to equal the energy use of equivalent disposable gowns (Ponder 2009). The only category where disposable gowns has a lower impact was in terms of water use, mainly because of the water needed for cotton irrigation and laundry for the reusable gowns (Ponder 2009). The amount of water needed for reusable gowns could be reduced with more efficient laundry techniques or a transition from the cotton-polyester blend to 100% polyester (Ponder 2009). It is important to note that the biocidal component of the reusable gowns was incorporated into the life cycle assessment; therefore inflectional control was the same between the disposable and reusable gowns.

The implementation of new ideas and green practices within the medical field is slow due to patient safety uncertainties. The reprocessing of medical equipment is a solution that helps reduce the overall waste produced by a hospital, but its development is hindered by social hesitation. The idea of reprocessing is to use quality control standards to remanufacture medical equipment by cleaning, sterilizing, and recalibrating (Kwakye, Pronovost et al. 2010). Reprocessing is an advanced way of reusing and recycling devices and machines in a hospital that would otherwise end up in the waste stream (Kwakye, Pronovost et al. 2010). Devices are categorized low, medium, or high depending on potential risk. Unger and Landis found that reprocessed dental burs had over 40% environmental savings across various impact categories (Unger and Landis 2014). Devices with high risk factors are not usually reprocessed because they are not cost effective. However, cost savings are apparent with low and medium risk devices. Reprocessing also allows for more developed countries to donate medical equipment to developing countries, enhancing the other healthcare systems.

In the Pittsburgh area, one non-profit medical surplus organization has collected and donated over $173 million dollars worth of expired medical products to developing countries over the last 25 years (Links 2014). In turn, this has diverted over 6 million pound of waste in Pittsburgh landfills (Links 2014). Partnering with a surplus organization can help hospitals redistribute their unused, yet ‘expired’, products to a second life instead of the landfill. Understanding the relationships between product manufacturing, use, and end-of-life can have significant economic, environmental, and social impacts on the current landscape of the US healthcare industry (Souhrada 1988, Gilden, Scissors et al. 1992, McGurk 2004, Blenkharn 2007, DiConsiglio 2008, PGH 2008, McGain, Hendel et al. 2009, Bai, Vanitha et al. 2013, WHO 2013).

The majority of the research concludes the need for more LCA results and applicable outcomes. The focus of this research varies from investigating impacts from specific medical procedures and products, hospital operations (i.e., energy consumption), waste quantity, and disinfection assessment. The relationship between LCA results and the impact on the complex healthcare industry is yet to be fully understood.

3.2 INITIAL HEALTHCARE LCAS

In 2010, a partnership between the University of Pittsburgh's (Pitt) Sustainable and Green Design group and Magee-Womens Hospital (Magee) of the University of Pittsburgh Medical Center was formed. The goal of the partnership was to better understand the environmental impacts of a healthcare institution and to develop environmental impact reduction strategies. Magee is one of the best women's hospitals in the country (U.S.News 2013). Magee is also nationally recognized for their green initiatives and has received over 10 awards from Practice Greenhealth, the US's premier sustainable healthcare program. The partnership between the sustainable engineers at Pitt and hospital personnel at Magee has grown tremendously over the last 5 years in response to the positive reaction from the healthcare community on the quantitative data provided by the collaborative sustainable healthcare research.

The work presented in Section 3.2 was in response to an OBGYN physician at Magee that wanted to understand the environmental impact of her practice. This study has had a significant impact on the partnership as well as the healthcare community and was fundamental to answering the second research question "what tools and strategies are needed to advance LCA in the healthcare industry?" This work was published in *Science of the Total Environment* as "Life Cycle Assessment Perspectives on Delivery an Infant in the US" (Campion, Thiel et al. 2012).

3.2.1 Birth Study

This portion of the research used process LCA to quantify the environmental impacts of a vaginal delivery in a labor and delivery room (LDR) and a cesarean birth in an operating room (OR) at Magee-Womens Hospital (Magee) of the University of Pittsburgh Medical Center (UPMC). This case study was chosen to help direct the sustainability efforts for this hospital which delivers over 10,000 infants per year and is developing robust greening efforts throughout the hospital. The research goal was to help understand the relative environmental consequences of each component of the birth process in order to optimally target areas for improvement for the most common procedure in this hospital.

In order to achieve this goal, the first objective was to create a process LCA framework specific for hospitals. The second objective was to quantify the LCA data and evaluate the results for vaginal delivery and a cesarean birth. A research team was developed including engineers with expertise in LCA, physicians, nurses, and the hospital's facility manager. Cultivating these relationships was necessary for obtaining an insider's perspective of hospital operations and managerial complexities and discussing how hospital personnel could use the LCA framework and results.

3.2.1.1 Birth Study Methodology

LCA Goal & Scope. The functional unit of this study was the birth of one baby. The boundaries of the study, Figure 18, focused on a single birth including components such as energy consumption, material production, sterilization, and material disposal. Due primarily to scarcity of LCI data regarding laundry services, cleaning chemicals, and anesthetics, the use and manufacturing of these items were not included in the study. For the purpose of this research, the environmental impacts due to the hospital's construction or building materials as well as the manufacturing of large machines within the OR and LDR were not included. With respect to the construction of the hospital, LCA studies are inconsistent (Bilec, Ries et al. 2010). Some existing research has assumed that the impacts of the construction phase are negligible (Junnila and Horvath 2003); others report that environmental impacts associated with construction are underestimated (Hendrickson and Horvath 2000).

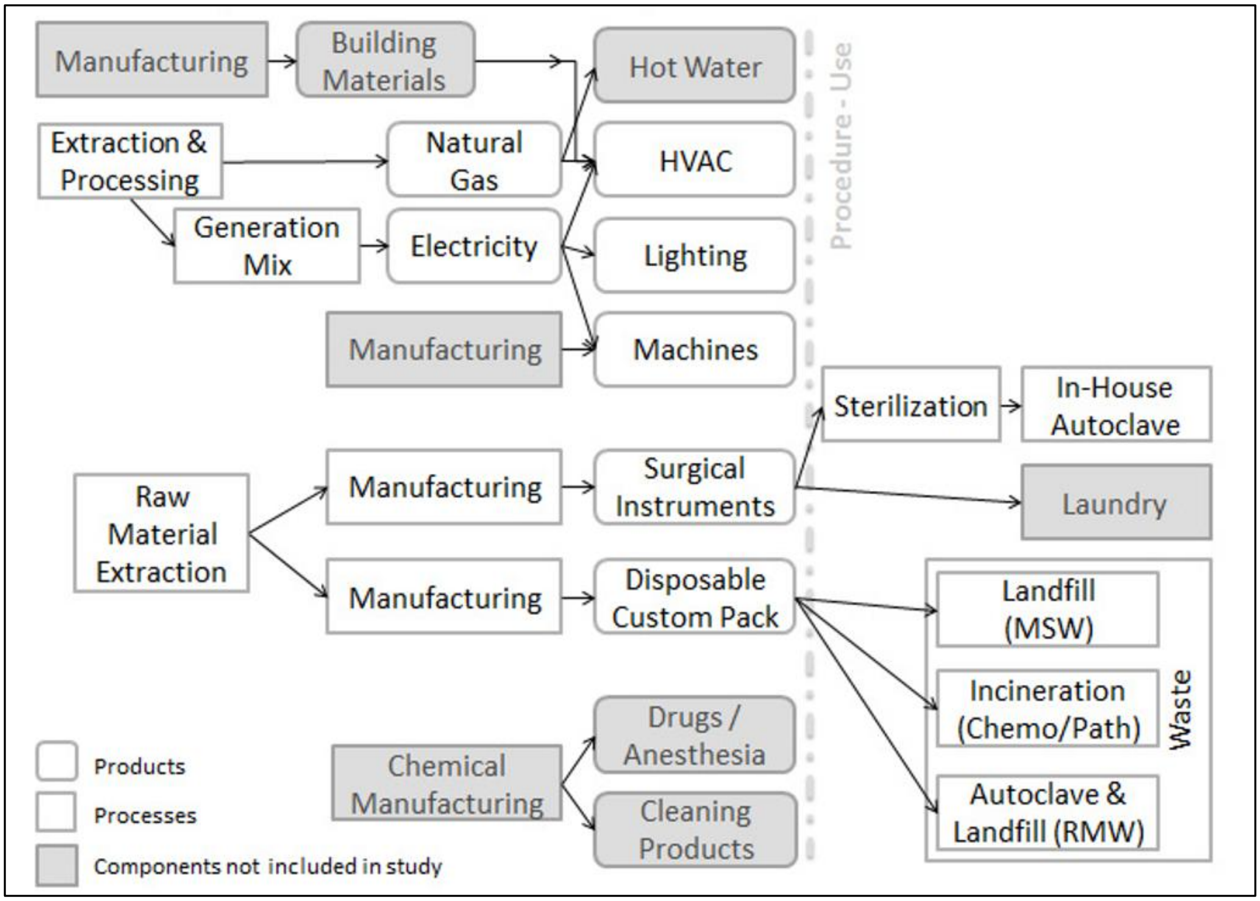


Figure 18: Birth procedure system boundary

To provide system boundaries on the birth itself, this study defined vaginal birth as the expulsion of the infant and placenta only (stage 2 and 3 labor) and cesarean section as the activities occurring door to door during the surgery. This system boundary excluded the labor prior to delivery due to its poorly defined onset, wide variability in duration, location in or out of the hospital, and variability in medical interventions leading up to the birth. Setting this limit on the system boundary limits our conclusions to the birth itself, but also allowed the LCA to be feasible while still providing usable information to assist environmental efforts in our birth center. This system boundary also allowed for a comparison of the birth itself with the understanding that labor prior to delivery and post-birth care can vary dramatically for women in both groups.

Based on a review of approximatley 15,000 births, the duration of vaginal birth used in this study was assumed to be 65 minutes (Janakiraman, Ecker et al. 2010); placental delivery was assumed to be 15 minutes (Jangsten, Mattsson et al. 2011). The ratio of women having their first birth to women who have previously given birth was found to be 40/60 based on Magee's delivery patterns. Assumptions for the cesarean section were based on a door to door time for all comers of 75 minutes, including repeat and primary cesarean (Ismail and Huda 2009). Consideration of anesthetic choices was excluded.

Life Cycle Inventory. Data from the hospital were collected to develop the LCI. Data collection included weighing of disposable custom packs and reusable surgical instrument packs, observing machine electrical consumption, and obtaining information from hospital specifications for lighting and heating, ventilation, and air conditioning (HVAC) parameters. In general, each component was then translated into the appropriate LCI unit process. Various published databases house the unit processes that correspond to a specific product or process, therefore database selection is important. The LCI unit processes were selected based on the following logic: (1) use US based databases (USLCI) (NREL 2010); (2) use the most robust database (ecoinvent) (Frischknecht, Jungbluth et al. 2005); (3) use other database if unit process was not available in either USLCI or ecoinvent. The other databases used when USLCI or ecoinvent were not applicable or available were determined by comparing the physical description and application of the material to the unit process description.

LCI Materials. There are two unique custom packs, a disposable and a reusable, used in both types of birth at our case study hospital. Items in a disposable cesarean custom pack and disposable vaginal birth custom pack were weighed and separated by product material type. A summary of the materials, products, material production databases, and material disposal databases is shown in Table 9. If a product was comprised of more than one material, then the total weight of the product was divided by the number of materials in the product. For example, a cautery tip polisher, 2.6 grams, is made of aluminum grit and polyurethane plastic; therefore, each material was assumed to be 1.3 grams of the total product. This method was used because many of the mixed material products were difficult to disassemble and accounted for a small percentage of the total custom pack. The custom packs were believed to represent the majority of the waste produced during a delivery with the exception of gloves, masks and sutures. These materials were not included in the study as they were considered to represent a small proportion of the waste.

The contents of the disposable custom pack were assumed to have entered Magee's waste streams. Magee calculates that 80% of their waste is disposed of in the Municipal Solid Waste (MSW) stream, and 20% enters the Regulated Medical Waste (RMW) or "Red Bag" waste stream. The MSW from Magee is transported 20 km to a municipal solid waste landfill. RMW from Magee travels approximately 50 km in total, first to an autoclave facility for sterilization and then to the municipal solid waste landfill for disposal. Placentas are disposed of according to state law, which in this case includes transporting them nearly 600 km to an incineration plant located in North Carolina. The LCI databases chosen to represent disposal of individual materials are shown in Table 9. Databases used in waste calculations not shown in this table include: Franklin USA 98 (Franklin Associates Ltd 1998) for transportation of wastes to disposal facilities, ecoinvent system process 2.0 (Frischknecht, Jungbluth et al. 2005) for biowaste incineration to represent disposal of chemo/pathogenic waste, and USLCI 1.6 (NREL 2010) for the electrical consumption of autoclaving RMW. This case study assumed that other waste streams at Magee including recycling, hazardous waste, and electronic waste, were not generated during births.

Table 9: Life cycle inventory of disposable custom packs for birth procedures; RNA = North American geographical code; RER = European geographical code; S = system process

Material	Product Examples	Material Production		Material Disposal		Cesarean Pack (g)	Vaginal Pack (g)
		LCI Database	Database Process Name	LCI Database	Database Process Name		
Cotton	OR towels, lap sponge, gauze	IDEMAT 2001[b]	Cotton fabric I	ecoinvent System Processes 2.0[a]	Disposal, inert material, 0% water, to sanitary landfill/CH S	491.2	110.7
Polyvinyl-chloride (PVC)	Umbilical cord clamp, ear/ulcer syringe	USLCI 1.6[c]	Polyvinyl chloride resin, at plant/RNA	ecoinvent System Processes 2.0[a]	Disposal, polyvinylchloride, 0.2% water, to sanitary landfill/CH S	342.7	36.5
Low-density polyethylene (LDPE)	CSR wrap, gowns, drapes	USLCI 1.6[c]	Low density polyethylene resin, at plant/RNA	ecoinvent System Processes 2.0[a]	Disposal, polyethylene, 0.4% water, to sanitary landfill/CH S	1633.1	281.9
High-impact polystyrene (HIPS)	Needle counter	USLCI 1.6[c]	High impact polystyrene resin, at plant/RNA	ecoinvent System Processes 2.0[a]	Disposal, polystyrene, 0.2% water, to sanitary landfill/CH S	17.3	12.5
Ethylene vinyl acetate	Light handles, needle counter	ecoinvent System Processes 2.0 [a]	Ethylene vinyl acetate copolymer, at plant/RER S	ecoinvent System Processes 2.0 [a]	Disposal, plastics, mixture, 15.3% water, to sanitary landfill/CH S	21.4	12.5
Polypro-pylene (PP)	Trays	USLCI 1.6[c]	Polypropylene resin, at plant/RNA	ecoinvent System Processes 2.0[a]	Disposal, polypropylene, 15.9% water, to sanitary landfill/CH S	38.2	61.1
Polyester/ Rayon	Combine dressing	IDEMAT 2001[b]	Polyester fabric I	ecoinvent System Processes 2.0[a]	Disposal, plastics, mixture, 15.3% water, to sanitary landfill/CH S	17.3	-
Stainless Steel	Cautery Pencil	IDEMAT 2001[b]	X90CrCoMoV17 I	ecoinvent System Processes 2.0[a]	Disposal, aluminium, 0% water, to sanitary landfill/CH S	29.4	-
Aluminum grit	Cautery tip polisher	ecoinvent System Processes 2.0[a]	Aluminum oxide, at plant/RER S	ecoinvent System Processes 2.0[a]	Disposal, aluminium, 0% water, to sanitary landfill/CH S	1.3	-
Paper	Labels, inventory sheet	BUWAL 250[d]	Paper woody C B250	ecoinvent System Processes 2.0[a]	Disposal, paper, 11.2% water, to sanitary landfill/CH S	6.4	-
Poly-urethane (PU) foam	Cautery tip polisher	ecoinvent System Processes 2.0[a]	Polyurethane, flexible foam, at plant/RER S	ecoinvent System Processes 2.0[a]	Disposal, polyurethane, 0.2% water, to sanitary landfill/CH S	1.3	-

Items in a reusable surgical instrument pack for both a cesarean birth and a vaginal birth were weighed and summarized, results shown in Table 10. The reusable surgical instrument packs are largely comprised of stainless steel instruments. However, the reusable packs are wrapped in a disposable wrap and, in the case of the cesarean pack, contain OR towels which are generally disposed of in MSW rather than sterilized and reused. Databases were identified for the production of the materials within the reusable surgical instrument packs. The LCI of the disposable materials within the reusable surgical instrument pack included material production with no allocations for reuse, as well as disposal in MSW stream.

Table 10: Life cycle inventory of reusable custom packs for birth procedures; RNA = North American geographical code; RER = European geographical code; S = system process

Materials	LCI Database	Database Process Name	Cesarean Pack	Vaginal Pack	Assumptions	Data Source
CSR Wrap (g)	USLCI 1.6[a]	Low density polyethylene resin, at plant/RNA	300.0	0.0	Disposable	Weighed
OR Towels (g)	IDEMAT 2001[b]	Cotton fabric I	200.0	-	Disposable	Weighed
Stainless Steel Allocation	**LCI Database**	**Database Process Name**	**Cesarean Pack**	**Vaginal Pack**	**Assumptions**	**Data Source**
Stainless Steel Instruments (g)	IDEMAT 2001[b]	X90CrCoMoV17 I	5054.8	1956.3	Reusable	Weighed
Decontamination Electrical Consumption (kWh/cycle/pack)	USLCI 1.6[a]	Electricity, at grid, Eastern US/US	2.43	2.43	1 cycle per pack	Machine Specs
Autoclave Electrical Consumption (kWh/Cycle/pack)	USLCI 1.6[a]	Electricity, at grid, Eastern US/US	0.14	0.14	1/10 cycle per pack	Machine Specs; Assumptions

The LCI of the reusable stainless steel instruments included the production of the stainless steel, allocated over the anticipated life span of the instruments, as well as the electrical consumption of the cleaning process that occurs in between each use of the instruments. The stainless steel instruments were assumed to have a life span of 10 years, based on repurchasing estimates, and to be sterilized once per day, resulting in 3,650 procedures and sterilization washes per custom pack. This calculation was used to allocate the production costs of the stainless steel instruments per functional unit.

In order to assess the environmental loading from the sterilization process, the electrical consumption of the standard decontamination and autoclaving procedures was also acquired. This data collection included the electrical loading associated with the sterilization process in the "LCI Materials" section because the results of the reusable materials were impacted by the electrical consumption, while HVAC electrical loading was a separate entity. The first step in cleaning the reusable instruments is a decontamination washer. Only the electrical consumption required to run the machine was considered in the LCI, and this included the electricity to power the drying system. The second step is sterilization of the reusable instruments with an autoclave. At Magee, there are 3 industrial size autoclaves that run approximately 10 to 12 times per day. The autoclaves reach a high "over kill" temperature of 274°F to ensure 100% sterilization. For the allocation of the autoclave, only the electricity consumption was considered, which included the control system and vacuum pump for the autoclave. Based on observations at Magee, it was assumed that 10 kits are sterilized during each autoclave cycle.

LCI Energy Consumption. In order to estimate the electrical consumption of the machinery during each birth, the machines in the OR and in the LDR were inventoried, and Magee facilities engineer and hospital staff verified the use of the equipment for each procedure. Researchers recorded machine manufacture, model, medical function, and power rating.

For both the OR and LDR, the fetal heart monitor with printable readouts were not included in the machine load totals because electronic monitoring is generally favored except in rare situations. The patient beds have an electrical input when used to adjust the bed; however, it was not frequently adjusted throughout each birth and was therefore excluded. The television and radio in the LDR were assumed to be off during the birth and also not included. The electrical loading of certain variable-draw machines, such as cauterizing tools, was calculated as a maximum, and therefore conservative, value.

The electrical loading for vaginal and cesarean section births was a summation of the LDR and OR machines' power in watts, Table 11 and Table 12. Lighting information was obtained through the hospital lighting specifications. The machine loading was then multiplied by the study's assumed birth durations- 80 minutes for vaginal birth and 75 minutes for cesarean section birth (Ismail and Huda 2009, Janakiraman, Ecker et al. 2010, Jangsten, Hellstrˆm et al. 2010). The USLCI 1.6 database process "Electricity, at grid, Eastern US/US" was modified to match Pennsylvania's electricity production mix, which is 46% coal, 14% natural gas, 36% nuclear, and 4% renewable energies.

Table 11: Machine data for labor and delivery rooms (vaginal birth)

Machine Information		
Labor and Delivery Room (Vaginal Birth)		
Type of Equipment	Manufacturer	Watts
Travel monitor	WYSE	45.6
Travel Movitors	WYSE	1575
Computer monitor	Planar	144
Unkown	Datascope	36-72
Patient Bed	Hill Rom	816
Epidural Machine	MedPat	4.5
Baby Scale	Detecto	10
TV	Phillips	144
Fetal Monitor	Phillips	n/a
Blanket Warmer	Olypmic Medical	180
Infant Warmer System/ Neontal System	Ohmenda	759

The machine use for the operating room, or the cesarean section birth procedure, was also studied.

Table 12: Machine data for operating rooms (cesarean birth)

Machine Information		
Operating Room (Cesarean Section)		
Type of Equipment	Manufacturer	Watts
Infant Warmer	Datex Ohmeda	7.98
Baby Scale	Olympic	10
ESG: Electrosurgical Generator	Valleylab	800
Anesthesia Machine	Datex Ohmeda / GE Medical	1200
BIS Machine	Aspect	84
Gas Machine	Phillips	45
Bedside Monitor with modules	Phillips	30
Patient Warmer	Cincinnati SubZero	1000
Fluid Warmer	Sims Level 1	115
SCD Machine	Kendall	50
OR Table	Skytron	600
Infusion Pump	Cardinal Health Alaris	150
Gravity Convection Incubator	Precision	100
Computer Screens	Generic	720
Computer Towers	Generic	2340
Power Conditioner	Powervar	252
OR Light System	Skytron	500
Vaporizor	Datex Ohmeda / GE Medical	n/a
Fetal Monitor	Phillips	n/a
Infant Extraction Machine	Gyrus	n/a

In order to attribute the heating, ventilation and air conditioning (HVAC) energy expenditure of a single room in a complex hospital system, a fundamental approach to load calculation was taken. A bin type model was used, which assumed steady-state and calculated heating, cooling and dehumidification load in a specific space. This enabled accurate estimation of HVAC loading while avoiding HVAC system modeling that would create difficulties in allocation. Bin models are well documented and commonly used in systems load calculations and sizing (American Society of Heating 2009). The assumptions and bin energy model information used in this study can be found in Appendix A.

Life Cycle Impact Assessment. Environmental impacts from the inputs and outputs of both birth procedures were calculated using TRACI 2 version 3.01 (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) developed by the US Environmental Protection Agency (EPA) (Bare, Norris et al. 2003b). Impact categories analyzed and reported include global warming, acidification, carcinogenics, non-carcinogenics, respiratory effects, eutrophication, ozone depletion, ecotoxicity, and smog.

3.2.1.2 Birth Study Results and Discussion

The production of the disposable custom packs makes up a significant percentage of the ozone depletion and smog categories, due largely to the production of cotton and manufacturing of polyvinylchloride components in the packs. Waste disposal and transportation are the main contributors in the impact categories of carcinogens, non-carcinogens, eutrophication, and ecotoxicity. Machine, lighting, and HVAC loading contributed the highest percentage for both modes of delivery in the categories of global warming potential, acidification, and respiratory effects categories Figure 19. This was due to the production and consumption of electricity and natural gas required to run the machines, lighting, and HVAC system.

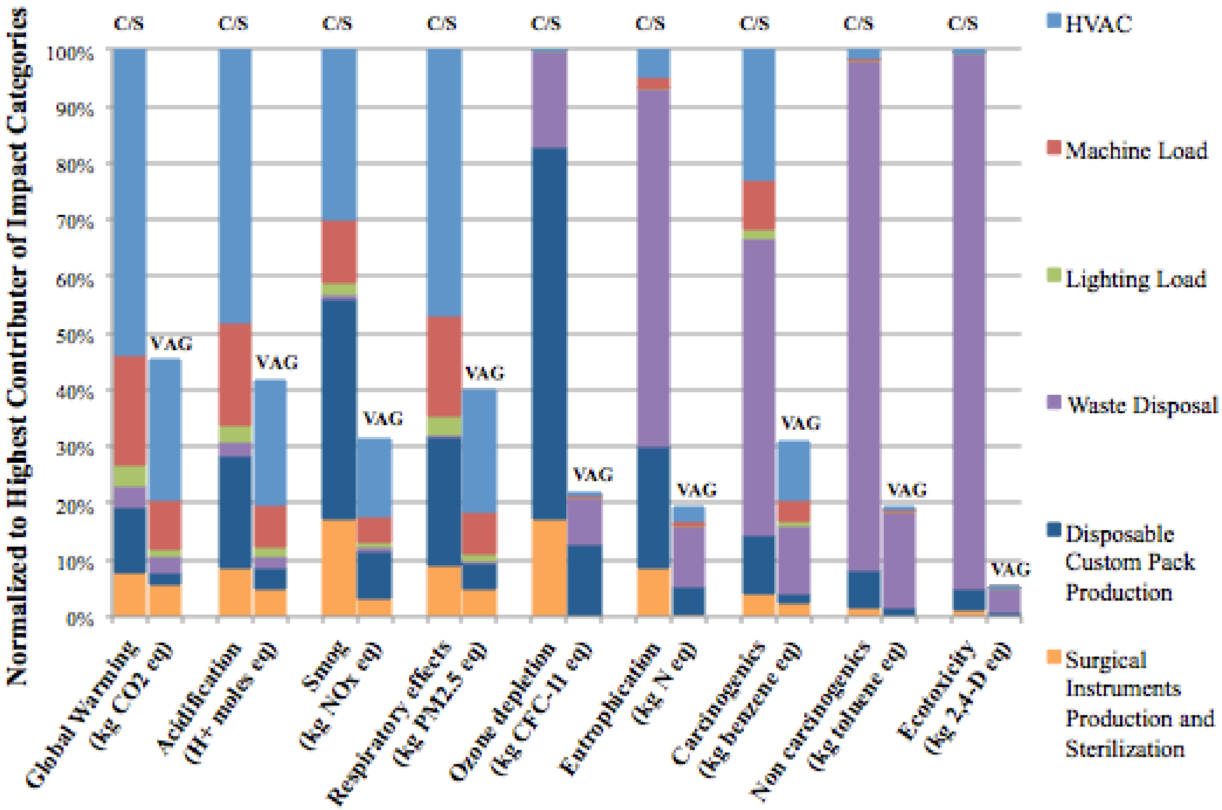


Figure 19: Total results normalized to cesarean birth. C/S = cesarean section; Vag = vaginal birth; HVAC = heating, ventilation, air conditioning

Disposable and Reusable Materials. The production of disposable and reusable materials of both birthing modes is summarized Figure 20. The production of disposable materials contributes the highest in every impact category for the cesarean section birth and five out of nine categories for the vaginal birth. Minimizing any infrequently used materials in the custom pack, and substituting reusable supplies when possible, is a high yield area for intervention. The proportionally greater effects of the vaginal reusable surgical pack are the result of a lesser quantity of disposable materials. While the cesarean section reusable surgical pack requires the same sterilization process, the larger quantity of materials in the cesarean section disposable custom pack minimizes the relative impacts of the reusable instruments in these categories.

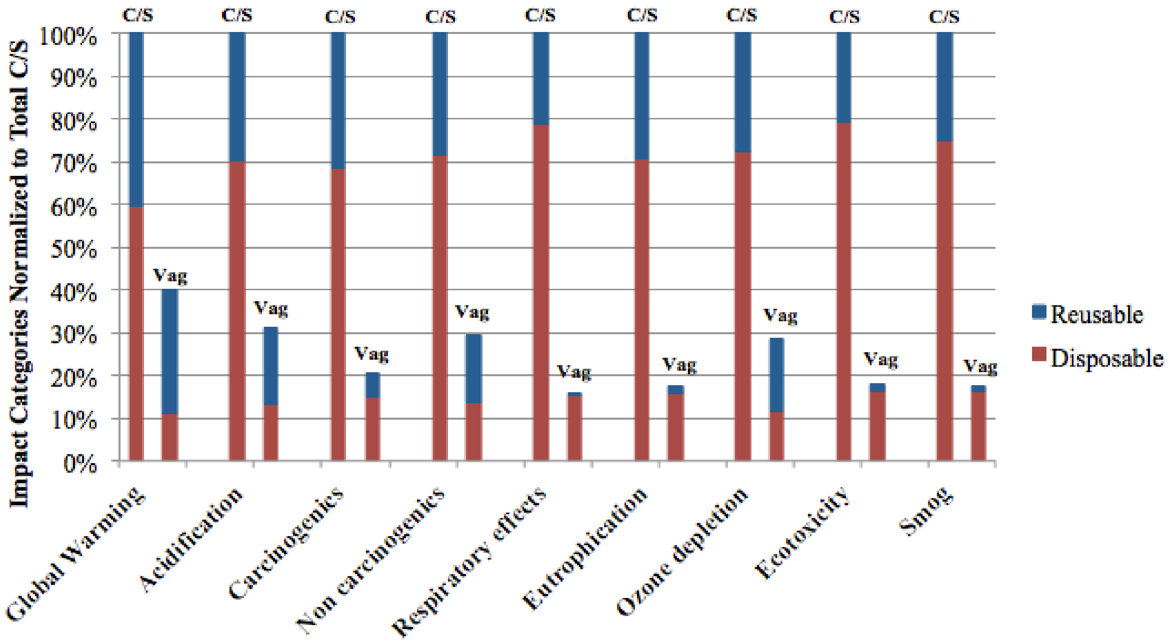


Figure 20: Environmental impact results of disposable and reusable materials normalized to cesarean birth. C/S = cesarean section; Vag = vaginal birth

Significant variations in the assumed lifespan of the reusable surgical packs did not affect overall results. A sensitivity analysis of the assumed 10 year lifespan reveals negligible variation in the relative environmental impacts of reusable stainless steel instruments. Assuming a stainless steel instrument lifespan of 5 years resulted in an overall increase of 0.04% in the environmental impacts relative to the impacts of a 10 year lifespan. An assumed lifespan of 15 years resulted in a 0.1% relative decrease in environmental impacts of the stainless steel instruments. This further supports that the sterilization process, rather than the material production process, is a significant contributor to the environmental impacts associated with the reusable surgical packs.

Of the disposable materials, cotton, LDPE (low density polyethylene), and PVC (polyvinyl chloride) were the most consequential materials in all of the impact categories. Blue OR towels represented 90% of the cotton, gowns and drapes represent 92% of the LDPE, and suction tubing represented 69% of the PVC. Minimizing blue towel use, or substituting a more sustainable material, such as dye-free 100% biodegradable cotton, would lessen the environmental impact of this material. Although the laundry process was not considered in this LCA, as blue towels are typically disposed of in waste, consideration should be given to washing and reusing blue towels given the high environmental burden of producing cotton. The second major category for disposable materials was LDPE plastic, used in gowns and drapes. Reusable gowns and drapes would minimize use of this plastic, but further LCA analysis is needed to help quantify the degree to which this might be expected to lessen environmental impacts. Cost effective alternatives to PVC tubing are being used in Magee's Neonatal Intensive Care Units (NICU's) to avoid neonatal exposure. These alternatives should be further researched and considered for use in the operating room as well.

The results show that the cesarean section birth has a higher environmental footprint compared to a vaginal birth, which is an indication of procedure complexity. The increasing reliance on disposable materials for both procedures contributes to higher levels of hospital waste, which could be diverted through the use of reusable materials. Efforts to reduce reliance on disposable products have the potential to reduce waste and environmental cost. Developing custom disposable packs that eliminate unused supplies, substitute equivalent materials with a lower environmental footprint, and are designed for efficiency is another important target area for environmental efforts.

Waste and Disposal. The total impacts from Figure 19 suggest that waste disposal, which includes transportation and the actual disposal process, contributes the highest percentage to the impact categories carcinogens, non-carcinogens, eutrophication, and ecotoxicity. With the exception of ecotoxicity, these categories are made up of over 60% plastic disposal to landfill, with polyethylene (PE) representing at least half of that number, see Figure 21. PE is a major component, by weight, of both disposable custom packs. The disposal of aluminum from cesarean section custom packs represents over 70% of the ecotoxicity category for cesarean section waste transportation and disposal. The RMW waste at Magee is landfilled at the same site as the MSW waste; thus, this transportation related impact is combined in Figure 21. Transportation of waste does not contribute significantly to the four impact categories examined in Figure 21 as transportation usually results in CO_2 emissions associated with global warming potential and other impact categories not examined.

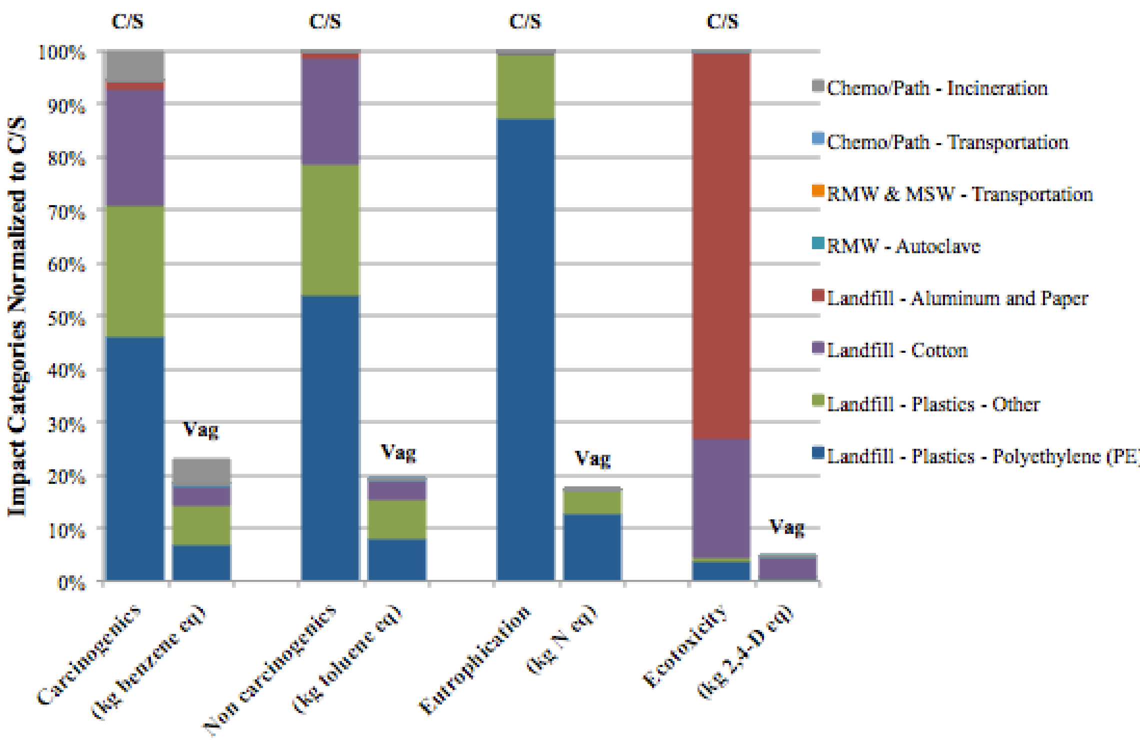


Figure 21: End-of-life impacts for cesarean section and vaginal birth products; C/S = cesarean section; vag = vaginal birth

There is no comprehensive US LCI database for waste disposal and for this reason ecoinvent 2.0 was used in this study (Moreno, Weidema et al. 2011). Ecoinvent uses data from Switzerland and includes short-term emissions to air from incineration of landfill gas and leachate as well as treatment of leachate in wastewater treatment systems and municipal incineration of sludge. It is not standard practice in the US to incinerate municipal solid waste sludge, so this category may overestimate US landfill emissions. Ecoinvent 2.0 also accounts for long-term emissions to groundwater after the base lining of the landfill fails, resulting in the allocation of a range of environmental impacts to a specific material type. For example, leaching of heavy metals into groundwater is included in the impacts from cotton disposal when cotton itself contains no heavy metals. For future work, available literature should be used to create more accurate waste disposal models (Barlaz 2006, Gentil, Damgaard et al. 2010).

Machines, Lighting, and HVAC. Because of the associated impacts with consuming fossil fuels, the machines, lighting, and HVAC loading contributed the highest percentage to global warming potential, acidification, and respiratory effects for both modes of delivery. The HVAC system is in operation 24 hours a day, regardless of whether or not a birth is occurring and would, therefore, be expected to have an even higher relative impact when looking at the entire birthing unit over time. Optimizing the HVAC, instituting set back programs when the room is not in use and basing the number of required air turnovers on evidence in the infectious disease literature would be high yield areas for intervention, resulting in significant environmental and cost savings. Implementing occupancy sensors and low energy lighting could also reduce the amount of electricity consumed and associated impacts. Further analysis of the HVAC system can be found in the supplementary material.

3.2.1.3 Birth Study Conclusion

For all births, the processes contributing the most to environmental impacts were energy consumption due to HVAC, the end of life impacts of the disposable custom packs, and the production of the disposable custom packs. Therefore strategies should target these categories to reduce the overall the environmental impact of birthing options.

The production of both the disposable custom pack and reusable surgical pack for the cesarean section resulted in higher environmental impacts than the disposable and reusable materials in the vaginal birth packs. Understanding the differences in environmental impacts between disposable and reusable materials is an important consideration when evaluating the assembly of the custom packs and the necessity of certain materials and products contained within them. Future studies of the products and material composition in the disposable packs will further assist in preferred purchasing and environmentally conscious hospital decision-making.

For consistency in this research, standard LCI databases were used to represent waste impacts, but in future work, the LCI processes should be refined using cite specific data to more accurately portray end of life of medical materials. In addition to waste audits, energy auditing of medical equipment may increase the accuracy of LCA results.

3.3 ENHANCED HEALTHCARE LCAS

The work presented in Section 3.3 builds off of the results found in Section 3.2. After completing the LCA study of two different birth procedures, it was evident from the results that disposable products have significant environmental impacts. As such, it was important to delve further into the use of disposable products in the healthcare industry and develop strategies to streamline disposable products and provide environmentally preferred alternatives. The work presented in Section 3.3 uses LCA and design for the environment (DfE) principles in tandem to illustrate streamlining efforts of disposable custom packs that could be replicated for all healthcare procedures. Understanding how the healthcare industry could utilize LCA and other environmental strategies such as DfE in a realistic application was fundamental to answering the second research question "what tools and strategies are needed to advance LCA in the healthcare industry?" This work was published in the *Journal of Cleaner Production* as "Sustainable Healthcare and Environmental Life-Cycle Impacts of Disposable Supplies: A Focus on Disposable Custom Packs" (Campion, Thiel et al. 2015).

3.3.1 Sustainability Healthcare Tools

Design for the environment (DfE) provides a suite of sustainable strategies for designers, engineers, and organizations to consider. Life cycle assessment is often used in concert with DfE to quantify the environmental impacts and trade-offs of DfE strategies. LCA has become more recognized over the years, as evidenced by ISO 14040 standards and published reports (ISO 1997a, Baumann and Tillman 2004, Birch, Hon et al. 2012). For this study, DfE strategies were applied to the disposable custom packs and quantified the environmental changes through LCA, developing recommendations that can be applied to custom packs in general.

Design for the Environment. The term DfE emerged in the early 1990's, around the same time as environmental management ISO 14000 standards were established. DfE developed from manufacturers' desire to better understand, manage, and reduce the environmental impacts throughout the manufacturing process (Fiksel 1996, ISO 1997a). DfE in a broader sense is a set of principles that outline the necessary steps to design and develop environmentally responsible products and processes (Fiksel 1996).

DfE strategies are applied during the design phase of a product (Lagerstedt, Luttropp et al. 2003, Pujari 2006, González-García, Lozano et al. 2012). One study examined the functional profile of radio equipment, highlighting that there are multiple demands in product development, such as environmental, profitability, political, and safety (Lagerstedt, Luttropp et al. 2003). Using DfE strategies helped frame the goals of the product in this particular study, reducing environmental impacts while increasing product functionality (Lagerstedt, Luttropp et al. 2003). One such study addressed the marketability of eco-products, applying DfE strategies to incorporate several functional demands and multidisciplinary representation such as designers, engineers, marketers, and investors (Pujari 2006). A more recent study used both DfE and LCA to address the environmental impacts and alternatives for a wooden wall product (González-García, Lozano et al. 2012). First, an LCA of the wooden wall product was conducted, defining the processes and material flows of the product and associated environmental impacts. DfE strategies were then applied based on the LCA results, ensuring that the focal areas had maximum output potential (González-García, Lozano et al. 2012). Explicitly using DfE strategies for product development can increase the number of product alternatives. In the healthcare industry, DfE strategies could address current challenges such as the use of disposable materials or waste management by applying life cycle thinking and developing alternative options.

3.3.2 Custom Pack Study

One research area in need of further study is the use of disposable and single-use materials in healthcare delivery. The shift toward disposable materials was initially driven by a variety of factors including but not limited to the potential for infection control, convenience, and cost. The current use of single-use disposables in healthcare, however, has become costly, wasteful, and to some extent, unnecessary (Karlsson and Pigretti Öhman 2005, Tudor, Barr et al. 2007, PGH 2008, Swensen, Kaplan et al. 2011). Disposable materials in the US contribute to healthcare's estimated production of 33 pounds of waste per patient bed per day or approximately 5.9 million tons of waste each year (PGH 2008). Proper waste management programs and source-reduction strategies could save hospitals up to 55% in waste hauling costs (Zimmer and McKinley 2008). The production, use, and waste generation of disposable materials provide opportunities for improvements within healthcare, as the industry attempts to reduce expenditures.

To address the use of disposable materials in healthcare, this study analyzed the life cycle environmental impacts of disposable custom packs. A disposable custom pack is a set of sterile, disposable products prepackaged for a specific procedure with the aim of reducing time, errors, and contamination risk. Specifically, a custom pack used to deliver a child was investigated; see Figure 22. Once a custom pack is opened, every item is discarded, even if an item is not used. Clinicians have the ability to add items to a pack, yet often find it more difficult to remove unnecessary or obsolete items. This tends to result in inflated packs with extraneous items. In 2010, there was over 51 million inpatient procedures performed in the US (CDC 2010). Because at least one disposable custom pack is used for every procedure, a few excess products in each pack could significantly contribute to unnecessary waste (economic and environmental) in the healthcare industry. To determine the potential design and impact of sustainable custom packs, design for environment (DfE) principles and environmental life cycle assessment (LCA) were applied to the *disposable* custom packs analyzed in this study. It should be noted that there are often *reusable* custom packs also associated with most procedures. A reusable custom pack is a set of sterile, reusable products, typically stainless steel instruments or cotton linens that are cleaned via the hospital's central service autoclaves or commercial laundry facilities. The reusable custom pack used to deliver a child was not considered in this study.

Figure 22: Examples of opened disposable custom packs

3.3.2.1 Custom Pack Study Methodology

This study analyzed custom packs from 12 US hospitals, 2 Thai hospitals, and 1 nonprofit medical supply organization. The custom packs are prepared and used for traditional vaginal birth; there are over 2.6 million vaginal deliveries annually in the US (CDC 2013). Requests for disposable custom packs were sent to gynecological departments and 15 custom packs were received Table 13. Participation in this study was voluntary and no payment was issued. Products within each custom pack were separated, weighed, and categorized according to the constituent materials. Materials used in each product were identified through manufacturing data and previous studies (Campion, Thiel et al. 2012). The environmental impact from the production, use, and disposal of each custom pack was analyzed using process life cycle assessment (LCA). The contents and LCA results for each custom pack were compared and design for the environment (DfE) strategies were utilized to develop recommendations for creating a streamlined custom pack in conjunction with new LCA results.

Table 13: Overview of disposable custom packs and associated hospital information

ID #	Hospital Region	Births per Year	Pack Weight (kg)	Sustainability Initiatives
US 1	Midwest	1,900	1.760	LEED Certified expansion
US 2	Mid Atlantic	800	1.524	Green Team
US 3	South Atlantic	14,400	1.462	n/a
US 4	Pacific Northwest	700	1.428	Green Team
US 5	Pacific Northwest	2,300	1.284	Practice Greenhealth Member; Green Team
US 6	Mid Atlantic	1,500	1.224	Green Team
US 7	Pacific Northwest	4,900	1.152	n/a
US 8	Mid Atlantic	500	1.132	Green Team
US 9	Mid Atlantic	1,500	1.126	Green Team
US 10	Mid Atlantic	10,200	1.034	Practice Greenhealth Member; Green Team; LEED Certified expansion
US 11	Mid Atlantic	300	1.002	Green Team
US 12	New England	8,500	0.954	LEED Certified expansion
Thai 1	Thailand	<800	0.955	n/a
Thai 2	Thailand	800	0.122	n/a
GL	Global Links	n/a	0.072	Medical surplus organization

Life Cycle Assessment. The material compositions of the products were analyzed using life cycle assessment (LCA). For the first stage, the goal of the LCA was to understand the environmental impacts of the materials and products within each of the custom packs and identify trends, areas for improvement, and streamlining recommendations. The functional unit of the study was one disposable custom pack and the system boundary included raw material extraction, production, use, transportation, and end-of-life (EOL), as shown in Figure 23. Each disposable custom pack analyzed is considered its own unique functional unit, as you cannot explicitly compare each pack interchangeably in relation to a hospital's individual vaginal birth procedure. In other words, every hospital has its own set procedure for a vaginal birth – standard disposable custom pack, reusable instruments, incidentals, policies, etc. – and while attempting to understand the exclusive use of disposable custom packs, it was clear that a custom pack designed for Hospital A may be insufficient or too sufficient in relation to the needs of Hospital B.

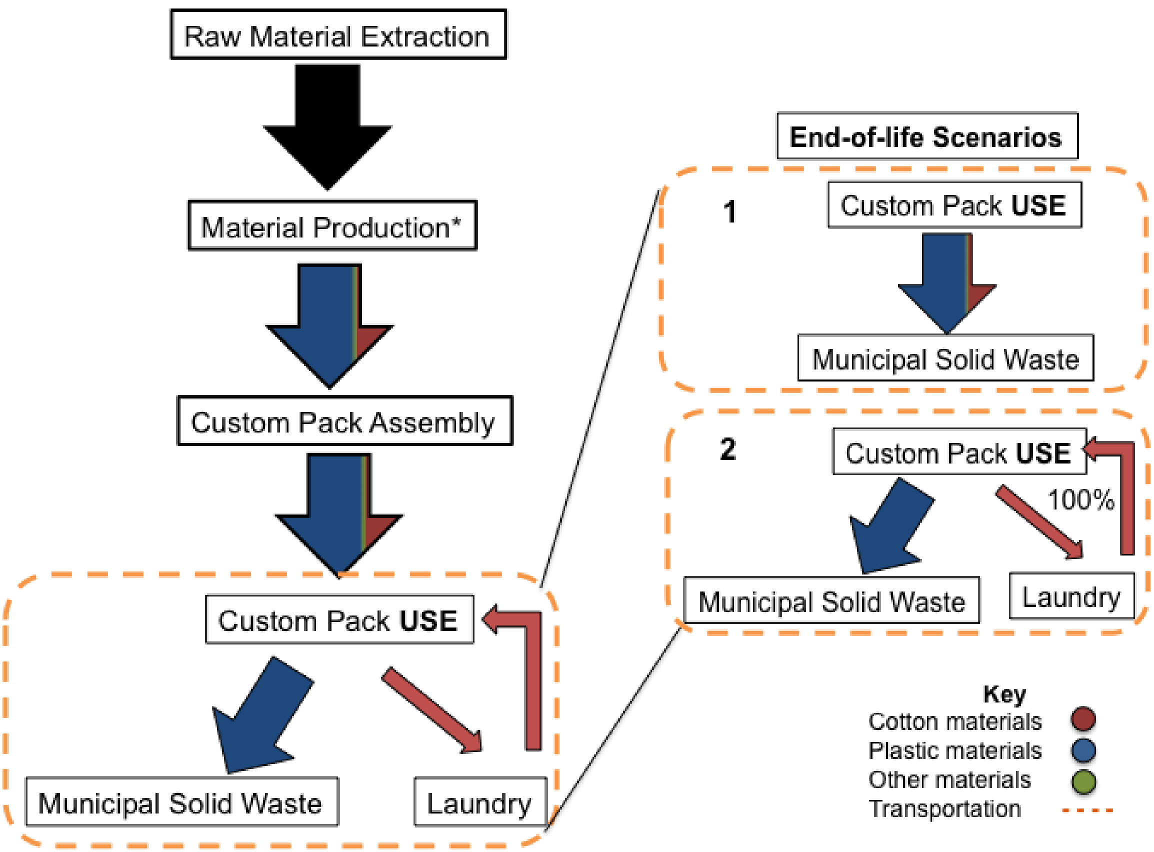


Figure 23: Process flow diagram of custom packs study: from raw material extraction to production, assembly, and use. End-of-life (EOL) scenarios are modeled as either (1) 100% municipal solid waste (MSW) of all products or (2) Laundering of reusable cotton and MSW for all other products; Transportation scenario includes EOL impacts and transportation from hospital to MSW or Laundry; Arrow size is representative of material weight in pack; *Note - an overview of all unit processes used can be found in Supplemental Information

Two EOL scenarios were utilized in the LCA model, a municipal solid waste (MSW) or landfill scenario, and a laundry reuse of OR towels scenario (all other materials to MSW). The first EOL is 100% municipal solid waste (MSW) disposal of the custom packs, assuming all of the products were opened and used once. Other hospital waste streams were not considered based on previous literature, which concluded that the majority of waste was MSW as opposed to regulated medical waste, though it is acknowledged that the EOL of disposable custom packs depends on the hospital's interpretation of medical waste definitions and may vary by institution (Campion, Thiel et al. 2012, Thiel, Eckelman et al. 2015). The second EOL scenario separates the cotton towels for laundering and reuse in other hospital departments (such as janitorial or housekeeping), while the rest of pack products were disposed of in MSW.

The second stage of the LCA, life cycle inventory, quantified associated emissions by matching each material found in the custom pack with a specific material or product database. The manufacturing of each material was considered representative of the pack product. For example, the unit process used for cotton is described as "textile, woven cotton, at plant". This study gave preference first to the ecoinvent database, second to USLCI database, and third to the Industry Data database, due to the robustness and availability of the unit processes; an overview of the unit processes can be found in Table 14 (Frischknecht 1996, FranklinAssociates 1998, PlasticsEurope 2003, Frischknecht and Rebitzer 2005). Authors have used these unit processes in previous healthcare studies (Campion, Thiel et al. 2012). The LCI includes a robust dataset of all intermediate goods and service inputs, such as energy consumption, materials used, and equipment utilized, for each unit process selected (Weidema, Bauer et al. 2013). Due to proprietary information, material identification was provided without country of origin;

therefore, as is common practice in LCA, missing data defaulted to available data in public and peer-reviewed sources.

Table 14: Life Cycle Inventory for Custom Pack LCA

	Product	Database	Unit Process	Geography
Materials	Gowns	ecoinvent	Polypropylene, granulate, at plant/RER U	Global
	Towels	ecoinvent	Textile, woven cotton, at plant/GLO U	Global
	Hard Plastic	ecoinvent	Polyethylene, HDPE, granulate, at plant/RER U	Europe
	Soft Plastic	ecoinvent	Polyethylene, LDPE, granulate, at plant/RER U	Europe
	Suction Bulbs	econivent	Polyvinylchloride, at regional storage/RER U	Europe
	Needle Counter	USLCI	High impact polystyrene resin, at plant/RNA	North America
	Needle Counter	ecoinvent	Ethylene vinyl acetate copolymer, at plant/RER U	Europe
	Paper	ecoinvent	Kraft paper, bleached, at plant/RER U	Europe
	Needle Counter	ELCD	Stainless steel hot rolled coil, annealed & pickled, elec. arc furnace route, prod. mix, grade 304 RER S	Europe
	Vacutainer	ecoinvent	Packaging glass, white, at plant/RER U	Europe
	Gloves	ecoinvent	Latex, at plant/RER U	Europe
Laundry & Waste	Landfill	ecoinvent	Disposal, municipal solid waste, 22.9% water, to sanitary landfill/CH U	Switzerland
	Diesel Truck	USLCI	Transport, combination truck, diesel powered/US	US
	Electricity	USLCI	Electricity mix/US U [1kWh]	NW PA, US
	Natural Gas	USLCI	Natural gas, combusted in industrial boiler/US [1m3]	US
	Steam	Industry Data 2.0	On-site steam average E [1 kg]	Industry
	Disinfection	USLCI	Acetic acid, at plant/kg/RNA [1kg]	North America
	Disinfection	ecoinvent	Hydrogen peroxide, 50% in H2O, at plant/RER U [1kg]	Europe
	Alkalis	USLCI	Sodium hydroxide, production mix, at plant/kg/RNA [1 kg]	North America
	Neutralizer	USLCI	Fluosilicic acid, 22% in H2O, at plant/US U [1 kg]	US

The third stage, life cycle impact assessment (LCIA), utilized the US EPA's TRACI (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) 2v4.00 for 9 impact categories and Cumulative Energy Demand (CED) via ecoinvent 2.1 for the embodied energy of the custom packs (Bare 2002, Bare, Norris et al. 2003a, Goedkoop and Oele 2004). TRACI classifies each LCI dataset as a life cycle stressor (land use, water use, chemical emissions, or fossil fuel use) and then characterizes each stressor as a mid-level impact category (ozone depletion, global warming or green house gas emissions, acidification, eutrophication, smog, carcinogens, non-carcinogens, respiratory effects, ecotoxicity) (Bare, Norris et al. 2003a).

Unfortunately, water use, which has considerable impact on the environment, has not yet been characterized at this time in TRACI (Bare, Norris et al. 2003a). SimaPro v8 and ecoinvent v3.0 have recently released water consumption inventory, yet they were released after this analysis was conducted (Weidema, Bauer et al. 2013).

End-of-Life. In this study, a majority of disposable custom packs contained sterile cotton towels. While many facilities dispose of these towels after one use, they *can be* laundered via standard hospital linen, ready for reuse. The towel typically is not returned to a sterile custom pack, but rather is utilized as a cleaning towel within the hospital or other second party. A US commercial laundry process and facility was modeled to estimate the impacts of towel reuse and is shown as EOL Scenario 2 in Figure 23. For this LCA analysis, it was assumed that all hospitals used this same laundry process. Despite on-site visits to commercial laundry facilities, the commercial laundry process for healthcare presented modeling challenges due to limited data exposing an understudied need in LCAs of the healthcare industry.

To develop the commercial laundry model, researchers first identified the local commercial laundry facility used for Western PA hospitals and gathered information. This included touring the facility, learning about truck times and routes for typical hospital locations and drafting the 18-chamber batch process: chemical additive locations, typical course for certain items (sheets are washed, pressed, ironed, then folded while towels are washed, pressed, dried, folded), depicted in Figure 24.

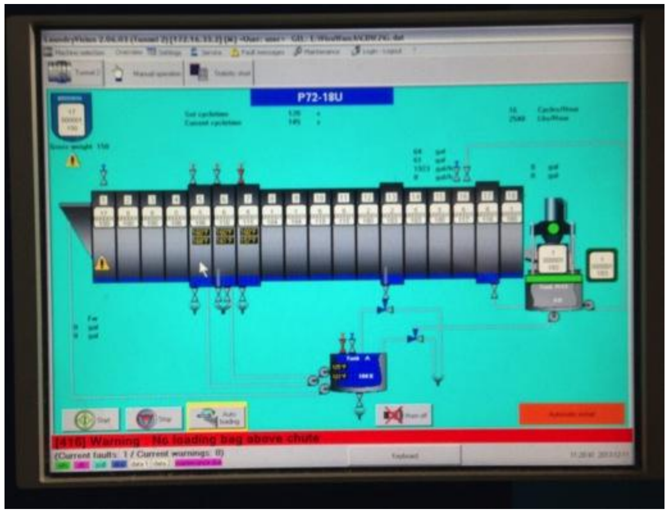


Figure 24: Automated system tracks laundry in each chamber. Includes the load's linen type, the quantity (weight), the generic source (hospital or nursing home, etc.), and inputs to each system; quantity of water, solvents, and temperature are determined by linen type and weight (from industry tour)

The goal and scope of the laundry was to identify the laundry process layout and quantify the impacts of the functional unit, 1 load of laundry at 59kg. For life cycle inventory, it was important to gather data on the current laundry facility Magee primarily uses. The machine information modeled was cross-referenced with industry specs, the electrical consumption was tailored to the Western PA electricity mix, the chemical wash was estimated from published reports and chemical MSDS, and the transportation distance was measured via Google Maps from Magee to their commercial laundry facility (Fijan, Fijan et al. 2008, Altenbaher, Šostar Turk et al. 2011, Overcash 2012, ACI 2013, DOE 2013). An overview of the machine layout and associated energy consumption is shown in Figure 25. For life cycle impact assessment, unit processes were chosen from the ecoinvent database, the USLCI database, and the Industry 2.0 database, shown in Table 14. The LCA calculated the impacts for 1 load (59 kg) of laundry and then delineated that to represent the impacts of 4 towels (the average for the US custom packs), which is approximately 0.33 kg. The building energy consumption was not included in the calculation and it was assumed that laundry machines had a 20-year life span.

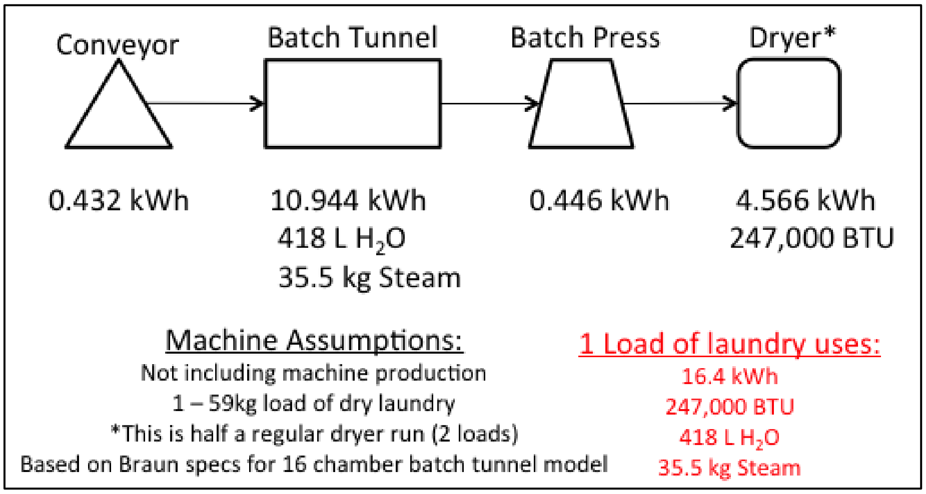


Figure 25: Process flow diagram of laundry machine layout with consumption values (Braun 2013)

Design for the Environment. For this study, three DfE strategies were utilized, as described in Figure 26. The first strategy, Design for Dematerialization, aims to reduce the total amount of materials used (in this case, products within the custom pack), therefore reducing energy and raw materials (Fiksel 1996). The second strategy, Design for End-of-Life, aims to recover, reuse, or recycle the materials utilized throughout the product's life cycle and reduce energy and waste (Fiksel 1996). The final strategy, Design for Capital Protection and Renewal, aims to ensure the safety, integrity, and efficacy of the product while maintaining a sustainable and safe environment for the human, natural, and economic resources needed; a driving factor in product selection for most healthcare institutions (Fiksel 1996). This research has made it clear that hospitals often need help with established processes for data driven decision-making. Therefore, this study interprets DfE in a much broader sense than its traditional application to demonstrate how DfE strategies can be readily implemented in the healthcare industry.

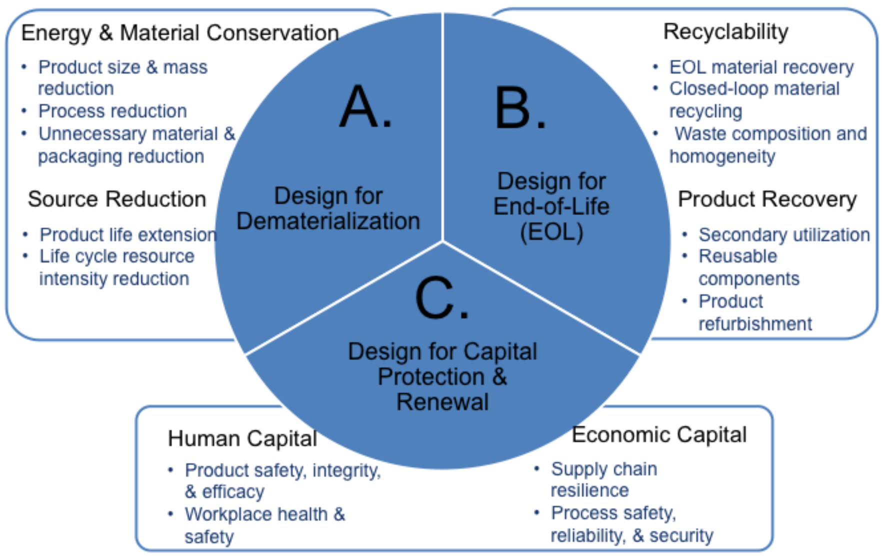


Figure 26: Design for the Environment strategies used in this study adapted from (Fiksel 1996)

3.3.2.2 Custom Pack Study Results and Discussion

Baseline Custom Pack Results. An overview of the participating medical facilities and the overall weight of their custom packs are shown in Table 13. The overall and component weights of all 15 custom packs are shown on the right columns and right axes of Figure 27 and Figure 28. The custom packs in these figures are listed by order of descending total weight. The average weight for the 12 US vaginal birth custom packs was 1.25kg with polypropylene composing an average 58% of the total pack weight. Gowns, drapes, and blue wrap (the material used to wrap sterilized products) in most hospitals are made of a polypropylene fabric. Cotton, typically used for OR towels, gauze, and laparotomy pads, was the second most prevalent material by weight at

0.027 kg or 20% of pack weight on average. The “Thai 1” pack contained a significant amount of local *saa* paper, located in the ‘other’ category, which is used for fluid absorption in place of cotton towels. The unit process for paper was used to model impacts from *saa* aw well as traditional paper across all custom packs; therefore, the environmental impacts for the local *saa* paper may be over estimated.

LCA Results. Ten environmental impacts resulting from the production, use, and disposal of the custom packs were examined There is a similar trend among all custom packs in that the cotton production had the highest environmental impacts, due to intense production processes. The following figures represent the LCA results for the materials and products within each of the US custom packs collected.

First, greenhouse gas emissions and eutrophication are presented. The emission of greenhouse gases to the atmosphere causes a rise in global temperatures, similar to the greenhouse effect (EPA 2008c). Eutrophication is the phenomena where increased levels of nutrients, typically nitrogen and phosphorus, run off into lakes, streams, and rivers. As the nutrient pool, there is an increased level of algae blooms to the point where the algae cover a significant surface area of the water. Over time, the algae prevent oxygen from penetrating the water, therefore killing off any aquatic species below the algae blooms. Also, eutrophication interrupts traditional drinking water systems, harming community drinking water (Bare, Norris et al. 2003a).

Figure 27 shows the GHG emissions of all custom packs, in descending order by pack weight. The quantity of cotton in the custom packs was the determining factor for the highest value of GHG emissions, which was almost 17.5 kg of CO_2 equivalents or 88% of Pack 1. The hospital that submitted Pack 10 conducted a streamlining effort in 2010, and their primary goal was reducing total pack weight. They focused on polypropylene because it was the majority material by weight, but the LCA results show that the environmental impacts of cotton, a material comprising less of the pack by weight, may result in greater environmental impacts than other, more common materials. This supports the need for LCA incorporation into streamlining efforts.

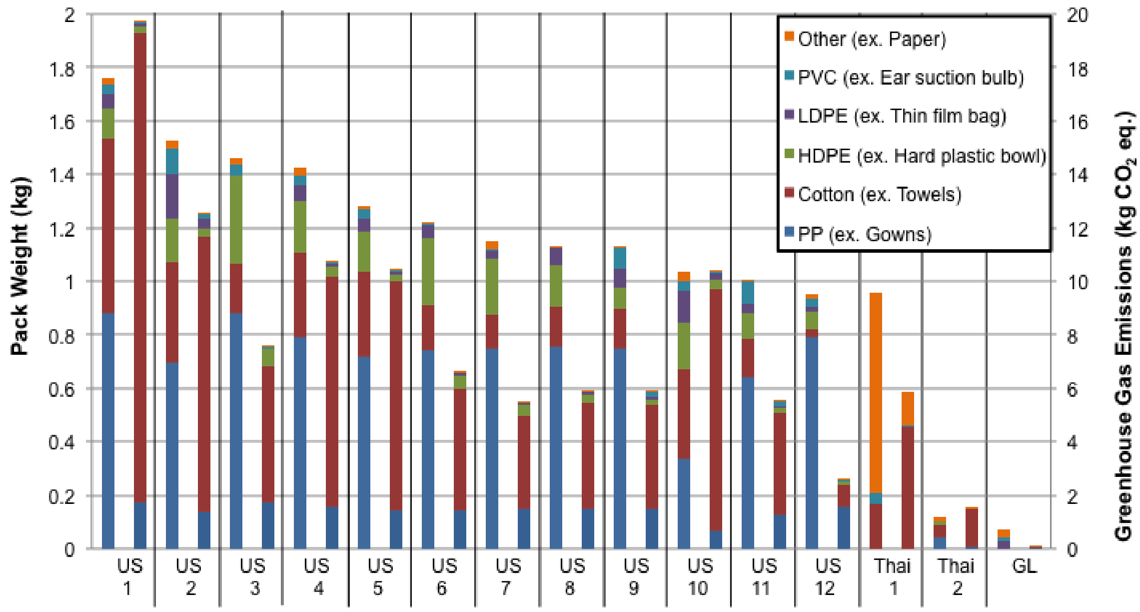


Figure 27: Weight (left column) and greenhouse gas emissions (right column) of custom packs by material composition. Packs listed in descending order by weight; PVC = polyvinyl chloride; LDPE = low density polyethylene; HDPE = high density polyethylene; PP = polypropylene; GL = Global Links; *Note – each custom pack is specifically designed for their respective hospital, as described in Section 2.1*

Figure 28 also demonstrates that cotton has higher eutrophication impacts than polypropylene. The LCA results conclude that single-use cotton products made from traditionally grown cotton have significant impacts on the environment. It is estimated that the agricultural production and textile manufacturing of 1 kg of cotton in US can produce upwards of 9 kg of CO_2 equivalents, use approximately 130 MJ of energy, and consume almost 19 m^3 of water (Chapagain, Hoekstra et al. 2006, Cartwright, Cheng et al. 2011, Pruden 2012).

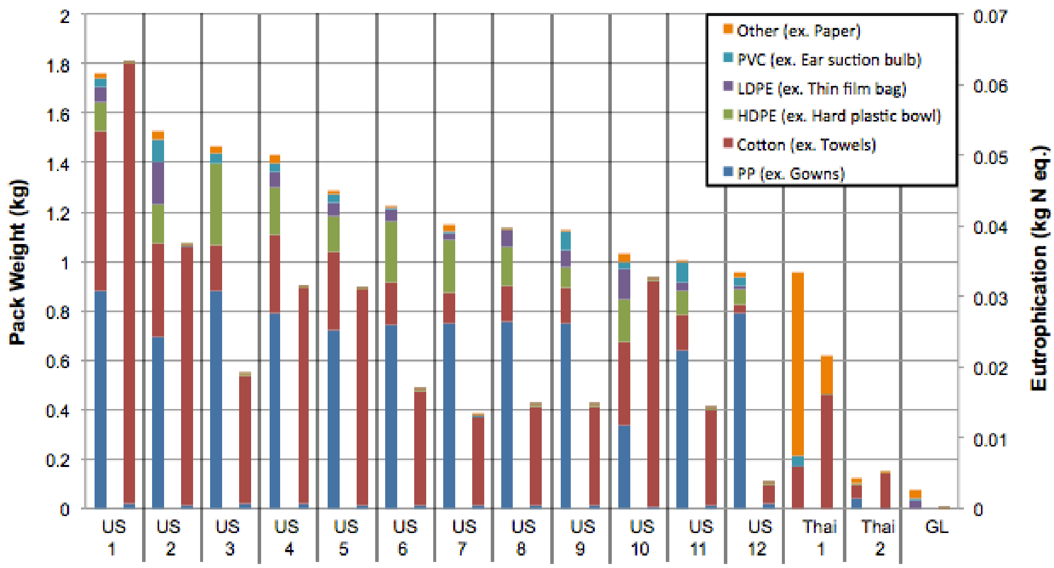


Figure 28: Weight (left column) and eutrophication impacts (right column) of custom packs by material composition. Packs listed in descending order by weight; PVC = polyvinyl chloride; LDPE = low density polyethylene; HDPE = high density polyethylene; PP = polypropylene; GL = Global Links; *Note – each custom pack is specifically designed for their respective hospital, as described in Section 2.1*

Ozone depletion, Figure 29, describes the depletion of ozone primarily from atomic halogens (CFC's), also known as refrigerants (Bare, Norris et al. 2003a).

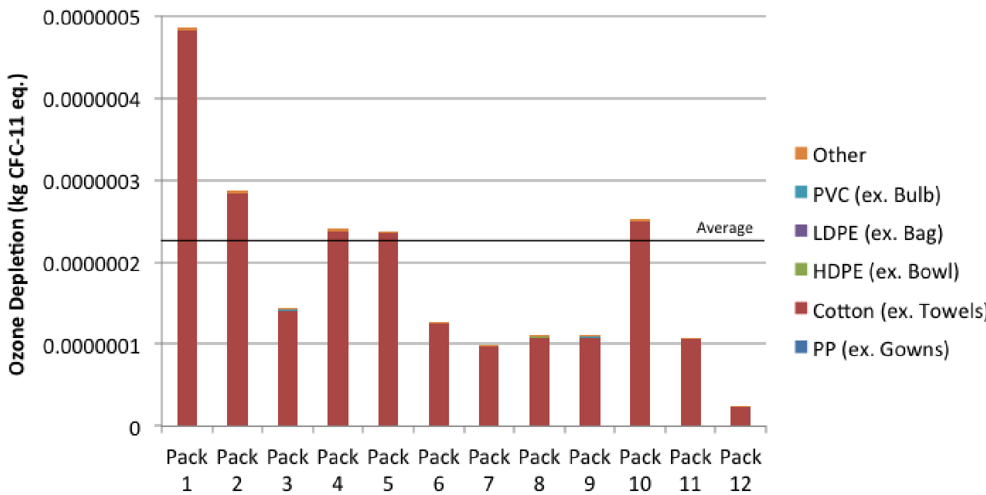


Figure 29: Ozone Depletion; PVC = polyvinyl chloride, LDPE = low-density polyethylene, HDPE = high-density polyethylene; PP = polypropylene

Smog, Figure 30, creates a haze that pollutes the atmosphere, typically from NO_x and SO_x compounds emitted from exhaust pipes (Bare, Norris et al. 2003a).

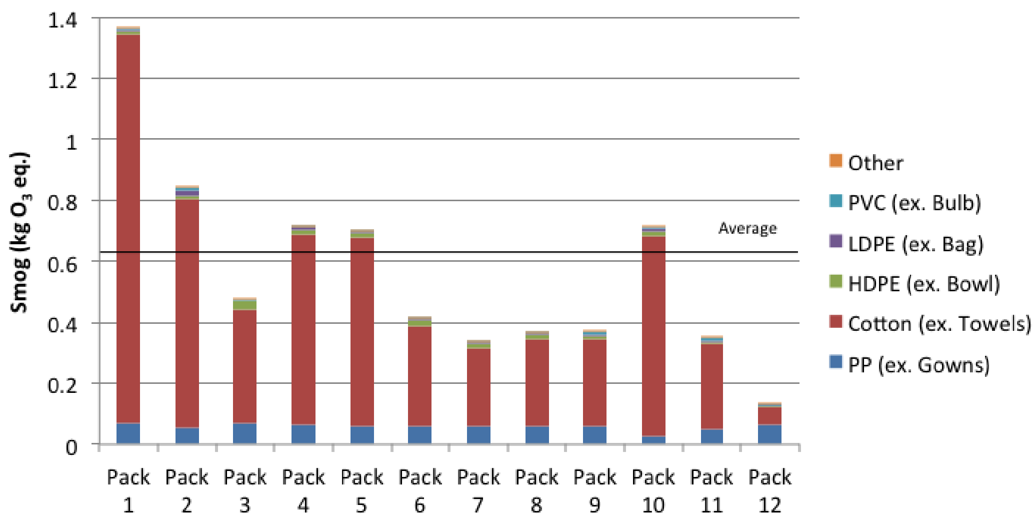


Figure 30: Smog; PVC = polyvinyl chloride, LDPE = low-density polyethylene, HDPE = high-density polyethylene; PP = polypropylene

Acidification, Figure 31, refers to increased levels of the hydrogen ion (H+), due to the addition of acids or other compounds in the environment. The acidifying compounds, most notably NO_x and SO_x, mix with the natural elements such as rain, snow, or dust, and cause damage to the built environment, bodies of water, and various plants and animals (Bare, Norris et al. 2003a).

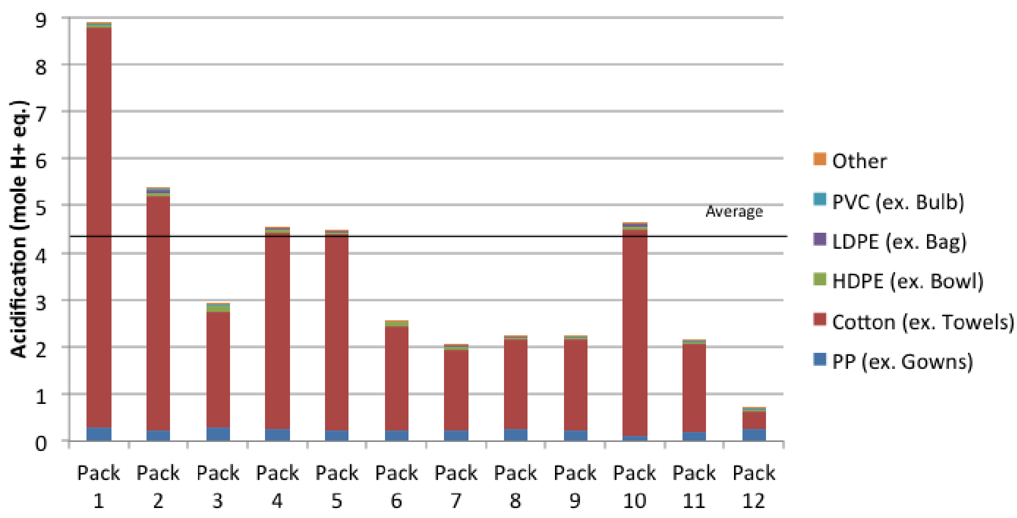


Figure 31: Acidification; PVC = polyvinyl chloride, LDPE = low-density polyethylene, HDPE = high-density polyethylene; PP = polypropylene

Carcinogens, Figure 32, are human health impacts that have an increased change of relating to cancer-like illnesses (Bare, Norris et al. 2003a).

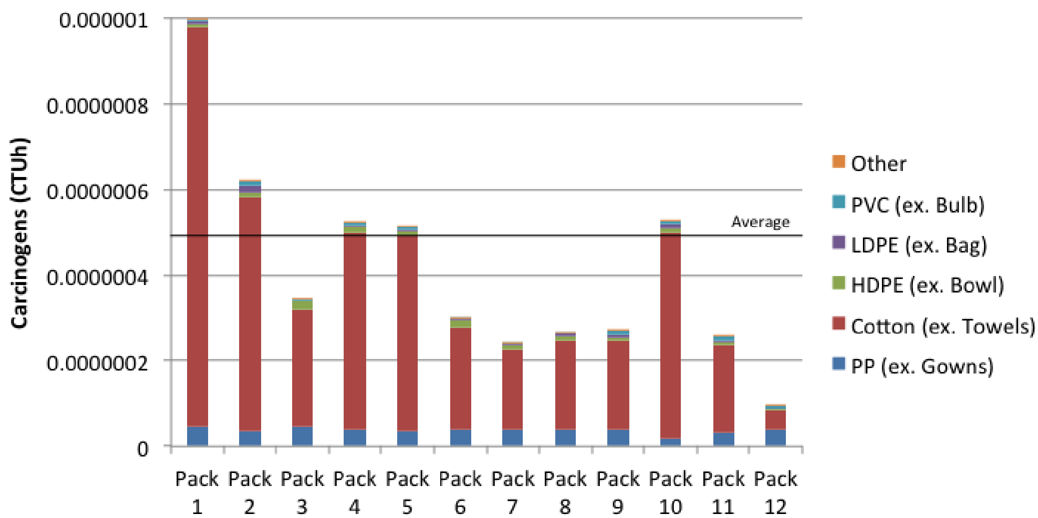


Figure 32: Carcinogens; PVC = polyvinyl chloride, LDPE = low-density polyethylene, HDPE = high-density polyethylene; PP = polypropylene

Non-Carcinogens, Figure 33, are human health impacts that may not cause cancer-like illnesses, yet are still detrimental to the human body (Bare, Norris et al. 2003a).

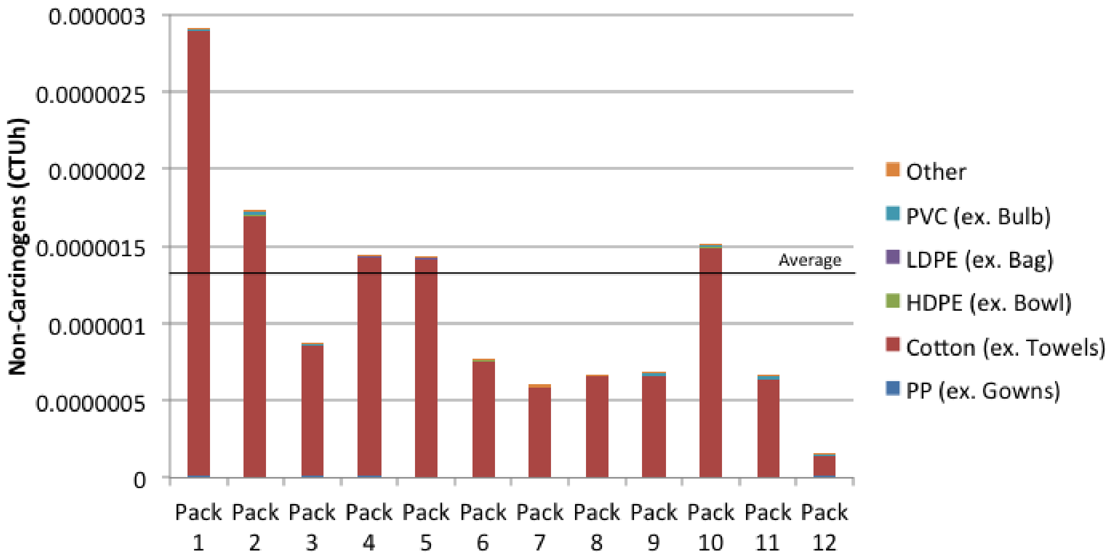


Figure 33: Non-Carcinogens; PVC = polyvinyl chloride, LDPE = low-density polyethylene, HDPE = high-density polyethylene; PP = polypropylene

Respiratory effects, Figure 34, relate to the amount of particular matter in the atmosphere. When humans breathe particulate matter into their lungs, there are increased chances of asthma and other respiratory illnesses. Examples of particulate matter sources include car exhaust, construction debris, and dust (Bare, Norris et al. 2003a).

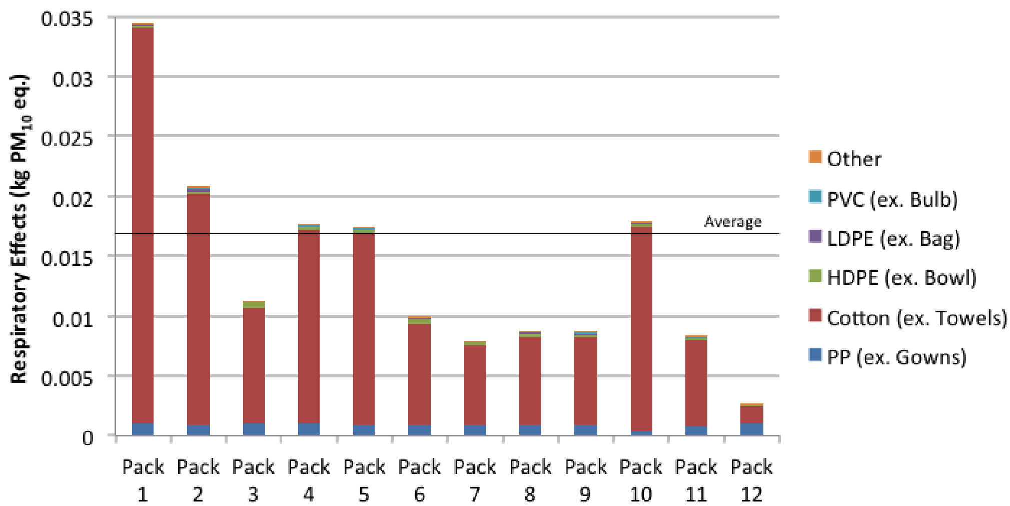


Figure 34: Respiratory Effects; PVC = polyvinyl chloride, LDPE = low-density polyethylene, HDPE = high-density polyethylene; PP = polypropylene

Ecotoxicity, Figure 35, represents the toxicity of air and water from the release of chemicals (Bare, Norris et al. 2003a).

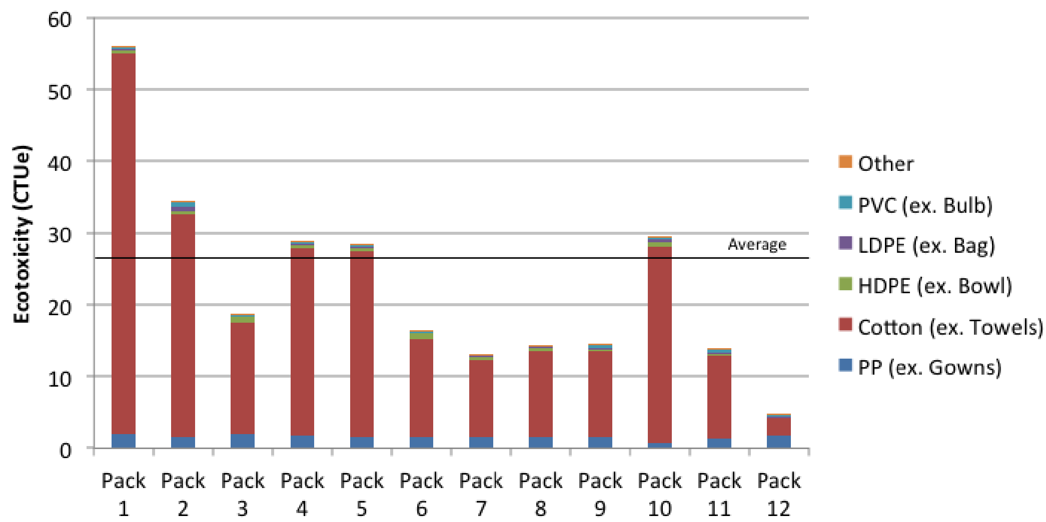


Figure 35: Ecotoxicity; PVC = polyvinyl chloride, LDPE = low-density polyethylene, HDPE = high-density polyethylene; PP = polypropylene

Cumulative energy demand (CED), Figure 36, also known as embodied energy, is an all-encompassing category that measures how much energy it takes to produce and manufacture all of the materials used (Rolf Frischknecht 2007). CED can be used as a screening indicator for other environmental impacts, can be compared against the primary energy used for the product, and is considered a good introduction to life cycle thinking (Frischknecht, Jungbluth et al. 2007b). There are many published reports that state the significance of including CED (Hammond and Jones 2008, Dixit, Fernández-Solís et al. 2012, Bates, Carlisle et al. 2013, Thiel, Campion et al. 2013).

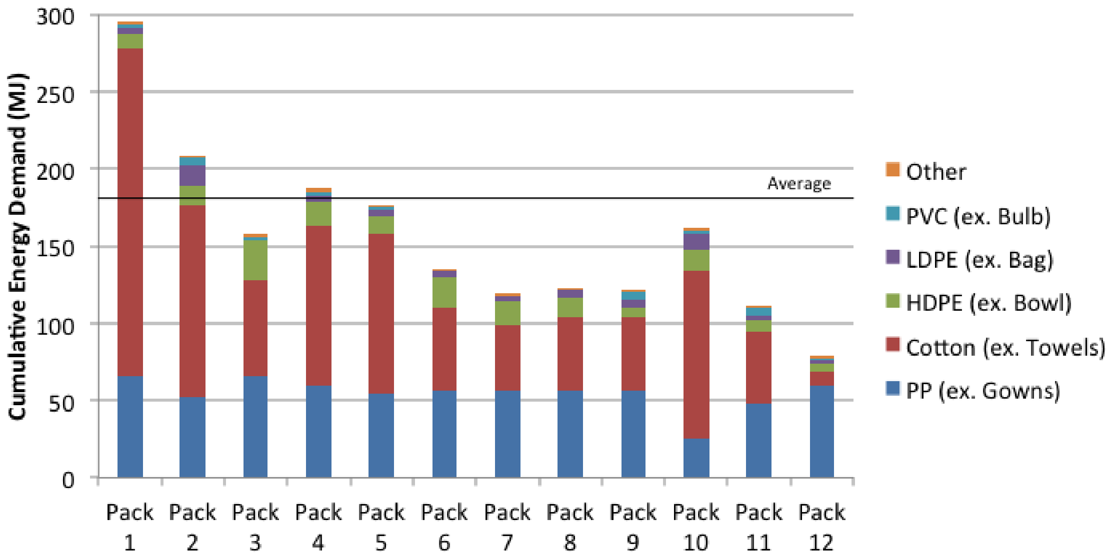


Figure 36: Cumulative Energy Demand; PVC = polyvinyl chloride, LDPE = low-density polyethylene, HDPE = high-density polyethylene; PP = polypropylene

In every life cycle impact category, cotton is the highest producer for every disposable custom pack. Polypropylene is the second leading material. By limiting the amount of cotton in the custom pack, significant environmental savings will be found in every impact category. If cotton products are needed throughout the procedure, they should be considered reusable and laundered accordingly.

Design for Dematerialization: Product Evaluation. Design for dematerialization strategy evaluates all of the products in each of the packs; Table 15 highlights the products found in all packs. An understanding of the product inventory of each pack enables those streamlining the packs to identify unnecessary or unused material. This information was also used in the *Environmentally Preferred Custom Pack Design* section for the design of the green custom pack. For example, each custom pack contained either a laparotomy sponge or a packing sponge for absorption purposes, with the main difference between the two being a string that can be x-rayed on the laparotomy sponge. Leg drapes were found in 8 out of 12 US custom packs; however, according to professional opinion, leg drapes, used for infection control, are not necessary for vaginal births. Eliminating leg drapes from each custom pack would reduce GHG emissions by 2.8 kg of CO_2 equivalents per pack, extrapolating out to 224 kg of CO_2 equivalents if each of the 8 hospitals removed leg drapes in 10 of their packs (80 total births).

Table 15: Product and material inventory of vaginal birth disposable custom packs

Product	Inventory in US Hospitals	Inventory in Thai & Global Links	Average Weight (kg)	Notes
Content List	11/12	2/3	0.002	Basic paper sheet
Plastic Wrapper	12/12	3/3	0.040	Encompasses entire pack
Towels	11/12	0/3	0.150	Either OR towels or absorbent towels
Gowns	12/12	0/3	0.170	Typically 1 XL gown
Under Buttocks Drape	12/12	1/3	0.090	Used for table and mother protection
Legging	8/12	0/3	0.070	Not entirely necessary
Lap Sponges	4/12	0/3	0.018	Either lap sponges or packing sponges used
Gauze	9/12	3/3	0.002	Used for fluid absorption
Packing Sponge	8/12	0/3	0.018	Either lap sponges or packing sponges used
OB Pad	7/12	0/3	0.014	Used for fluid absorption
Bulb Syringe	12/12	1/3	0.032	5/12 had 2 bulb syringes
Umbilical Cord Clamp	11/12	3/3	0.002	Global Links had two cord clamps
Needle Counter	7/12	0/3	0.040	Either 10-, 20-, or 30- needle counts
Placenta Basin	12/12	0/3	0.080	Used to hold all custom pack products
Placenta Foam Lid	3/12	0/3	0.070	Used for placenta basin
Baby Blanket	6/12	0/3	0.120	Baby blanket and abdominal sheet used in similar capacities
Abdominal Sheet	10/12	0/3	0.080	
Cover Sheet	12/12	0/3	0.130	Table cover sheet

Eleven out of 12 custom packs contained cotton towels, and the number of cotton towels in the US custom packs varied from 1 (US Pack 7) to 7 (US Pack 1). As discussed above, the production of disposable cotton towels was a major factor in environmental life-cycle impacts. The average number of towels in all US custom packs was 4, and if this were reduced to 2 towels about 24 kg of CO_2 equivalents would be reduced from each birth. Decreasing and then reusing disposable cotton products in the OR has the potential to significantly reduce associated environmental impacts.

The two Thai packs and the not-for-profit pack did not include towels. The two Thai packs had an additional *reusable* pack that consisted of cloth gowns, towels, and sheets, not included in this disposable pack study. The not-for-profit pack represents the basic necessities for vaginal birth, including an under-buttocks drape, gauze, a razor, two umbilical cord clamps or strings for the removal of the umbilical cord, soap, and gloves. As mentioned in the introduction, the *reusable* custom packs were *not* considered in this study in order to maintain the system boundary of what hospitals perceive as *disposable*, represented by their disposable custom pack. Because most US custom packs utilized cotton towels as 'disposable' items, this study delved further into alternative end-of-life options.

Design for End-of-Life: Laundry Incorporation and Reuse. To better understand the effects of laundering cotton products, this study assessed EOL options for 4 reusable towels (the average number of towels per pack). The laundry process model was comprised of 4 components: electrical load, chemical wash, steam, and natural gas. LCA results, Figure 38 show that the natural gas for the dryer and the electrical load for the machines contributed the most in each impact category when the average number of OR towels for a custom pack was laundered (4). The chemical wash was the least significant (<5%) in all impact categories.

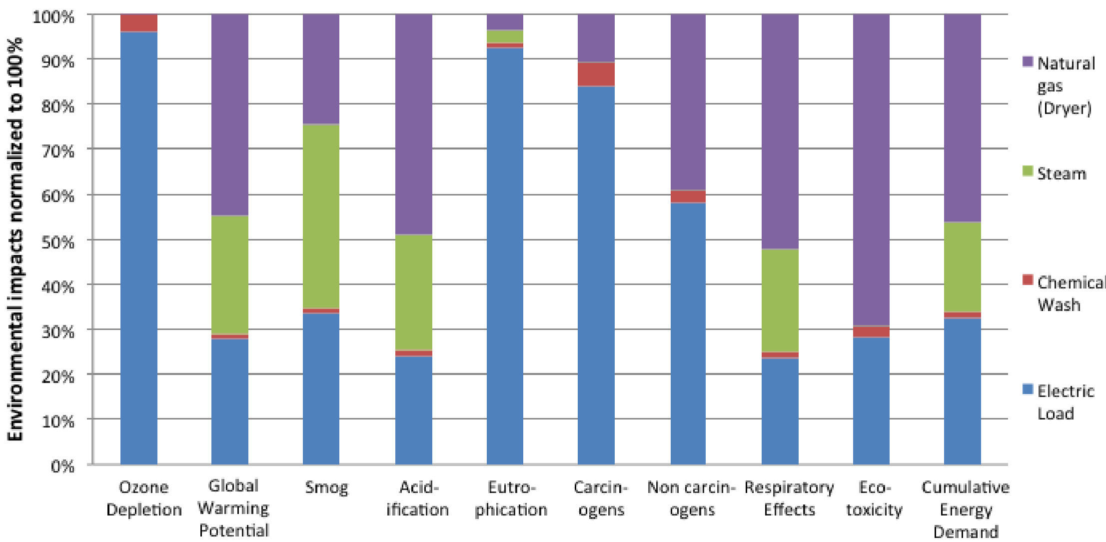


Figure 37: LCA results of process laundry model

As more towels are laundered, the environmental impacts associated with laundering increased; yet laundering was preferable to MSW disposal with allocation of production impacts, shown in Figure 39. For the cotton allocation, this study assumed 50% of production for original purpose (OR towel) and 50% to secondary purpose, as predicated in literature (Guinee 2002). According to hospital and commercial laundry personnel, the secondary purpose of an OR towel might include non-sterile hospital use like fluid absorption or cleaning. It is important to note that the cotton towels found in the disposable custom packs *should* be considered for reuse. The US Federal Drug Association does not regulate towels; the only regulation is maintaining the sterility of the disposable custom pack in total. After the laundry process, the towels are used as a clean, absorbent product and are only discarded if there are visible marks or wearing, which could have a life span of over 50 washes (Cartwright, Cheng et al. 2011).

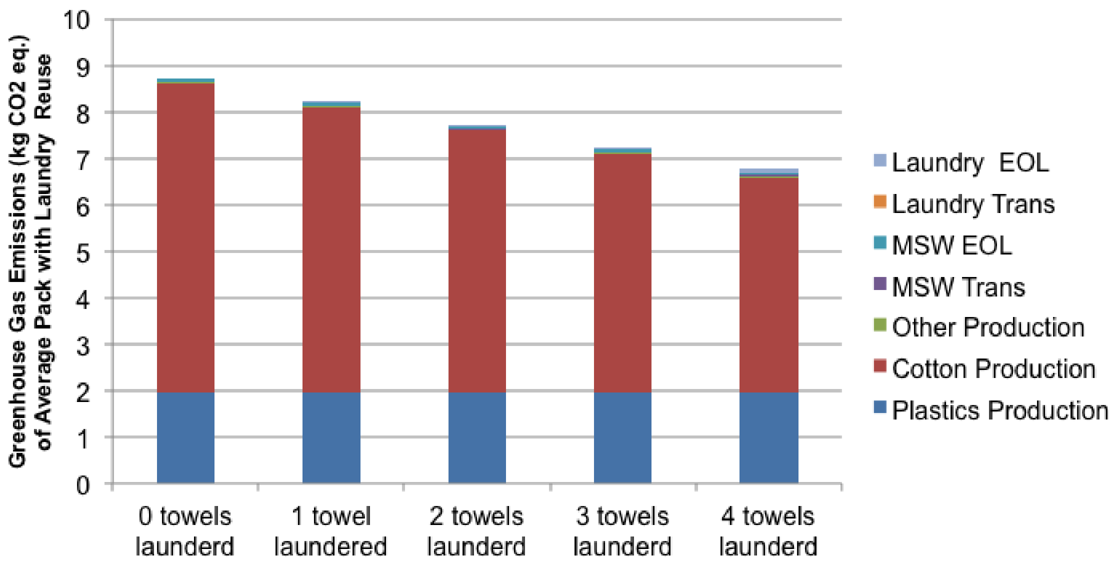


Figure 38: Greenhouse gas emissions average US disposable custom pack with parametric modeling of laundering. Custom pack data represented in Figure 6 is the average from the vaginal birth US disposable custom packs in this study, which includes 4 OR towels. Laundering 0 to 4 towels, 1 time; transportation to and from the hospital and laundering facility; EOL = end of life; MSW = municipal solid waste (landfill); trans = transportation (between hospital and facility)

Laundering was also the preferred EOL method for towels when considering eutrophication and other impact categories, shown in Figure 39. Laundering four disposable cotton towels one time reduced the environmental impacts of a single custom pack an average of 29% compared to landfilling the towels. Even though the cotton towels composed less of the custom pack by weight, laundering and reusing this single item has the potential to decrease total environmental impacts.

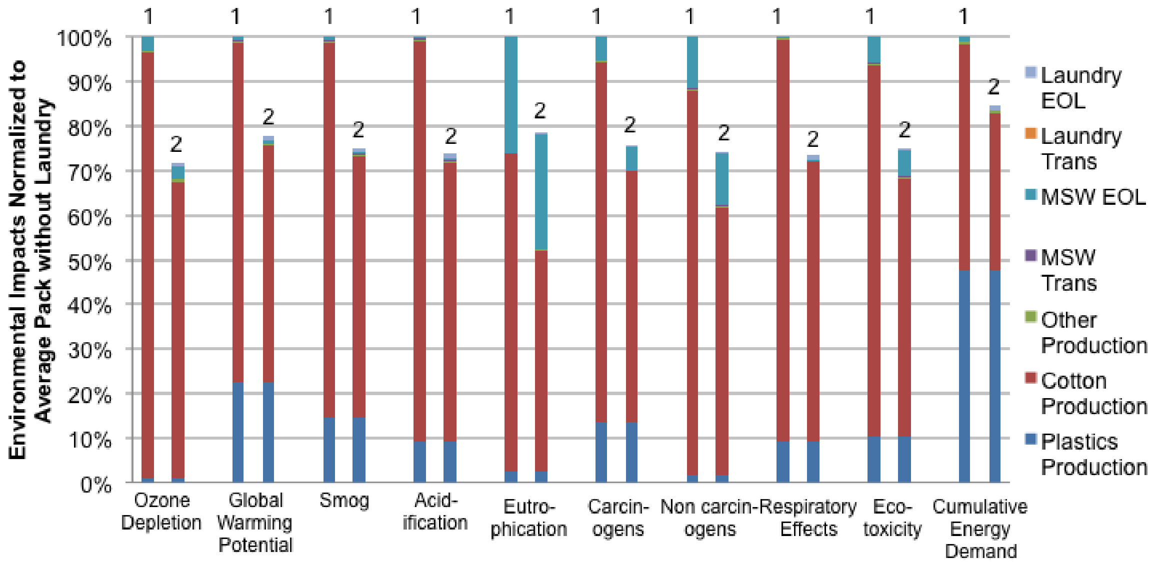


Figure 39: Environmental impacts of studied custom pack with two end-of-life (EOL) scenarios. Studied custom pack data is the average from US custom packs in this study. EOL scenarios are modeled as either (1) 100% MSW of all products or (2) Launder reusable cotton and MSW for all other products; Trans = transportation, MSW = municipal solid waste

Environmentally Preferred Custom Pack Design. An environmentally preferred custom pack was designed based on the DfE design for dematerialization and design for end-of-life strategies, in the context of a healthcare setting. Though this study recognizes that each custom pack analyzed pertained to a specific hospital, I was able to interpret the use of the products found to develop a custom pack that complements the function and purpose of a custom pack (i.e., sterility and efficiency) with environmental impacts. The design for dematerialization strategy helped identify products in the custom pack that were not environmentally preferable for a disposable custom pack, i.e., the cotton towels. Furthermore, the impacts of cotton are mitigated when laundry reuse is considered as an end-of-life scenario compared to traditional MSW disposal, which is typical of disposable custom packs.

The newly designed pack includes: (1) content paper list, (1) gown, (1) under buttocks drape, (5) gauze, (1) umbilical cord clamp, (1) bulb syringe, (1) basin, and (1) pack wrapper/table cover. There are no 'disposable' towels included in the custom pack, as it is assumed they would be included in a reusable pack or picked from the delivery room and laundered after use. Additional absorption products can be found in the labor and delivery room suite, along with sterile gloves, needles, saline, and reusable instruments. The designed custom pack is 0.84 kg, 33% less weight than the pack average at 1.26 kg. Figure 40 shows the designed custom pack has an 80% average savings across all impact categories compared to the average custom pack. This is primarily due to the lack of *single-use* cotton in the designed custom pack. If two *reusable* cotton OR towels were also considered in the environmentally-preferred custom pack design, there would still be an approximate 75% average savings across all impact categories compared to the average custom packs. The environmentally preferred custom pack contained more items than the not-for-profit custom pack, which had the lowest environmental impacts, in order to present a feasible example of a US streamlined custom pack.

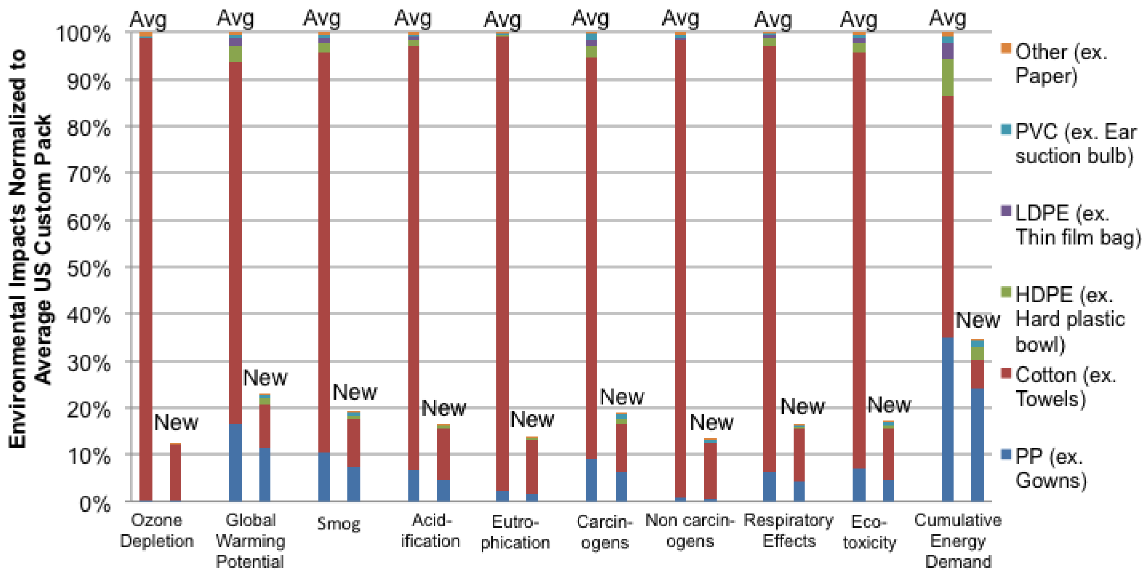


Figure 40: Environmental impacts of the studied custom pack compared with the environmentally preferred custom pack design. Avg = average custom pack design from US data only; New = new custom pack design with (1) content paper list, (1) gown, (1) under buttocks drape, (5) gauze, (1) umbilical cord clamp, (1) bulb syringe, (1) basin, and (1) pack wrapper/table cover

Discussion & Recommendations. Disposable custom packs are utilized in nearly every medical procedure performed in a hospital in the US and many other countries around the world. The purpose of a disposable custom pack is to increase efficiency by grouping together all materials needed for a procedure. Custom packs also help protect the sterility of products by reducing the number of "touch points", or human interactions. While the functional unit of this study was one unique disposable custom pack, broader questions could be raised in term of what products and materials are truly needed to birth a baby, and the answers to these questions will likely vary according to cultural practices, social norm, and material availability. Additionally, there is a temporal aspect as birthing a baby has changed over time. Streamlining custom packs by focusing on quantity and types of materials significantly affects a hospitals overall environmental impacts. The recommendations for developing a custom pack, streamlining programs are as follows:

1) *Use design for the environment strategies and LCA results in collaboration with clinician input to develop best practices to determine which products should be included in custom pack products*

Hospitals may find it easier to identify products as necessary or obsolete by evaluating custom packs of other hospitals or organizations, as is the case for the disposable polypropylene leg drapes found in 8 of the 12 custom packs in this study. Best practices can be developed utilizing DfE, LCA, and other sustainability tools, and shared amongst healthcare facilities. For example, Pack 1 is used by a hospital considered to be green due to a LEED-certified building expansion. However, Pack 1 has the greatest number of towels (7) of any of the analyzed custom packs, and as the LCA results show, Pack 1 has the largest environmental impacts. Providing this hospital with the LCA results along with strategies for streamlining the custom packs may yield a positive outcome for custom pack reductions.

2) *Reduce* ***disposable*** *cotton products and reuse after laundering when possible*

Cotton was the largest contributor in every life cycle environmental impact category, due to the intensity of cotton production. It is recommended that hospitals reduce the amount of cotton in their custom packs to the lowest tolerable limit from a clinician's perspective. Even if this study overestimated the cotton production by 50%, cotton would still be the dominating product in every category. The commercial laundering process, though producing its own emissions, had less impact than the cotton production of virgin cotton and is preferable to landfilling used towels within the bounds of the data used in this study.

3) *Streamlining has the potential to reduce cost, waste and environmental impacts and should be considered in greening efforts*

Reducing custom pack sizes through streamlining efforts can save money, reduce waste, and improve environmental impacts. Custom pack size can be reduced and unutilized products can be removed through regular valuation of a custom pack by the medical team. The *DfE capital protection and renewal strategy* should include the input of clinicians, environmental services, and procurement staff. For example, one of the analyzed custom packs costs $18.28 while another costs $26.47; the latter also weighing more. Leg drapes, which cost approximately $2.97 per pair, were found in 8 of the custom packs in this study. If these 8 hospitals removed leg drapes from their custom packs, they could jointly save over $60,000 annually. A resource-efficient custom pack with products that are properly designed for EOL will ultimately reduce the price of the custom pack, reduce the costs of disposal, and reduce the environmental impacts associated with custom packs.

Limitations. One limitation of this study was the absence of the reusable custom pack or any other incidentals associated with the birth of a child. Incorporating this information could help achieve the highest in total environmental impacts by delineating which materials and products should be considered disposable versus reusable. Further, reuse potential and allocation assumptions for specific pack products, such as towels, could be strengthened. Another limitation was the global and Europeans unit processes selected to represent the pack materials; future studies should better align medical industry product manufacturing data with life cycle inventory. Additionally, the inclusion of cost could be of great interest to hospitals and medical product suppliers and an important factor towards streamlining efforts. Solely looking at environmental impacts, the not-for-profit pack has the lowest environmental impacts. While not included in this analysis, understanding the health outcomes of mother and child would be an important consideration in selecting a disposable custom pack.

3.3.2.3 Custom Pack Study Conclusion

This study identifies disposable cotton towels as a significant component of the environmental impacts of custom pack materials. Cotton production requires a significant amount of water, land, fertilizer, and labor; approximately 6.6 kg of CO_2 equivalents and 0.024 kg of N equivalents are emitted into the atmosphere for the production of 4 towels per study results.

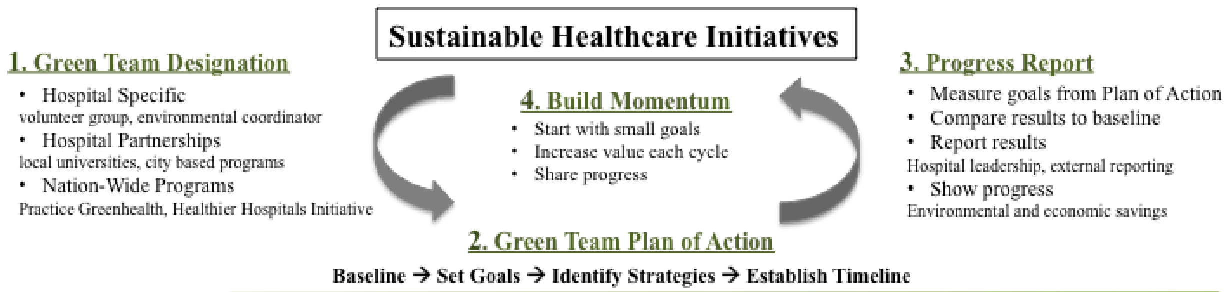
3.4 ADVANCED HEALTHCARE LCAS

It is apparent that there is considerable room for LCA integration in the healthcare industry. Every sustainable healthcare project completed at Magee has been well received by the healthcare community, who has requested more studies and data driven results. The future of healthcare LCAs is limitless and the applications, especially in the use phase of a healthcare institution, are just beginning to emerge into the realm of sustainable healthcare. Below is a description of how LCA can be applied to healthcare in the micro – hospital wide – and macro – healthcare industry – scale. The work presented in Section 3.4 supports the answer to the second research question "what tools and strategies are needed to advance LCA in the healthcare industry?"

3.4.1 Lessons Learned and Replicability

For any healthcare institution attempting to reduce their impact on the environment, the first major step is acquiring support from hospital personnel. There are a variety of avenues that could initiate sustainable action such as hospital specific groups (a volunteer-based green team, Magnet nursing committee, unit-specific committee), hospital partnerships (collaborating with local universities via the engineering or public health schools, city-wide carbon emission reduction programs), or national groups (Practice Greenhealth, Healthier Hospitals Initiative, Healthcare Without Harm) (PracticeGreenHealth 2012, 2030 2013). At Magee, there is a volunteer green team, which consists of nurses, clinicians, administrators, procurement, and environmental services. In 2008, Magee leadership realized the value of having a green team and brought on a full-time Environmental Initiative Coordinator to oversee the green team, become the liaison between national groups such as Practice Greenhealth to maintain membership, establish hospital-wide educational programs for patients and staff, and continue to champion all sustainability efforts at the hospital. This has been a successful investment for Magee and has rendered positive changes. The Environmental Initiative Coordinator position was originally supported via local foundation funding and is now fully supported by Magee.

An overview of different sustainable healthcare initiatives and strategies can be found in Figure 41. First, a green team or designated program for sustainable initiatives needs to be established, as described above. Second, the green team should define a plan of action. There are a range of tactics depending on the experience level of the green team and previous sustainability success. For programs beginning their green efforts, measuring the hospital's baseline is a crucial first step. Without the baseline, it is difficult to quantify any changes that may occur throughout the green program. After the baseline is established, for whichever focus area is most appropriate for the hospital – waste, food, purchasing, energy consumption, education – the next step is to set specific goals. The goals could be percentage based (e.g., increase recycling by 10%) or monetary based. Strategies for attaining the sustainability goals along with personnel responsibilities legitimize the process and make the endeavor feasible. It is important to set a designated timeline for the whole plan of action; therefore, it is easy to track progress and have a definitive end date for the project.



Focal Areas	Beginner	Intermediate	Experienced
Waste Reduction	Establish baseline: how much waste is there and what type of waste (municipal, medical, recycling, pathogenic, etc.)	Initiate recycling programs: increase recycling receptacles, signage, reduction percentage goals and designated timeline	Revaluate the supply chain – product biodegradability or reuse; increase reduction goals
Preferred Purchasing	Establish baseline: who is the supplier? How much product is designated to each unit?	Initiate a preferred purchasing plan: identify red list items, request detailed information about materials, ask for product alternatives, observe product use and trends in specific units	Revaluate the supply chain – product biodegradability or reuse (either central service or laundry); increase "green" purchases; streamline unit products
Food Programs	Establish baseline: where does the food come from? How much is waste? what is the food made out of?	Initiate a sustainable food program: research onsite-gardening potential, gather supplier information and food alternatives, consider composting potential (of food waste and/or disposable cafeteria products)	Increase use of organic products (either from hospital garden or local sources), increase food waste reduction goals; eliminate soda / snack foods / fast food items
HVAC & Building Consumption	Establish baseline: identify trends in utility data, inventory HVAC, lighting, machines, sensors, automated systems	Initiate a HVAC reduction plan: compare ROI on lighting change outs, automated building systems, efficiency rates of HVAC machines, established ENERGY STAR rated machines for new products	Continue tracking the utilities and overlay the data with building automation data - finding trends and more areas for improvement; purchase renewable energy
Other	Take into account hospital-specific items (cleaning supplies, laundry, central services, transportation, water)	Identify other green challenges for the hospital: increasing laundry (where is the laundry and how efficient is it?), central service machines, increase public transportation	Target pharmaceutical waste plans and water management; incentive plans for staff well-being (healthy eating, gym memberships, flu shots, etc.)
Education	Seminars and work lunches on sustainable topics; identify **who** collects hospital data	Establish environmental programs for patients and staff (gardening, preferred purchasing, energy use reduction, etc.)	Shift the hospital culture to becoming more conscientious of the environment and human induced impacts

Figure 41: Sustainable healthcare initiatives plan of action adapted from ((PracticeGreenHealth 2012). HVAC = heating, ventilation, air conditioning, ROI = return on investment

Once the sustainable plan of action is in place and the project has been completed, it is important that the green team report their successes. Comparing the results to the original baseline quantifies any changes that may have occurred. The green team could also extrapolate the monetary savings of the project, an aspect that hospital leadership is attracted to. The progress report can be documented for external reporting measures such as Global Reporting Initiative, Practice Greenhealth tracker, or carbon footprint reports.

After the initial green team project is completed and reported to hospital leadership, the green team recognition increases. The green team will then assess what to take on next, either building on the previous project or moving on to another focus area. The green team will go through the process again: identify baseline, set goals, identify strategies, establish timeline, gather data and results, compare results to baseline, report. Each round of green team goals and projects will increase their level of impact as momentum grows.

Integrating life cycle assessment into sustainable healthcare initiatives is an advanced strategy for quantifying the environmental impacts of the industry. Calculating baseline metrics – such as kilowatt-hours of electricity, tons of waste, or gallons of water – and associated environmental impacts allow hospital personnel to fully understand their footprint within the industry. Calculating the environmental impacts of any product or process, especially in the resource intensive healthcare industry, can be a daunting endeavor, but without the initial understanding of a healthcare institution's footprint, any improvements will be undervalued.

To start, a healthcare institution can quantify their carbon footprint or global warming potential with tools such as the Greenhouse Gas Protocol or the EPA-developed Corporate Carbon Footprint (WRI and WBCSD 2013, EPA 2014c). With any sustainable initiative, as described previously, starting small helps build momentum for larger-scale analyses. Utility data may be the easiest set of information to calculate the carbon footprint, which can be tracked over a number years depending on data availability. The carbon footprint will also reflect any contractual changes, such as renewable energy services, that may have occurred. Waste management is another aspect of the healthcare industry that collects data to easily adapt to carbon footprint software, tracking truck hauls and tons of landfill, regulated medical waste, and recycling. Because waste reduction plans are considered low-hanging fruit of sustainability initiatives, the carbon footprint should also reflect these efforts.

Beyond carbon footprint, other environmental impacts that relate to the healthcare industry include eutrophication and water usage, carcinogens, smog, and respiratory effects. Investing in software or analysts that can quantify these environmental impacts would benefit any required reporting and set an example of healthcare sustainability initiatives that are advancing the understanding of traditional healthcare collected data. The Global Reporting Institute has developed sustainable reporting guidelines that can be used for a variety of sectors to track critical data and other services (GRI 2013). Though these LCA tactics are not as well known on an institution level, their presence will be more apparent as carbon footprints and sustainability reporting become more prevalent.

Taking sustainable healthcare to the macro scale will most likely relate to nation-wide programs like Practice Greenhealth or Medicaid/Medicare. Creating collaborative platforms for healthcare institutions to share their progress and to work together to overcome sustainability issues such as leadership push back or financial restraints will result in a uniformed approach towards sustainable healthcare. The changing landscape of the US healthcare system will also be of benefit for sustainability motivation; where the community health needs assessments (CHNA) is required by each hospital to discuss the local population and any significant health problems, such as asthma or obesity (Laymon, Shah et al. 2015). Identifying what the local community needs in terms of healthcare can influence targeted sustainability goals that connect the hospital to the public.

Hospitals have the ability to take on sustainability challenges themselves, by creating a green team and other supportive partnerships. Eventually though, sustainable healthcare should be integrated into nation-wide programs such as Medicare and Medicaid that follow a similar format to the HCAHPS surveys (discussed in Section 4.2.1.2); where hospitals are obligated to report on their sustainability efforts in order to be compensated for the Medicaid or Medicare programs (HCAHPS 2014).

Similarly, applying an energy data disclosure program, used traditionally for city-specific commercial spaces, as a benchmarking tool would be another way to compare and contrast how hospitals are performing around the country. New York City, Washington D.C., and Seattle have had success with energy benchmarking disclosure programs across the commercial building sector using ENERGY STAR's Portfolio Manager to collect utility data, assess energy efficient strategies, and compare relative building energy consumption. The energy disclosure programs can expand to include carbon footprints and other environmental impacts. Hospital energy discloser programs could begin in each city and then later span the entire country, accounting for any regional differences such as energy/fuel mix, state regulations, and hospital-specific initiatives.

Sustainable programs geared primarily towards commercial buildings have been well established over the last 20 years in the Unites Sates, therefore using the foundation of these programs and adapting them to the needs of the healthcare industry would be one way to successfully integrate national programs. The healthcare industry will continue to change and there are tools and resources available to shift healthcare towards a more sustainable industry.

4.0 EVIDENCE-BASED DESIGN AND LCA APPLICATION

This research investigates the building and healthcare industries aiming to advance necessary contributions and provide strategic recommendations on the development of LCA in both sectors. One significant aspect of the research presented is that the healthcare industry, though considered a separate entity from the building industry, consists of many building operations. The impact that building design and operations has on building occupants, such as patients or hospital personnel, can be substantial. It is important to understand how the healthcare industry is applying sustainable building strategies to better patient and staff satisfaction in conjunction with building performance.

Evidence-based design (EBD) has been the primary method for understanding hospital design in relation to occupant satisfaction. Metrics including employee and nursing turnover, medication dispensing errors, and hospital acquired infection rates have been used to assess *traditional* hospital design within the field of EBD (Ulrich 1991, Schweitzer, Gilpin et al. 2004, Sadler, DuBose et al. 2008, Zimring, Ulrich et al. 2008, Huisman, Morales et al. 2012). However, there has been a recent momentum for green building design and certification to accompany new hospital construction. Green building design typically focuses on the physical properties of the building – construction materials, energy efficient systems, and water use reduction. Previous green building occupant studies have analyzed company-collected data such as worker productivity, employee absenteeism, or sick leave; yet their results do not necessarily reflect design features (Kats, Alevantis et al. 2003, Ries, Bilec et al. 2006, Seppänen and Fisk 2006, Loftness, Hakkinen et al. 2007, Wiik 2011). EBD methodology can be used to assess the effects of *green* hospital design, offering a unique data analysis opportunity that better defines the impact of green building features on occupant satisfaction, and improving metric selection for future analyses of green buildings.

EBD has the potential to be utilized in conjunction with the IPD/LCA pathway described in Section 2.4, as the needs of EBD, IPD, and LCA overlap with necessary collaborators and project goals. EBD could also be integrated into GBRS certifications, targeting pre- and post-occupancy surveys of patients and staff and focusing on the building use phase of the healthcare facility. GBRS certifications that are grounded in life-cycle thinking and assessments and have EBD influence have the potential to enhance how buildings are designed and operated from an environmental, social, and economic perspective.

4.1 INTRODUCTION AND BACKGROUND

4.1.1 Chapter 4 Organization

In Chapter 4.0 a literature review of evidence-based design (EBD) studies is presented, followed by a green building EBD study that focused on the environmental impacts (designated by LEED Silver certification) and occupant satisfaction (EBD) between two different hospital units. Next, strategies for integrating EBD, green buildings, and LCA are explored. The evolution of Chapter 4.0 addresses the third research question "how can green buildings and LCA be integrated into EBD to enhance the environmental and occupational impacts of building design?" This work was submitted to the *Buildings and Environment* journal as "Understand Green Building Design and Healthcare Outcomes: An Evidence Based Design Analysis of an Oncology Unit".

4.1.2 Evidence-Based Design Literature Review

Evidence-based design (EBD) is defined as "the process of basing decisions about the built environment on credible research to achieve the best possible outcomes" (Cochrane and Fellowship 1972). EBD has primarily applied to the design of healthcare facilities on the idea that the design quality of physical spaces can affect patient outcomes and quality of care (Ulrich 2001). In other words, certain environmental design strategies could improve patient health while other design strategies may worsen patient health (Ulrich 2001). Physical aspects of a hospital relating to patient satisfaction include acoustic quality, outside view, lighting, single occupancy room (versus a shared space), and building aesthetics (product selection, color schemes, furniture layout) (Ulrich 2001).

In an influential 1984 study, Ulrich found that patients randomly assigned to a corridor with windows overlooking trees went home almost one day sooner than those assigned to rooms with windows overlooking a brick wall (Ulrich 1984). Studies specific to sustainable medical facility design have emerged, using hospital performance metrics such as employee and nursing turnover, medication dispensing errors, and hospital acquired infection rates (Williams 1988, Berry, Parker et al. 2004, Joseph and Rashid 2007, Rechel, Buchan et al. 2009, Huisman, Morales et al. 2012). Since 2004, the growth of EBD studies has grown rapidly, attesting to the importance of spatial design and occupant receptivity (Zimring, Ulrich et al. 2008).

There are three distinct areas in which EBD impacts healthcare occupants. The first EBD area is occupant safety. Patients have a high risk of contracting a hospital acquired infection or an air-borne infection. With EBD strategies such as single-room occupancy, high-efficiency particulate air filters, hand sanitizer stations, easy clean machines and furniture, and accessible sink locations relative to patient rooms (Zimring, Ulrich et al. 2008). The second EBD area is reducing medical errors. Medical errors have been related to noise, light, population acuity discrepancy and multi-patient rooms (Blomkvist, Eriksen et al. 2005, Zimring, Ulrich et al. 2008, Choi, Beltran et al. 2012). The third area of EBD relates of pain, sleep, stress, and depression. Some common themes found across all of these aspects of patient care include the effects of natural daylight and electric light, connection to outdoor space such as gardens, noise reduction strategies such as acoustic panels, mindfulness culture, and single-occupancy rooms (Zimring, Ulrich et al. 2008)

EBD also has a strong impact on hospital personnel. The addition of patient lifts alleviates staff injuries related to patient handling (Zimring, Ulrich et al. 2008). Staff stress is also a major problem, resulting in high turnover rates, employee burnout, and unhappiness (Montgomery 2003). Lighting, unit configuration, acoustic quality (noise and distraction levels), designated personnel space in patient rooms, and aesthetics are all EBD strategies that can improve the staff productivity, similar to the patient impacts discussed above (Zimring, Ulrich et al. 2008). Quantitative understanding of hospital building design choices is needed to help continue transforming sustainable development and the health of building occupants.

4.2 HOSPITAL EBD STUDY

This study aims to enhance green building design by better understanding the effects existing structures and design elements on occupants. Evidence-based design (EBD) focuses on occupant satisfaction typically in the context *of* healthcare *building design*; however, EBD is not entirely reflected in *green building design*. Conversely, green building design focuses on resource efficiency and environmental responsibility throughout a building's life cycle. According to the American Institute of Architects (AIA), healthcare is expected to be the leading industry for new building construction in 2014 and 2015, highlighting the need for green, efficient buildings that can demonstrate improved occupant health and behavior (Baker 2014). The goal of this study is to understand the impact that EBD has on a green building space and support the integration of green building design criteria into traditional EBD metrics.

Case Study. Magee-Womens Hospital (Magee) of the University of Pittsburgh Medical Center is a national leader in women's healthcare and research. Since 2005, Magee has been recognized for their environmental initiatives by Practice Greenhealth and has developed environmental educational programs for new parents and new hospital staff. Because Magee is a major birthing hub for Western Pennsylvania (over 10,000 babies delivered each year (AHA 2014)), medical floors such as women's oncology were seeing significant overflow from the labor and delivery service. As such, in 2011, Magee decided to expand their hospital by adding a 4^{th} floor (14-bed intensive care unit) and a 5^{th} floor (28-bed gynecological medical-surgical unit) to the main hospital building. This approximate 40,000-ft^2 addition had an initial publicized cost estimate of $20,000,000 (Stantec 2011). Magee's dedication to environmental sustainability and patient recovery rates guided their efforts towards LEED-Silver certification and evidence-based strategies for the hospital expansion.

The expertise from the sustainability consultants, the Green Guide for Healthcare, and the LEED certification checklist determined the green design features for Magee's addition, shown in Table 16. Strict indoor air quality (IAQ) measures during construction and throughout building occupancy served as both an infection control measure and a LEED IAQ credit. Products were selected based on local materials, recycled content, and the use of low-VOC (volatile organic compounds), lead-free, and formaldehyde-free materials. Additional recycling receptacles were placed throughout the private and public space for easy recognition and increased use. Magee's addition was awarded LEED-Silver certification in 2012.

Table 16: Green building design and evidence-based design features of Magee-Womens Hospital addition

	Green Building Design (GBD)	Evidence-Based Design (EBD)	GBD + EBD
Building Features	• Automatic monitoring and adjustment of ventilation air • High-efficiency plumbing fixtures • High-efficiency HVAC and lighting systems • Energy Star rated computers and electrical equipment • 90% of construction waste was recycled	• Electrical and medical gas outlet are located in the patient room head halls at staff height • Seamless flooring • Decentralized nursing and charting stations • Additional staff support areas • Color palette of blues and beiges	• Access to natural light • Lighting dimmers • Electrical and medical gas outlet are located in the patient room head halls at staff height • Corridor acoustical panels • Therapeutic music • Nightlight designs reduces patient falls • Materials were locally sourced with high recycled content
Patient Family Care Features	• Use of low-VOC, low-formaldehyde, mercury-free, and lead-free products • Recycling containers in patient rooms and public areas	• Patient rooms provide a "family zone" and a "caregiver zone" • Programmable locks on wardrobes • Sleeper sofas for family members • Waiting and Meditation Rooms increase privacy • Maximized individual control of HVAC and lighting	• UPMC has a no smoking policy • Selected "home-like" products and materials (wood, natural fabric patterns, etc.) to limit an institutional feel • Environmental health education for staff and patients • Organic vegetable garden with healthy food choices
Infection Control Features	• Patient rooms are ventilated by rooftop air-handling equipment and HEPA filtration • Greengaurd Environmental Institute IAQ standards for fiberglass roller shades for exterior windows	• Solid surface countertops minimizes mold growth • All drywall is mold resistant • Hand washing stations are provided in each patient room and in common areas	• Sealed lenses in lighting fixtures minimizes dust • Hands-free faucets and paper towel dispensers • Waterless hand sanitations provided throughout

Evidence-based design approaches included shadowing of unit staff by a nurse (hired by the design engineers) and multiple focus group meetings with hospital administrators, clinicians, former patients, and former patient family members. In response, designers included patient lifts, multiple lighting levels within patient care areas, increased electrical outlets for family use, and decentralized nursing and charting stations. The patient rooms were organized with distinct family and caregiver zones; each new unit has a family lounge with several seating clusters and a meditation room. Designers also conducted a sound study for increased acoustical performance within each space of the unit. In addition, hospital technologies were blended with natural light, home-like materials, and a soothing blue beige color scheme to create a healing environment (Stantec 2011).

4.2.1 Hospital EBD Case Study Methodology

This study was designed after the completion of Thiel, et al.'s work in which they conducted a whole building analysis (Thiel, Needy et al. 2014). While their study is unique in that a whole system was analyzed, one of the shortcomings was discerning the key relationships between green design and metrics. The aim of this study was to decrease the number of variables but maintain a reasonable scale so that recommendations to the decision-makers would be relevant. This study was able to minimize variables such as policy changes, economic growth or decline, and hospital cultural changes (i.e., Magnet Status), since the same leadership, majority of staff, and patient acuity (women's oncology) stayed relatively the same.

The methods section first discusses the approach for the longitudinal study between two units, Unit 2800 (traditional/pre-move) and Unit 5800 (green/post-move). Second, the metrics used to analyze quality of care, productivity, expenses, utilities, staff satisfaction, and patient satisfaction in conjunction with corresponding data collection methods are described. Last, the statistical method used to obtain the results is reviewed.

4.2.1.1 Longitudinal Study Design

In June 2012, Magee opened a new, LEED-Silver certified women's oncology unit, Unit 5800. The new unit's previous location, Unit 2800, is considered a traditional hospital space and is now occupied by the labor and delivery service. The study was conducted over a 37-month period. Data was collected 18-months pre-move for Unit 2800 (traditional/pre-move) from December 2010 to May 2012 and 18-months post-move for Unit 5800 (green/post-move) from July 2012 to December 2013; June 2012 was not considered due to the variability in unit transfer.

The layout and orientation of Unit 2800 and Unit 5800 are similar. There are three potential views for both units: a courtyard garden, a city view, or a synthetic green roof. The synthetic green roof was installed in the spring of 2012; patients on Unit 2800 prior to the move saw only a concrete roof with HVAC equipment. The location of nursing and computer stations also moved from a central room in Unit 2800 to separate stations for every two patient rooms in Unit 5800 as shown in Figure 42. In addition, family care lounges were designed to create a comfortable setting for visitors located at the beginning of the unit.

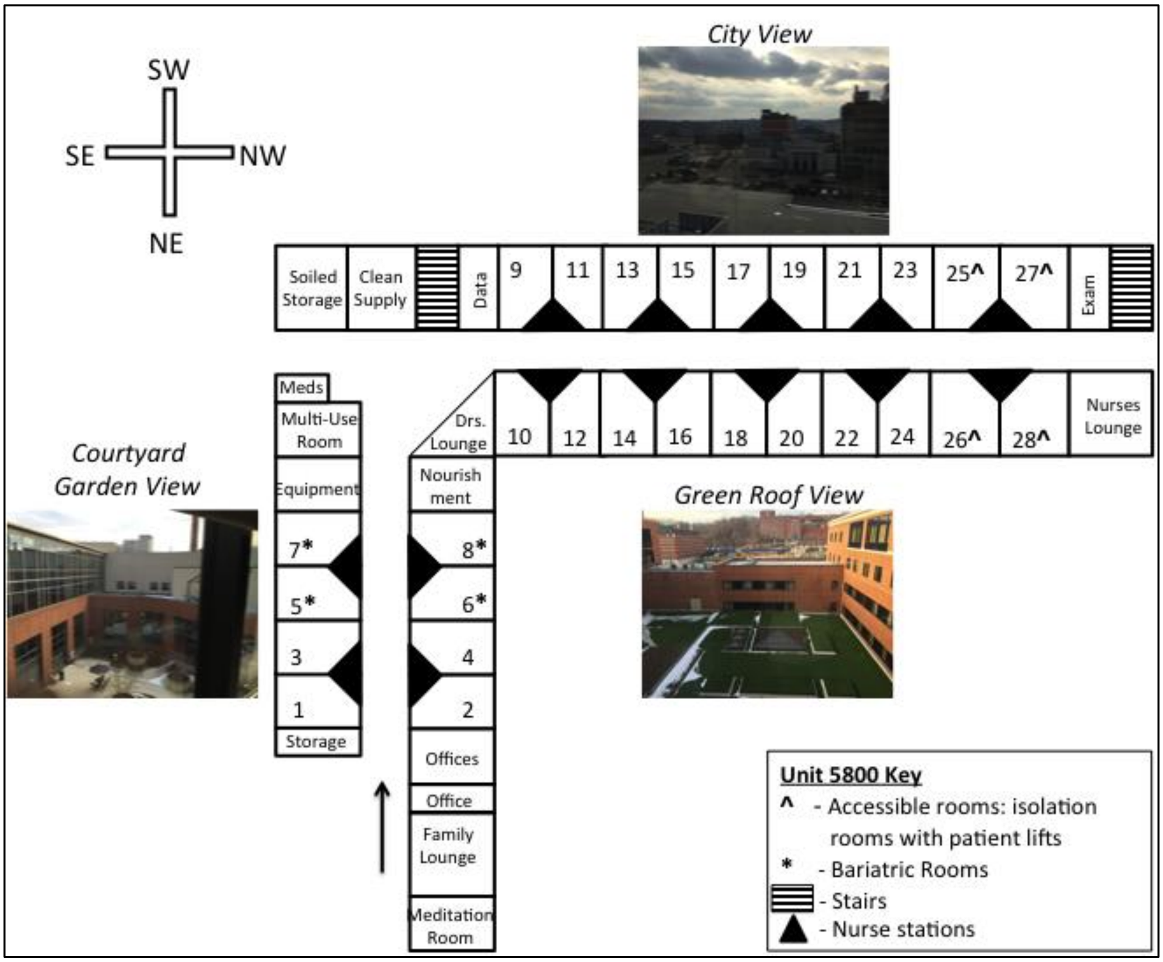


Figure 42: Layout of Unit 5800

4.2.1.2 Metrics and Data Collection

For this study, over 45 metrics were analyzed to assess the differences between Unit 2800 and Unit 5800. Previous studies outlined metrics based on quality of care, productivity, utilities, expenses, staff satisfaction, and patient satisfaction that were then catered towards this specific study (Thiel, Needy et al. 2014). An overview of the metrics collected can be found Table 17.

Table 17: Metrics Overview. LOS: length of stay, PIB: patient in bed, ADE: adverse drug event, CLI: central line infection, APR-DRGs: all patient refined diagnosis related groups, DCD: design cost data, MCF: million cubic feet, cf: cubic feet, sf: square feet, kWh: kilowatt hours, kgal: kilo gallons, lbs – pounds, LDR: labor and delivery room, PCTs: patient care technicians

	Metric Name
Quality of Care	Admissions per month
	Total Patients in a Bed (monthly census)
	Average LOS (per PIB)
	ADE Dispensed Near Miss (B)
	ADE Dispensed Reached Pt, no harm [C]
	ADE Doses dispensed Harm (D)
	Doses Dispensed per month
	Doses Dispensed per Patient Day
	ADE Dispensed (B) per Doses Dispensed
	ADE Dispensed (C&D) per Doses Dispensed
	ADE Dispensed (B,C,D) per Doses Dispensed
	Central Line Infection Rate: #BSIs days
	Case Mix Index per month
	Actual Mortalities per month
	Mortality Rate
	APR-DRGs
Productivity	Total Patient Days (bi-weekly)
	Direct Staff Available for Care (bi-weekly)
	Direct Staff Required for Care (bi-weekly)
	Full-time Employee Staff Paid (hours / bi-weekly)
	Direct Hours per Total Patient Day
	Total Paid Hours Per Total Patient Day
	Performance: Required Hours / Direct Hours
	Productivity: Required Hours / Paid Hours
	Worked Hours Per Patient Day (DCD Benchmark)

	Metric Name
Expense	Salaries & Benefits (monthly)
	Inpatient & Outpatient Revenue (monthly)
	Profit: Revenue - Expenses (monthly)
	Supplies (monthly)
	Total Room Charges (monthly)
	Total Labor (Salaries & Benefits) Expenses per PIB
	Medical / Surgical Supply Expense per PIB
	Total Operating Expenses by PIB
Utilities	Gas (mcf) - raw per month
	Gas (cf / sf) - per month
	Natural Gas (cf) - raw per month
	Natural Gas (cf / sf) - per month
	Electric (kWh) - raw per month
	Electric (kwh / sf) - per month
	Electric (kwh / PIB) - per month
	Steam (lbs) - raw per month
	Steam (lbs/sf) - per month
	Water + Sewer (kgal) - raw per month
	Water + Sewer (gal / sf) - per month

Table 17 (continued)

Staff Satisfaction	Total Number Employees
	Total PCTs
	Total Nurses
	Total Other Employees (director, educator, etc.)
	Tenure <2 years
	Tenure 2 to 4.9 years
	Tenure 5 to 9.9 years
	Tenure 10 to 14.9 years
	Tenure 15+ years
	Time to Fill
	Turnover - Number of Employees
	Turnover - Years of Service
	Vacancy - Number of Openings
	Vacancy - Ave Position Age (days)

Patient Satisfaction: HCAHPS	Hospital Recommendation
	Hospital Rating
	Cleanliness of hospital environment
	Quietness of hospital environment
	Pain well controlled
	Nurses listen carefully to you
	Nurses treat you with courtesy and respect
	Nurses explain in a way you understand
	Call button help as soon as wanted it
	Help with toilet as soon as you wanted
	Doctors listen carefully to you
	Doctors treat you with courtesy and respect
	Doctors explain in a way you understand
	Staff did everything to help with pain
	Staff tells you what new medicine was for
	Staff described medicine side effects

Quality of Care. The patient population of each unit and associated pharmaceutical metrics determined quality of care. For patient population, the Clinical Systems Analyst from Magee's Quality Department used the Chargemaster program to identify the admissions, census, length of stay (LOS), case mix index (CMI), and number of mortalities on a per month basis for each unit time period. The CMI is used as both a clinical and financial indicator to measure the morbidity of the patient and corresponding resource intensity; the higher the CMI value, the more acute the patient is while requiring increased resources (Bilec, Geary et al. 2010). The Environmental Initiatives Coordinator acquired the number of adverse drug events (ADEs) that occurred on each unit via mandatory error reports. There are three levels of ADEs reported: B = an error occurred, but did not reach the patient; C = an error occurred, reached the patient but had no effect; D = an error occurred, reached the patient and needed to be monitored or investigated.

One metric that has recently phased out of Magee's Chargemaster is the 'expected mortality' of patients, which was originally designed using Atlas Abstracts. In its replace, the more specific all patient refined diagnosis related groups (APR-DRGs) numbers have been assigned to designate patient acuity. APR-DRGs use a 1 to 4 scale to indicate minor, moderate, major, or extreme severity of illness or risk of mortality (Avrill, Goldfield et al. 2003). Magee's Infection Control Coordinator was able to assist in obtaining the APR-DRG values for the patients, as well as the number of central lines performed and any central line infections that occurred on a monthly basis through Theradoc, a clinical surveillance system, and the US Center for Disease Control's National Healthcare Safety Network. Last, the Project Manager of Revenue Initiatives and Analytics was able to gather the data for the total number of doses dispensed per month and doses dispensed per patient day of each month, which was cross examined with the number of ADEs accounted for throughout the two units.

Productivity. The majority of the staff productivity metrics are found in bi-weekly nursing reports that are commonly generated by many US hospitals. The Director of Regulatory and Compliance collected the nursing reports which included data on the number of total patient days, direct staff available for care, direct staff required for care, staff paid, total paid hours per total patient day, direct hours per total patient day, performance (required hours per direct hours), productivity (required hours per paid hours), and worked hours per patient day. The number of staff available for care refers to the scheduled staff shifts, which are decided on via trended data from previous nursing reports to meet the needs of the unit. The number of staff required for care refers to actual census and acuity of the patient mix during the reporting period and what the minimum nurse to patient ratio must be according to hospital policy. Staff paid represents the total number of employee shifts paid out during the bi-weekly reporting period. Total paid hours per total patient day is an indicator of staff to patient ratio. The direct hours per total patient day metric represents the relationship between the number of direct hours, based on patient acuity, and number of patient days, based on patient population.

Performance rate and productivity rate are not necessarily a function of trended data from previous reports, but a ratio goal set by Magee. At Magee, the performance rate aims to be 100%, which means that Magee is staffing the perceived optimal number of full time employees in relation to patient census and acuity. Conversely, Magee's productivity goal is 70%, which represent that number of direct care hours required by patients is about 70% of the nurses' workday while the other 30% is dedicated to miscellaneous activities such as meetings, setting up or cleaning up minor procedures, performing minor procedures, or paperwork.

Utilities. The Facilities Manager was able to provide the raw utility data for Magee. At Magee, there are three boilers that use petroleum gas to produce steam to provide district heating throughout the building. Magee also uses natural gas to power the regulation on-site generators and other necessary power sources. Electricity use, represented by kilowatt-hours, in Western PA is a mix of 46% coal, 36% nuclear, 14% natural gas, and 4% renewables (DOE 2013). Energy efficient strategies have been implemented over the last five years, such as the two-year phase-out of T-12 light bulbs to T-5 bulbs, which use about 45% less energy than T-12s. Water and sewage use are calculated in the same metric, gallons, and represent the amount of water used and the amount of effluent produced by Magee. The raw utility data provided allows researchers to normalize the data based on building square footage and number of patient beds to address the increase of the addition in June 2012.

Expenses. The Director of Finance was able to compute the expense data for the two units at Magee. Data included staff salary and benefits, cost of unit supplies, unit revenue, unit profit (revenue – expenses), and total room charges. The unit revenue was calculated by adding the inpatient and outpatient room charges; approximately 86% of all room charges were considered inpatient and 14% were considered outpatient. The room charges also represented the breakdown of patients requiring a medical-surgical room (i.e., oncology) charge or a labor and delivery room charge. Staff salaries and benefits were combined to represent labor expenses. The cost of unit supplies included product categories such as medical surgical supplies, IV sets and solutions, dressings, linens, and office supplies. Each cost was normalized to 2013 prices to account for any inflation that occurred during the study period.

Staff Satisfaction. Staff satisfaction was calculated via human resource (HR) metrics and a building occupancy survey. The HR metrics include total number of employees, staff tenure, turnover rates, number of vacancies, and time-to-fill and were provided by the Senior HR Manager. Throughout the study period, Magee underwent organizational changes in regards to hiring tactics. In particular, the inclusion of a culture survey and mandatory educational sessions for patient care technicians (PCTs) was designed to hire PCTs that better aligned with Magee's mission. The HR metrics are representative of typical organization data collection.

To understand how the green design and evidence-based design features of the new unit were impacting staff satisfaction and productivity, a building occupancy survey was distributed to all Unit 5800 staff. A copy of the survey questions is located Appendix B. The occupancy survey was based off of previous occupancy surveys well studied by the recognized Center for the Built Environment at the University of California, Berkley (Zagreus, Huizenga et al. 2004, Altomonte and Schiavon 2013). The survey for this research was reviewed and approved by the university's internal review board in the spring of 2014 and a secure survey link was emailed to staff twice over a three-week period in May 2014. There was a 40% response rate from staff.

The occupancy survey was broken down into eight distinct sections. The first section, Background, covered gender, age, occupation, tenure, and shift time. The second section, Workspace Use and Layout, was directed towards understanding the impact of the unit layout on staff. One unique question asked about the use of the meditation room, an evidence-based design feature that was prioritized for patient family care experience. The third section attempted to understand the impact of the unit aesthetics such as appearance, color schemes, and furnishings, with an emphasis on which outside view the staff member saw most of throughout the day. Thermal Comfort and Air Quality, the fourth section, questioned the level of satisfaction of temperature and air quality in patient rooms and the temperature and air quality in the shared workspace. The fifth section, Lighting, asked about electric and natural daylight in the patient rooms and the electric and natural day light in the shared workspace. The sixth section, Acoustic Quality and Speech Privacy, asked about the noise level on the unit, the ability to have private conversations, and level of distraction. Productivity was surveyed in the seventh section, asking how the overall thermal comfort, air quality, lighting, and outside view influenced unit staff productivity. The final section was a logic question that asked staff if they had worked on Unit 2800 prior to the move in 2012. If they answered "yes" survey volunteers were asked the same series of Workspace Use and Layout questions from the first section about their experience on Unit 2800. Approximately 70% of respondents were able to answer questions about Unit 2800.

Patient Satisfaction. Patient satisfaction can be a subjective set of metrics to understand for a number for reasons. First, there have been studies that show that patient satisfaction is the perception of health care and may not necessarily reflect the essential care received (Manary, Boulding et al. 2013). For example, if the medically correct response pathway is to do one thing, but the patient is adamant the clinicians do something else, the patient may perceive their health care as unsatisfactory, when in fact it is medically sound. Additionally, patient satisfaction surveys are delicate in nature and getting approval for inpatient surveys can be difficult. However, the Center for Medicare and Medicaid Services developed a national survey in 2002 for patient satisfaction – the hospital consumer assessment of healthcare providers and systems (HCAHPS) survey (Jha, Orav et al. 2008, HCAHPS 2014).

The HCAHPS survey has been a successful endeavor since it was implemented nationally in 2006 with its first public reporting period in 2008 (HCAHPS 2014). All US hospitals that participate in the Medicare and Medicaid programs are required (and incentivized) to collect and submit HCAHPS data in order to receive their annual payment support. The goals of HCAHPS are to 1) standardize the survey and implementation procedure for objective comparisons of hospitals, 2) HCAHPS public reporting creates incentives to improve quality of care, and 3) HCAHPS public reporting increases accountability and transparency of a hospital's quality of care (HCAHPS 2014). The HCAHPS survey is 32 questions long and contains 21 patient-perspective specific questions on topics such as communication with doctors, communication with nurses, responsiveness of hospital staff, pain management, communication about medication, discharge information, cleanliness of hospital, quietness of hospital, and transition of care. The survey is distributed at random to patients anytime between 48 hours to 6 weeks post discharge via postal mail, telephone, mail and telephone, or active interactive voice response (HCAHPS 2014). Magee had 542 HCAHPS participants for Unit 2800 and 587 for Unit 5800 for the study period.

4.2.1.3 Statistical Analysis

The metric data collected was analyzed via two-sample T tests to account for statistical differences between the two units studied. The statistical program MiniTab Express v1.2 was used for the analysis. Each data set had a normal distribution and variance and calculated with a 95% confidence interval. Data sets with a *P* value less than 0.050 were not considered statistically significant.

4.2.2 Results and Discussion

The Results and Discussion will address each group of metrics in the following order: quality of care, productivity, expenses, utilities, staff satisfaction, and patient satisfaction. An overview of the metrics analyzed can be found in Table 17.

Each metric that had a statistically significant difference between the pre-move Unit 2800 and the post-move Unit 5800 is explained in Figure 43. A positive change represents an increase in the metric for Unit 5800 compared to Unit 2800 while a negative change represents a decrease in the metric for Unit 5800 compared to Unit 2800. There were some metrics not considered statistically significant, which are described in Table 18 along with the mean of the data points for both Unit 2800 and Unit 5800.

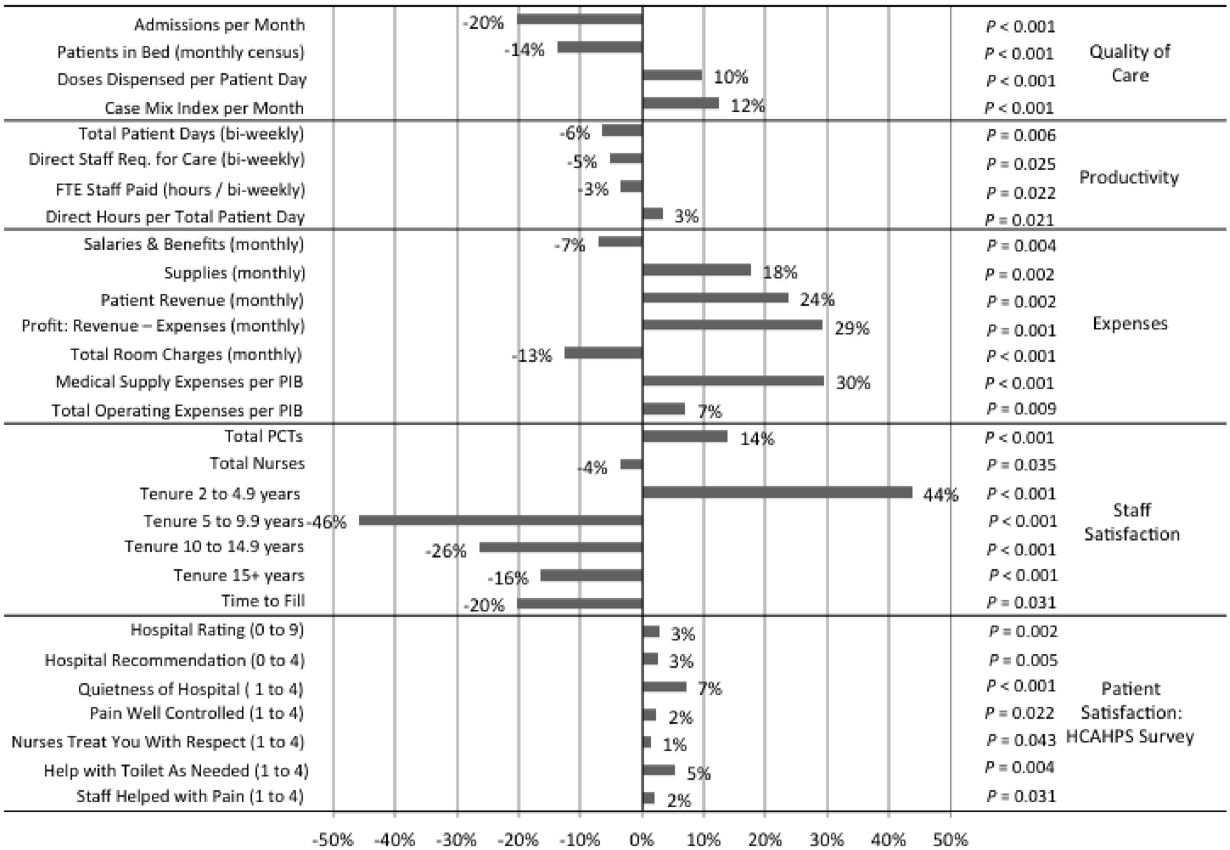


Figure 43: Statistically Significant Results; the percentage reflects the change for Unit 5800 (green/post-move) compared to Unit 2800 (traditional/pre-move); req. = required, FTE = full time employee, PIB = patient in bed, PCTs = patient care technicians, HCAHPS = hospital consumer assessment of healthcare providers and systems; a positive change represents an increase in the metric for Unit 5800 compared to Unit 2800, a negative change represents a decrease in the metric for Unit 5800 compared to Unit 2800

Table 18: Results for All Metrics Analyzed; LOS = length of stay, PIB = patient in bed, ADE = adverse dose event, Pt = patient, CLI = central line indections, APR-DRGS = all patient refined diagnosis related groups, DCD: design cost data, MCF: million cubic feet, cf: cubic feet, sf: square feet, kWh: kilowatt hours, kgal: kilo gallons, lbs = pounds, Unit 2800 = pre-move (December 2010 to May 2012), Unit 5800 = post-move (July 2012 to December 2013), a positive change represents an increase in the metric for Unit 5800 compared to Unit 2800, a negative change represents a decrease in the metric for Unit 5800 compared to Unit 2800.

	Metric Name	Unit 2800 Mean	Unit 5800 Mean	Trend
Quality of Care	Average LOS (per PIB)	3.51	3.41	-
	ADE Dispensed Near Miss (B)	0.11	0.22	+
	ADE Dispensed Reached Pt, no harm [C]	0.44	0.44	=
	ADE Doses dispensed Harm (D)	0.33	0.33	=
	Doses Dispensed per month	**	**	-
	ADE Dispensed (B) per Doses Dispensed	0.00	0.00	+
	ADE Dispensed (C&D) per Doses Dispensed	0.00	0.00	=
	ADE Dispensed (B,C,D) per Doses Dispensed	0.00	0.00	=
	Central Line Infection Rate: #CLI days	**	**	-
	Actual Mortalities per month	0.44	0.72	+
	Mortality Rate	0.23	0.43	+
	APR-DRGs	1.99	1.96	-
Productivity	Direct Staff Available for Care (bi-weekly)	31.35	30.45	-
	Total Paid Hours Per Total Patient Day	12.03	12.45	+
	Performance: Required Hours / Direct Hours	0.92	0.90	-
	Productivity: Required Hours / Paid Hours	0.65	0.64	-
	Worked Hours Per Patient Day (DCD Benchmark)	10.89	11.02	+
Utilities	Gas (mcf) - raw per month	12,897.10	12,447.50	-
	Gas (cf / sf) - per month	1.55	1.42	-
	Natural Gas (cf) - raw per month	12,719,536.00	14,352,500.00	+
	Natural Gas (cf / sf) - per month	15.24	16.41	+
	Electric (kWh) - raw per month	2,590,933.00	2,735,956.00	+
	Electric (kwh / sf) - per month	3.10	3.13	+
	Electric (kwh / PIB) - per month	8,0710.40	7,537.10	-
	Steam (lbs) - raw per month	9,530,566.00	10,733,278.00	+
	Steam (lbs/sf) - per month	11.42	12.29	+
	Water + Sewer (kgal) - raw per month	4,546	4,925	+
	Water + Sewer (gal / sf) - per month	5.46	5.64	+
Expenses	Total Labor (Salaries & Benefits) Expenses per PIB	**	**	+
Staff Satisfaction	Total Number Employees	41.50	42.56	+
	Total Other Employees (director, educator, etc.)	5.50	5.61	+
	Tenure <2 years	1.56	2.17	+
	Turnover - Number of Employees per month	0.56	0.72	+
	Turnover – Average Years of Service	6.98	2.13	-
	Vacancy - Number of Openings	13.50	5.50	-
	Vacancy - Ave Position Age (days)	41.70	34.37	-

Table 18 (continued)

Patient Satisfaction: HCAHPS Survey	Cleanliness of hospital environment (1 to 4)	3.52	3.58	+
	Nurses listen carefully to you	3.66	3.72	+
	Nurses explain in a way you understand	3.68	3.73	+
	Call button help as soon as wanted it	3.52	3.54	+
	Doctors listen carefully to you	3.72	3.78	+
	Doctors treat you with courtesy and respect	3.83	3.86	+
	Doctors explain in a way you understand	3.69	3.75	+
	Staff tells you what new medicine was for	3.74	3.72	-
	Staff described medicine side effects	2.99	3.00	+

4.2.2.1 Quality of Care

Quality of care measures the patient population and associated pharmaceutical metrics for each unit. In terms of patient population, there was a 20% ($P < 0.001$) decrease and a 14% ($P < 0.001$) decrease in number of admissions each month and number of patients in bed (PIB) each month for Unit 5800 (post-move) compared to Unit 2800 (pre-move). The patient length of stay (LOS) did not have a significant change between the pre- and post-move, averaging about 3.5 days for both units. The Case Mix Index (CMI), an indicator of patient complexity and resource intensity, had a 12% ($P < 0.001$) increase for the patient population in Unit 5800. In contrast, the all patient refined diagnosis related groups (APR-DRGs) which focuses on patient acuity, had no statistical significance between the two units with an average of 1.98 out of 4 (Avrill, Goldfield et al. 2003). This could potentially mean that the patient acuity level between Unit 2800 and Unit 5800 stayed relatively the same, yet the resources needed to care for the patients in Unit 5800 increased.

Pharmaceutical metrics also defined the quality of care. There were four different medical errors (described in the Methods section) measured for each unit: adverse drug event (ADE) B, C, D, and central line infections (CLI). All four medical error metrics were inconclusive of significant differences between the two units, whether each metric was measured individually, together, or normalized to the number of doses dispensed. The number of doses dispensed per patient day did have a 10% ($P < 0.001$) increase, eluding to the change in the Case Mix Index, Unit 5800 having more complex patients requiring more resources for care.

4.2.2.2 Productivity

Productivity metrics were captured by the hospital-wide nursing reports, produced bi-weekly by each Unit Director. For Unit 5800, there was a 6% ($P = 0.006$) decrease in total patient days compared to Unit 2800. The number of direct staff required for care also decreased 5% ($P = 0.025$). Though not statistically significant, the mean number of direct staff available for care was also slightly lower for Unit 5800. There was a 3% ($P = 0.022$) reduction in paid staff, but a 3% ($P = 0.021$) increase in direct hours per total patient day for Unit 5800. Neither the performance or productivity metric was statistically significant; the means for Unit 2800 and Unit 5800 were nearly the same at a 90% performance rate and a 65% productivity rate. Overall, the number of staff needed for Unit 5800 decreased in response to a smaller patient population, while the other productivity metrics stayed relatively the same compared to Unit 2800.

4.2.2.3 Utilities

None of the utility metrics had a statistically significant difference between Unit 2800 and Unit 5800. The new addition increased Magee's total overall square footage by 5% and the number of beds by 12%. The addition was not as substantial in relation to the entire building and is evident in all four utilities looked at: electricity, natural gas, water/sewage, and steam. An overview of the utilities in absolute value can be found in Figure 44. The data is not statistically significant enough to say that Magee's addition had enough energy efficiency strategies to reduce all hospital wide utility consumption, though there was downward trend in utilities per patient bed.

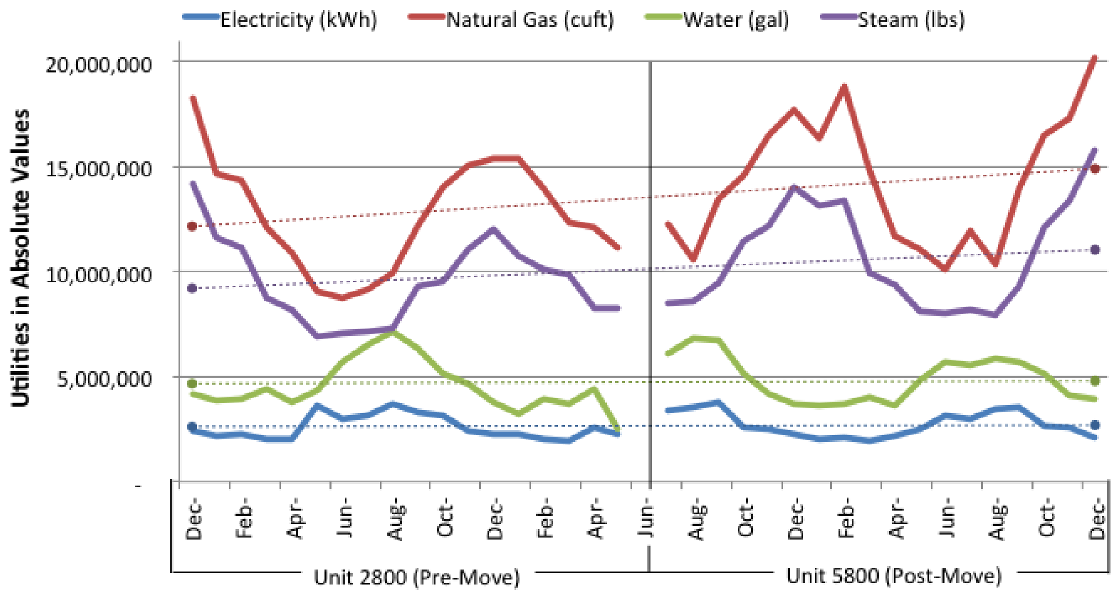


Figure 44: Utility data for Magee in absolute values; kWh = kilowatt hours; cuft = cubic feet; gal = gallons; lbs = pounds

4.2.2.4 Expenses

Seven of the eight expense metrics were statistically significant. Staff salaries and benefits per month decreased by 7.2% ($P = 0.004$) while the cost of medical supplies per month increased by almost 18% ($P = 0.002$). Unit 5800's inpatient revenue increased by 24% ($P = 0.002$) while total room charges per month decreased by 13% ($P < 0.001$) over Unit 2800. That said Unit 5800 had an average 29% ($P = 0.001$) increase in profit each month. Though the salaries and benefits normalized to PIB was the one metric statistically insignificant, there was a 30% ($P < 0.001$) increase in medical supplies per PIB and a 7% ($P = 0.009$) increase in operating expenses per PIB for Unit 5800. The expense metrics illustrate that Unit 5800 has patients that require more expensive treatment than the patient population found on Unit 2800. Specifically, the total room charge data was described as either a "medical room" or a "labor and deliver room (LDR)" and the average breakdown of room charges for Unit 2800 was 80% medical room and 20% LDRs while Unit 5800 had a 99% medical room rate with only 1% LDRs. The room charge breakdown suggests that the cost of supplies and operations for LDRs is less than what a medical room for oncology requires.

4.2.2.5 Staff Satisfaction

Staff satisfaction via the human resource metrics helped identify any staff changes from Unit 2800 to Unit 5800. The average number of staff on Unit 2800 was 41.5 people, while the average number of staff on Unit 5800 was 42.5. In general, the staff on Unit 2800 had longer tenure than on Unit 5800, as indicated in Figure 43. Unit 5800 found that there was a 42% ($P < 0.001$) increase in staff with less than 5 years of experience and there was a 27% ($P < 0.001$) decrease in staff with more than 5 years of experience compared to Unit 2800. In terms of staff positions, there was a 14% ($P < 0.001$) increase in patient care technicians (PCTs) and a 3.5% ($P = 0.0348$) decrease in nurses for Unit 5800. The number of other staff such as the unit director had no significant change between the units.

In regards to hiring metrics, neither Unit 2800 or 5800 had unwieldy changes. Over the course of 18-months pre-move, Unit 2800 had 11 staff turnovers of which 55% were PCTs and 36% were nurses. Unit 5800 had 13 turnovers during the post-move timeframe, 69% were PCTs and 31% were nurses. Although Unit 2800 had a slightly lower number of turnovers compared to Unit 5800, Unit 2800 had 14 vacancies while Unit 5800 had 6 vacancies. Unit 5800 also had a 20% ($P = 0.031$) decrease in vacancy time-to-fill, the average of 42 days in Unit 2800 dropped to 35 days in Unit 5800.

During the study's three-year timeline, there has been a hospital-wide issue with sustaining PCTs, as indicated by the turnover numbers for both units. The HR department has developed a cultural assessment for PCTs to take in addition to their application to educate potential candidates on Magee's mission. There has been some success with this pilot program, but PCTs apply via an open continuous requisition form that feeds all requests throughout the hospital. On the other hand, nurses apply directly to a specific opening for a unit. It is difficult to associate the retention of a PCT to the individual unit, when a PCT has little unit designation when applying. It has recently been brought to the Talent Acquisition team at Magee to advertise the green space when posting nursing positions for Unit 5800.

Staff satisfaction was also determined through a building occupancy survey, distributed voluntarily to all personnel on Unit 5800. According to the Background questions, 94% of respondents were female, while 6% were male, 56% of respondents were between the ages of 31 and 59, 69% were nurses, 50% had worked on Unit 5800 for more than 2 years, and 62% of respondents primarily worked the day shift. The other survey sections (Workspace & Layout, Aesthetics, Thermal Comfort & Air Quality, Lighting, Acoustic Quality, and Productivity) had one or two multiple choice questions specific to the survey section followed by a set of 5-point satisfaction scale questions and a set of 7-point enhanced scale questions. An overview of the all the satisfaction questions is described in Figure 45 and the enhanced questions is described in Figure 46.

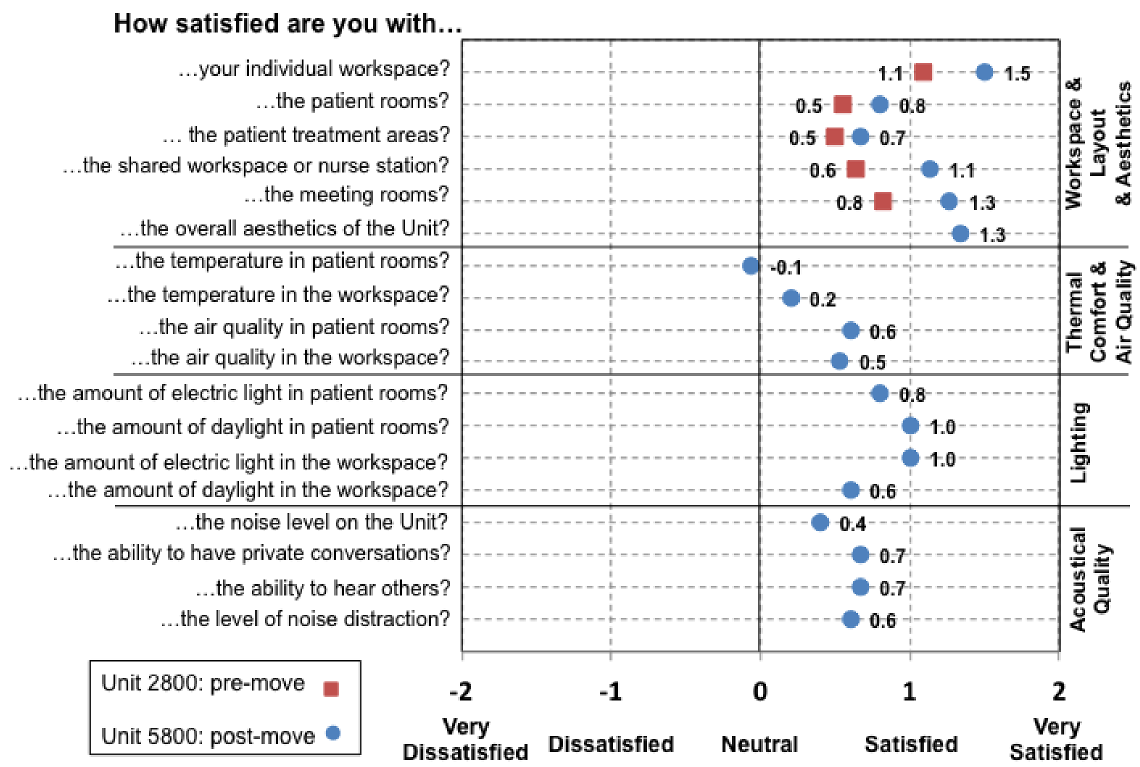


Figure 45: Staff satisfaction results

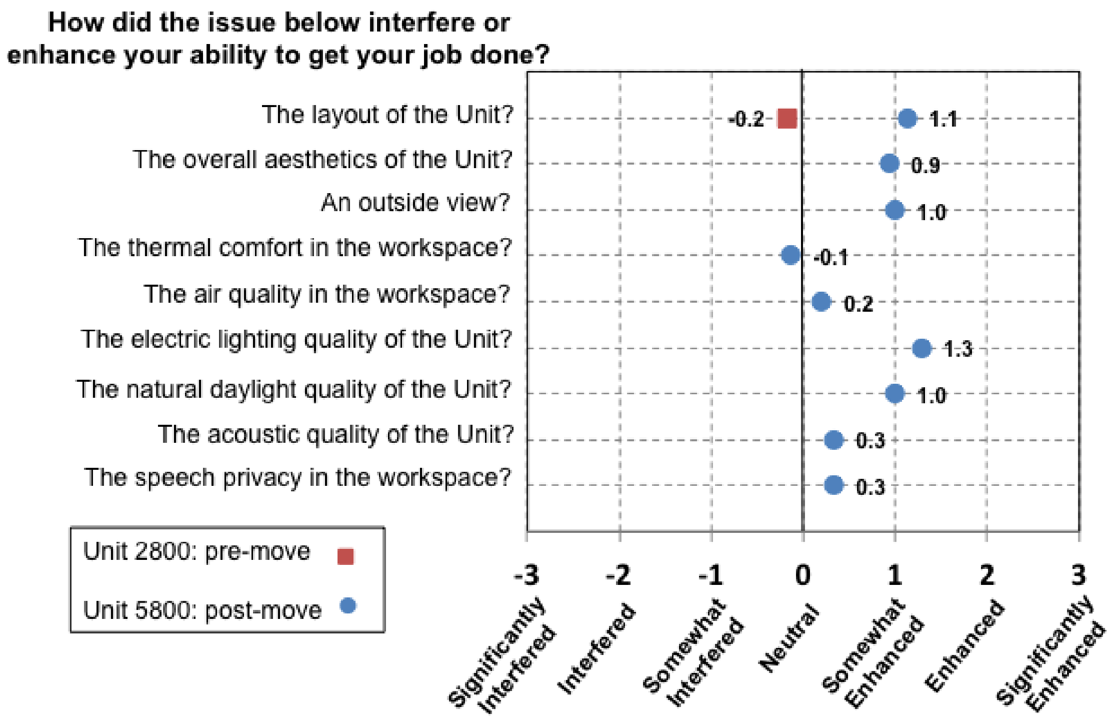


Figure 46: Staff Interfere or Enhance Survey Results

Workspace & Layout. The Workspace & Layout section was the only section survey volunteers were asked about for both Unit 5800 and Unit 2800, as indicated by the red square mark on Figure 45 and Figure 46. Due to survey length, only one section asked questions about both Unit 55800 and Unit 2800. When asked what percentage of the workday is spent in various locations in the unit, the top results show that 45% of staff spends their day in patient rooms and 30% of their day at a shared workspace or desk space (i.e., a nurse station). Of the five satisfaction scale questions asked for Unit 5800, the averaged hovered around 1.1 or “Satisfied”, while the average for Unit 2800 was about 0.7, or between “Neutral” and “Satisfied”. For job interference, the survey results indicate that the staff on Unit 5800 felt the layout of the unit “Somewhat Enhanced” their ability to get their job done, while the staff on Unit 2800 felt slightly less than neutral about the unit’s layout.

One revelation by the survey results was in regards to the Meditation Room, shown in Figure 47. The design of the Meditation Room was endorsed as a calming element for patient families and staff and as a location to have private conversations. Unfortunately, when asked "How do you use the Meditation Room?" 56% of respondents said that they do not use the Meditation Room at all. About 22% of staff said they did use the Meditation Room for private conversations, either with patient family member or with other staff and 17% said they use the quiet space for conference calls or for reporting. Only 6% of staff said they use the Meditation Room for meditation purposes or to have a quiet break. Though the idea of the Meditation Room resonates with EBD elements, the execution of the room was not as successful. Potential improvements could be to rename the space or making the space into an official patient family meeting room.

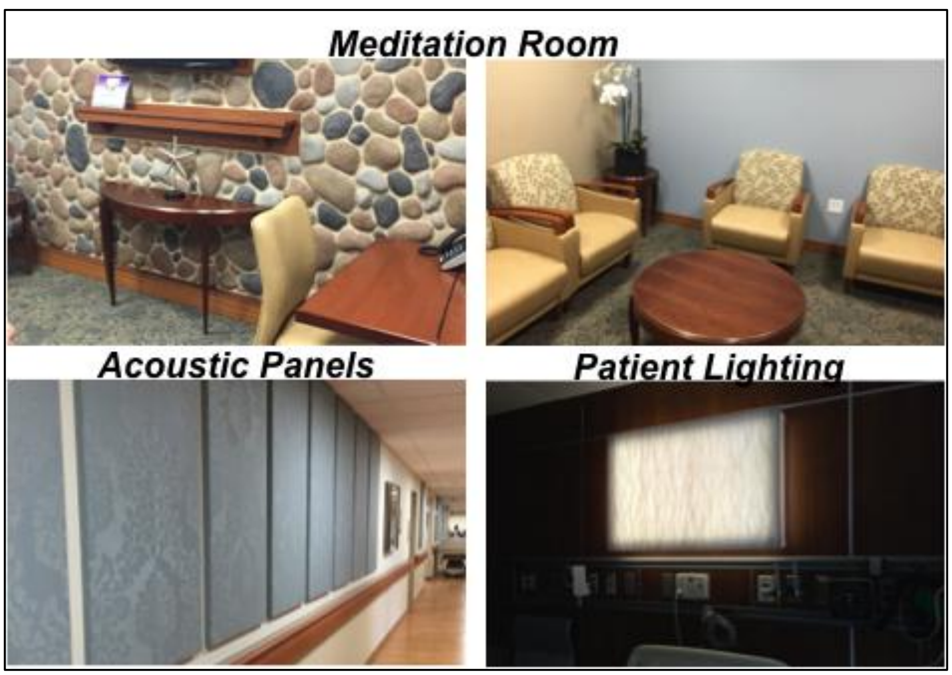


Figure 47: Unit 5800's Mediation Room, Acoustic Panels, and Electric Lighting

Aesthetics. The Aesthetics section of the survey was aimed at understanding how the design of Unit 5800 affected staff. Approximately 93% of survey respondents were "Satisfied" or "Very Satisfied" with the unit's aesthetics, including overall appearance, color schemes, and furnishings, yet only considered the overall aesthetics to "Somewhat Enhance" their ability to get their job done. Another important EBD element that has been well studied is the proximately to a window overlooking an outside view. There are three views that can be seen by the patient rooms: 12 rooms have a view the synthetic green roof, 8 rooms have a view of the city, and 4 rooms have a courtyard view, as shown in Figure 42. Of the survey respondents, 40% said they saw the green roof the most during a typical day while 33% saw the city view the most, which corresponds to the number of patient rooms on the north west corridor (16) versus the number of patient rooms on the north east corridor (8). The other 27% of survey respondents said they saw a combination of all views equally throughout their day. When asked how the outside view interferes or interferes with the ability to get the job done, a majority wrote in "It doesn't" or "none", however a couple wrote in "a workspace without windows would be miserable" and "nice to look outside and see a nice view, it breaks up the monotony". The overall aesthetics and outside view had similar "Somewhat Enhanced" responses for the staff's ability to get their job done.

Thermal Comfort & Air Quality. The most negative trending results found in the staff survey pertain to the thermal comfort of Unit 5800. The satisfaction for thermal comfort in the patient rooms and in the shared workspace had an average of -0.1 and 0.2, hovering at the "Neutral" selection. Though 73% of respondents said they had the ability to adjust or control thermostats, one of the EBD features was the installation of thermostats in each patient room for patient comfort and use, not exactly for staff use. This alludes to any thermal comfort discrepancy between patient (comfortable and has control) and staff (uncomfortable and no control). Again, the thermal comfort had a slight negative trend toward job interference at -0.1. Air quality, such as stuffy or stale air, faired better by survey respondents. For air quality in patient rooms and in shared workspaces, the results showed a 0.5 and 0.6 average response for satisfaction, halfway between "Neutral" and "Satisfied". The response for job interference or enhancement was generally "Neutral" at 0.2. Though thermal comfort and air quality were the most neutral of all survey responses, the design of the unit was directed toward patient control.

Lighting. Lighting, specifically natural day lighting, has been well studied in hospitals and commercial building spaces and linked to increased productivity levels and satisfaction (Zimring, Ulrich et al. 2008, Choi, Beltran et al. 2012). The amount of electrical light in patient rooms and in the shared workspaces resulted in a 0.8 and 1.0 or "Satisfied" response. Natural daylight in the patient rooms was also at 1.0 or "Satisfied", however natural daylight in the shared workspace had a lower response at 0.6 or halfway between "Neutral" and "Satisfied". Looking at the layout of Unit 5800, Figure 42, it is obvious that the majority of the rooms that have windows are patient rooms, where there is no transmissible daylight into the hallways and other shared workspaces because they are located on the interior of the unit.

Staff had the strongest response to the quality of electric lighting on the unit than any other issue posed, an example of a lighting feature shown in Figure 47. The average response for how electric lighting influenced job ability was a 1.3 between "Somewhat Enhanced" and "Enhanced" on the 7-point scale. The natural daylight on the unit had a 1.0 or "Somewhat Enhanced" average. When asked how does the natural light enhance or interfere with your ability to get your job done, one respondent wrote: "the windows provide a sense of openness that helps patients feel not quite as cooped up". Though slightly lower than the electric light, it must be acknowledged that any hospital unit has design challenges with layout and the incorporation of natural daylight into all areas of the unit.

Acoustics. The designers of Unit 5800 paid close attention to the acoustical quality and details, as quieter hospital units have been shown to help patient recovery and pain management, an example of the noise reducing panels shown in Figure 47 (Blomkvist, Eriksen et al. 2005, Gardner, Collins et al. 2009). Of the 4 satisfaction questions, the noise level on the floor had the lowest satisfaction average at 0.4 between “Neutral” and “Satisfied”. The ability to have a private conversation and the ability to hear others both had a 0.7 average and the level of distraction had a 0.6 average, both closer to “Satisfied” than “Neutral”. For the interferes or enhances the ability to get the job done line of questions, both the general acoustic quality and speech privacy in the workspace questions rendered a 0.3 or close to “Neutral” response. Some of the comments by survey respondents about Unit 5800 mention that the new HVAC system on the roof above the unit was very loud and interrupted staff work and initiated patient complaints, which may be the reason for the lower satisfaction results.

Productivity. The last section of the survey asked 4 questions in regards to survey volunteer’s perception on productivity; the results are shown in Figure 48. The thermal comfort had the lowest productivity response at 0.2, as mentioned above in the *Thermal Comfort* section. Lighting had the highest impact on productivity at 0.9, while air quality and the outside view had similar results at 0.5 and 0.6 respectively. The productivity results align with the satisfaction and interference/enhance questions for the sections described above.

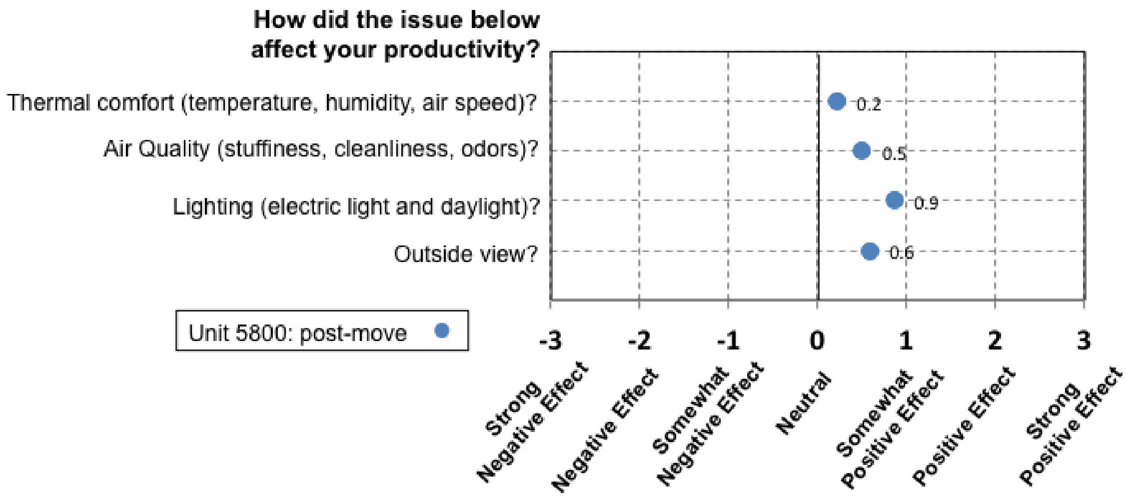


Figure 48: Staff productivity results

4.2.2.6 Patient Satisfaction

Patient satisfaction was determined by the hospital consumer assessment of healthcare providers and systems (HCAHPS) survey. Magee had 542 HCAHPS participants for Unit 2800 and 587 participants for Unit 5800 for the study period. This study looked at 16 HCAHPS questions, omitting background questions such as gender or race. All questions were based on a 1 to 4 scale (1 = never, 2 = sometimes, 3 = usually, 4 = always) with the exception of the hospital rating question that had a 0 to 9 scale (0 = not recommend to 9 = highly recommend). Compared to the Unit 2800 answers, there was an increase in all responses for Unit 5800, and 7 of the 16 questions were statistically significant.

There were two general hospital questions, both of which had a positive change from Unit 2800 to Unit 5800. The "would you recommend this hospital" question improved from a 3.70 to a 3.80, or a 2.8% (*P = 0.002)*, out of the 4-point scale. The hospital rating question (0 to 9 scale), improved from 8.33 to 8.57, or 2.5% *(P =0.005).* The hospital environment questions, about cleanliness and quietness, saw improvements as well. Though hospital cleanliness was statistically insignificant, the unit means had a slight increase from 3.52 to 3.58, while the hospital quietness had the largest increase in patient satisfaction from 3.42 to 3.68, or 7.1% ($P < 0.001$). Hospital quietness has been linked to better pain management and reduced stress.

Patients' perceptions of "pain well controlled" saw a 2.4% ($P = 0.022$) increase from 3.60 to 3.68. Coincidently, the "staff did everything to help with pain" had a 2.1% ($P = 0.021$) increase from 3.71 to 3.79 and the "help with the toilet as soon as wanted it" had a 5.3% increase ($P = 0.004$) increase from 3.42 to 3.61. The "call button: help as soon as wanted it" was not statistically significant, increasing from 3.52 to 3.54. Both the "staff tells you what new medicine was for" and "staff described medicine side effects" questions also had little to no difference between the units.

There were three nurse and three doctor specific questions in regards to patient care. The nurse or doctor "listens carefully to you" increased from 3.66 to 3.72 and 3.72 to 3.78, but neither were statistically significant. The "nurses treated you with courtesy and respect" increased from 3.78 to 3.84, or 1.4% ($P = 0.043$), while the doctors counterpart had a smaller increase from 3.83 to 3.86. The last set of nurse and doctor questions was "explain in a way that you understand", which rendered similar results for nurses from 3.68 to 3.73 and for doctors from 3.69 to 3.75. Of the six questions, only one was statistically significant, although there was a positive trend for the others.

4.2.2.7 Study Limitations

With any comparative study, limitations arise that must be noted. The motivation for building a new oncology unit was the overflow from the labor and delivery service (LDR). The patient mix on Unit 2800 was approximately 20% LDR and 80% oncology medical-surgical service, while the patient mix on Unit 5800 was only 1% LDR and 99% oncology. Though the study parameters attempted to minimize variables, the patient mix may have had more of an impact on the study results than originally predicted. Another limitation is the absence of an available pre-occupancy survey. Though more than half of the survey respondents were able to answer questions for both Unit 5800 and Unit 2800, a full pre-occupancy survey would have had more insight to the challenges of Unit 2800 during real-time as opposed to a year and half hiatus. The survey was also challenging because a number of the questions posed asking how one feature interferes or enhances the respondent's ability to get their job done (which is a standard set of building occupancy survey questions), the respondent – mostly nurses – may have felt as though the questioning was targeting their work ethic as opposed to the focus on the design feature. Also, due to survey length, only the Workspace & Layout set of questions were asked for both Unit 2800 and Unit 5800, while in hindsight, it would have been valuable to have comparisons among among all questions sets. One other limitation was the small study set of a 28-bed unit. Some metrics, such as adverse drug events or central line infections, only occurred once every other month, so the event to month ratio was very small and difficult to compare.

4.2.3 Conclusion

Results Summary. The general understanding of all the results hinges on the breakdown of patient mix. Unit 2800 (traditional/pre-move) had an average mix of 20% labor and deliver (LDR) and 80% women's oncology, while Unit 5800 (green/post-move) is 99% women's oncology. The main reason Magee decided to build the Unit 5800 addition was to address the labor and delivery overflow. By comparing the two units, Unit 5800 had about 20% ($P < 0.001$) less admissions per month and a 14% ($P < 0.001$) decrease in patients in bed (PIB) per month, which coincides with Unit 2800's 20% LDR patients mix. Oncology patients typically require more resources than LDR patients, as evidenced by the 10% ($P < 0.001$) increase in doses dispensed per patient day and 30% ($P < 0.001$) increase in medical supply expenses per PIB. Consequently, the case mix index (CMI), an indication of patient acuity and resource intensity, saw a 12% ($P < 0.001$) increase over Unit 2800.

The patient mix and population had an impact on the nursing reports or the set of productivity metrics. Unit 5800 has fewer patients than Unit 2800 during the study period; therefore, it is understandable that the direct staff required for care decreased by 5% ($P = 0.025$). Because there was less staff required for care, there was also a decrease in direct care available for care. The number of staff required by hospital policy for patient to nurse ratio decreased; therefore, staff scheduled to work also decreased. With less unit staff scheduled to work, the number of full-time employees paid decreased by 3% ($P = 0.022$). The human resource metrics also concluded that even though Unit 5800 had three more turnovers than Unit 2800, there were 40% less vacant positions. Time to fill also decreased by approximately 20% ($P = 0.031$) for Unit 5800.

For patient and staff satisfaction, the HCAHPS and building occupancy surveys were able to elucidate perceptions of Unit 5800 over Unit 2800. Both surveys trended in favor of Unit 5800. The only question with conflicting results was in regards to noise. The HCAHPS survey found that there was a 7% increase in "quietness of hospital environment" for green Unit 5800 from the patients' perspectives, the largest difference in any of the HCAHPS questions. However, the acoustic quality questions on the *staff occupancy survey* faired the closest to "neutral" than all other questions. An assumption for this discrepancy could be that Unit 5800 is inherently quieter than Unit 2800, as per the HCAHPS survey, and therefore any obtrusive noise – such as the HVAC systems on the roof as the staff survey states – may be more memorable than previous experiences on Unit 2800. Interestingly, one open-ended question posed "how does the natural daylight enhance or interfere with your ability to get your job done" was trying to understand how windows impact a person's daily work, but three responses said either "does not" or commented on how windows impact patients, not staff. During meetings with nursing management, they suggested that the responses might indicate the determined work ethic most recognizable with nursing staff; in other words, nurses will perform their work no matter what the conditions.

Conclusion. The addition of Magee's hospital aimed to increase patient recovery rates while reducing environmental impacts through evidence-based design and green building design features and strategies. This study attempted to capture the impact of both EBD and green building strategies by analyzing different metrics across a three-year period for the same unit (women's oncology) spanning the traditional hospital space and the new green addition. The goal of the study was to answer the question – *to what extent did green hospital building design features affect patient outcomes, employee performance, and satisfaction?*

This study delved into many aspects of a hospital unit to determine how EBD and green building design features could impact different performance metrics. Of the six metric categories analyzed, quality of care, productivity, and utilities all stayed relatively unchanged from Unit 2800 (traditional/pre-move) to Unit 5800 (green/post-move) with a slight decrease in number of staff needed due to lower census. Expenses, staff satisfaction, and patient satisfaction saw a general upward trend from Unit 2800 (traditional/pre-move) to Unit 5800 (green/post-move). In conclusion, the main findings related to green building design and evidence-based designs are as follows:

- After reviewing the patient satisfaction HCAHPS survey, the patients responded to the EBD features and the quietness of Unit 5800. The acoustic panels installed on Unit 5800 as an EBD feature for noise reduction corresponded to the hospital quietness question, which increased 7.1% ($P < 0.001$) from Unit 2800 (traditional/pre-move) to Unit 5800 (green/post-move). Magee is updating other units with these acoustic panels in response to the positive feedback from Unit 5800. In addition, all of the HCAHPS questions improved from Unit 2800 to Unit 5800.
- Based on the building occupancy survey for staff satisfaction, the workspace layout, lighting quality, and Meditation Room were the most noteworthy findings. A staff nurse was hired to help with the design of Unit 5800 to optimize the layout, which is evident by the interference or enhancement question average for workspace layout that increased from -0.2 (between somewhat interfered and neutral) on Unit 2800 to 1.1 (between somewhat enhanced and enhanced) on Unit 5800. Lighting, designed with EBD and green building strategies, rendered positive responses with an average 1.3 (between somewhat enhanced and enhanced) for electric lighting and 1.0 (somewhat enhanced) for natural daylighting for Unit 5800. While the evidence-based design of the Meditation Room was introduced as a calming element for patient families and staff and as a location to have private conversations, 56% of survey respondents said that they do not use the room at all.
- In order to understand the impacts that EBD and green building design has on hospital utilities, individual unit sub-metering systems are highly recommended. If hospitals are going to continue to invest in energy efficient solutions, it is important that hospitals are able to quantify the savings of their investments.

- The quality of care category, such as medical errors, had no significant change from Unit 2800 to Unit 5800. Considering that the patient population for Unit 5800 had a 12% ($P < 0.001$) increase in Case Mix Index and a 10% ($P < 0.001$) increase in doses dispensed per patient day, the fact that quality of care stayed the same is a positive attribute of Unit 5800.
- Despite previous findings that EBD and green building design features increase staff productivity (Thiel, Needy et al. 2014), the results of staff productivity for this study were unchanged from Unit 2800 (traditional/pre-move) to Unit 5800 (green/post-move).

Evaluating pre- and post-move metrics can help quantify which design elements (for both green building and EBD) have the largest impact on building performance (i.e., utilities) as well as occupant satisfaction and productivity. This information can help future building designers prioritize which design elements are worth investing in and what data is available for comparisons. Constant monitoring of utilities, staff satisfaction and human resources, nursing reports and quality of care, and HCAHPS surveys will educate any persons attempting to track, trend, and change specifics for a hospital unit or building. EBD and green building design features will continue to influence the healthcare industry through efficient design elements that create a holistic healing space for patient recovery and staff satisfaction.

4.3 EVIDENCE-BASED DESIGN AND LCA INTEGRATION

The built environment has a profound impact on the natural world as well as individuals' physical health and well-being (Devlin and Arneill 2003, Tester 2009, Feng, Glass et al. 2010).

Buildings are responsible for up to 40% of the total energy use and 70% of the total electricity use in the United States (US DOE 2009, Juan, Gao et al. 2010). Beyond that, people spend 90% of their time indoors and are exposed to air pollutant levels 2 to 5 times higher than outdoor values (EPA 2010). To offset the environmental, economic, and social impacts of the building industry, green and efficient building design has become more prevalent. However, the social and health benefits of green buildings can be difficult to quantify, and it is unknown if green buildings are performing as intended (Needy, Gokhan et al. 2007). Quantitative methods to assess the impacts of green building design choices are needed to continue advancing sustainable infrastructure and to improve the health of building occupants.

*Evidence-based design (*EBD) has been the primary method for understanding building design in relation to occupant satisfaction (Ulrich 2001). *Green building design* typically focuses on the physical properties of the building – construction materials, energy efficient systems, and water use reduction. Previous green building occupant studies have analyzed company-collected data such as worker productivity, employee absenteeism, or sick leave; yet their results do not necessarily reflect design features (Kats, Alevantis et al. 2003, Ries, Bilec et al. 2006, Seppänen and Fisk 2006, Loftness, Hakkinen et al. 2007, Wiik 2011). Evidence-based design (EBD) focuses on occupant satisfaction in the context *of* healthcare *building design*; however, EBD is not entirely reflected in *green building design.*

The use of the quantitative tool LCA has been well documented in relation to green building design (Optis 2008, Ramesh, Prakash et al. 2010, Singh, Berghorn et al. 2010, Rajagopalan, Bilec et al. 2012, Parrish and Chester 2014). *However, the link between LCA and EBD is nonexistent.* Integrating the environmental impact of occupant satisfaction though EBD strategies are a novel idea in quantifying design impacts from a different perspective (Castro, Mateus et al. 2014, Harris 2014, van Hoof, Rutten et al. 2014).

For healthcare, there is potential synergy and conflict between EBD strategies and the sustainability goals set forth by the design team. There is a strong tendency for cooperation among patient health and safety with sustainable sites, pollution reduction, material waste reduction, energy reduction, and management well being (Castro, Mateus et al. 2014). However, there may be more conflict with reducing operational energy and the quality of service provided. It is difficult to quantify building occupant perceptions; once this program is developed in a way that can connect EBD with LEED (or another green building rating system), and subsequently LCA, the results will provide quantitative data to allow for data driven decision-making that can further develop the sustainable built environment.

5.0 CONCLUSIONS

Chapter 5.0 summarizes the major findings from the first, second, and third research questions. Next, the progress of LCA in the building and healthcare industries, as indicated by the first, second, and third research questions, is analyzed to develop recommendations for future LCA applications. Last, future research on the topic of LCA applications is discussed. The evolution of Chapter 5.0 addresses the final research question "what strategies are needed to advance LCA in both the building and healthcare industries, with the assumption that the building industry may be able to provide recommendations for the healthcare industry?"

5.1 BUILDING OVERVIEW

Three building LCA studies were presented in Chapter 2.0. The first study quantified the environmental impacts of the building materials used in a net-zero energy building and compared the results to traditional building materials LCAs. The study found that the materials used for the renewable energy systems in the net-zero energy building had 10% higher global warming potential and nearly equal embodied energy per square foot relative to standard commercial building materials. Although some environmental impact categories were higher for the net-zero energy building materials, it is assumed that the net-zero energy building would have less environmental impacts during the building's use phase compared to traditional buildings. As more building are designed to meet net-zero energy goals, the embodied energy of the materials plays an increasingly important role. Life cycle assessment should be considered a necessary part of net-zero energy buildings to understand how the embodied energy of materials is allocated during a building's use phase. With more quantitative data that accurately depict sustainable processes (such as net-zero energy designation), the connection between materials, embodied energy, operational energy, and total life cycle energy will become clearer. Another significant finding was that LCAs conducted post building construction produce results that are informative to the building owner. In other words, the LCA results are static relative to potential building design or operational improvements; though the LCA results do have academic merit with respect to net-zero energy designation.

To improve upon the static building LCA results produced in the first study, a second study was presented that occurred in real-time (as opposed to post-construction) and incorporated life cycle cost assessment (LCCA) as an example of a building assessment that resonates with building owners and as platform for integrating LCA. The second building LCA study honed in on a retrofit case study of Building 669. Two different roof replacement scenarios were analyzed with LCA, LCCA, and energy modeling to provide the building owner with quantitative data to make an informed roof selection decision. Based on the LCA, LCCA, and energy modeling results of the two different roof options, it is recommended that Building 669 use a black EPDM roof over the white PVC roof for their retrofit. The LCCA analysis proved to be more of interest to the Building 669 owner. The Building 669 owner would look at initial costs first, maintainability second, and potentially other life cycle costs and/or energy considerations. This study concluded that budget limitations have a significant impact on a building owner's decision to invest in LCA, LCCA, or energy modeling for various retrofit projects or systems, though

LCCA is more likely to be applied over LCA and energy modeling. It was also evident from the study's results that an established process is needed to link LCA to other building assessments in order to reduce redundancies, identify shared information, and enhance traditional building decision-making.

The last building LCA study presented aimed at elevating the current status of building LCAs, as defined by the first and second studies, to an approachable process that could be realistically applied across the building industry. The last study developed a pathway between LCA and integrative project delivery (IPD), a building project delivery method. The pathway discussed how IPD could be an avenue for LCA and other supportive building tools such as LCCA or building information modeling (BIM). Transparency in EPDs (environmental product declarations) and market encouragement will continue to shift the building and construction materials industry, increasing the awareness of suppliers and producers. As automated building monitoring systems become more commonplace in managing buildings during the use phase, the addition of dynamic LCA (DLCA) could be a commercial tactic to tracking environmental impacts of a building throughout its use phase. Continuing to grow the body of building LCA knowledge will increase the need for green building validation, the use of environmentally preferred products, and the understanding of human consumption.

These studies represent the progress of building LCAs. Moving from a more static result of building materials LCAs to the inclusion of building tools like LCCA to a complete integrative approach to building LCAs. The use of LCA in green building rating systems such as LEED will increase the scientific merit behind green building certification. LEED also has a strong association with market transformation. Optimizing LCA in the building industry through integrative project delivery and the addition of building owner desired tools will improve green building certification and market transformation.

5.2 HEALTHCARE OVERVIEW

Three healthcare LCA studies were presented in Chapter 3.0. First, a comparative LCA was conducted on two different birth procedures: a vaginal birth and cesarean birth. The disposable materials, reusable instruments, machines and energy consumption, and waste management were considered for each birth. For all births, the processes contributing the most to environmental impacts were energy consumption due to HVAC, the end of life impacts of the disposable custom packs, and the production of the disposable custom packs. This study was paramount for future sustainable healthcare work at Magee.

The second LCA study presented was in response to the findings of the first study. This study analyzed the environmental impacts of disposable custom packs for a vaginal birth procedure from 12 US hospitals, 2 Thai hospitals, and 1 nonprofit medical supply organization. This study identifies disposable cotton towels as a significant component of the environmental impacts of custom pack materials. Cotton production requires a significant amount of water, land, fertilizer, and labor; approximately 6.6 kg of CO2 equivalents and 0.024 kg of N equivalents are emitted into the atmosphere for the production of 4 towels per study results. Three recommendations were made to streamline disposable custom packs for any procedure: 1) use design for the environment strategies and LCA results in collaboration with clinician input to develop best practices to determine which products should be included in custom pack products; 2) reduce disposable cotton products and reuse after laundering when possible; 3) streamlining has the potential to reduce cost, waste and environmental impacts and should be considered in greening efforts. The healthcare industry has great potential for reducing environmental impacts and the use of LCA to verify environmentally preferred products will have a profound affect on alternative material choices and EOL scenarios.

The last study presented is a set of strategies and recommendations that could be applied to any healthcare institution attempting to green their practice. The recommendations are based off of the results and strategies found in the two healthcare LCA studies presented, Magee's experience with greening efforts, and Practice Greenhealth guidelines (PracticeGreenHealth 2008). Once a green team is established, they will move through the greening process: identify baseline, set goals, identify strategies, establish timeline, gather data and results, compare results to baseline, report. Creating collaborative platforms and spaces for healthcare institutions to share their progress and work together to overcome sustainability issues such as leadership push back or financial restraints will result in a uniformed approach towards sustainable healthcare. The healthcare industry will continue to change and there are tools and resources available to shift healthcare towards a more sustainable industry.

5.3 BUILDING AND HEALTHCARE SYNTHESIS

The building and healthcare industries are seemingly different, yet their overlap is extensive, especially in the context of building occupants, material selection, and use phase. There is a tremendous amount of potential for LCA to enhance a sustainable environment for both the building and healthcare industries. After taking inventory of past and present applications of LCA in each industry, the following recommendations are suggested for the future use of LCA.

1) An *integrative approach* for any project type should be considered. Regardless of initial goals, setting up a project infrastructure that can adapt and evolve with a project's progress is beneficial for all parties involved. For example, in a building design project, an integrative approach can follow through the design, construction, and use phase of a buildings from a multitude of facets – design choices, product selection, building occupancy, energy consumption. For the healthcare industry, the projects developed are primarily found in the use phase of the industry therefore establishing a strong network foundation will be essential in the integrative approach. Projects in the healthcare industry will tend to build off of one another, especially in the realm of one institution, as evident by the past and present studies presented in the dissertation.
2) *Data collection* is a fundamental part of any project or assessment. Honing in on the data available and configuring the information in an understandable format allows for data driven decision-making. The EBD study highlighted the immense amount of data that hospitals collect on a daily or monthly basis and the impact of manipulating the data to identify trends and visualize changes in staff and patient satisfaction. This is also true for buildings and the more progressive role of dynamic LCA. Data uncertainty should also be addressed to minimize the variables and potential errors. Emphasizing the role of data within each project scope will further the sustainability goals and outcomes while developing a supportive evidence towards future projects.
3) The need for *transparency and public education* is the catalyst for all sustainable projects. Without the push from building occupants, patients, personnel, or organization

missions, the industry does not feel obligated to change. LEED is a successful example of market transformation and this could have a large impact on other industries like healthcare. Patients and staff that request information about product materials and manufacturing assemblies and waste management practices will challenge the status quo of healthcare manufacturers. Without questioning *what, why, how,* and *where* there is no requirement to disclose this information as long as they abide by the FDA. The culture of a sustainable built environment is the key to market transformation.

5.4 FUTURE WORKS

The research presented in this dissertation has contributed to the growing building and healthcare industries. One suggestion for future work in the building industry would be to implement the IPD/LCA pathway described in Chapter 2.4.1 to a building in the infancy of its project life. Testing the IPD/LCA pathway would legitimize the integrated approach and decipher which building assessment tools(s) (i.e., LCA, LCCA, or LEED) are well received by the building industry. For the healthcare industry, continuing to understand the environmental impacts of the products and procedures, especially for resource intensive departments such as orthopedic surgery, will benefit each institution, saving on environmental impacts and costs. Further examination of nation-wide programs, such as the Community Health Needs Assessments and Medicare/Medicaid compensation, could be a great opportunity to quantify the environmental impacts of the healthcare industry by linking preventive health measures (i.e., exercise, diet, check-ups) to the status quo of local communities, establishing a foundation for a sustainable and healthy environment.

The EBD study (Chapter 4.0 has great potential for future work. EBD primarily relates to building occupant satisfaction, while LEED is related to green building performance. LEED is more scientifically based because of LCA inclusion. A logical next step for EBD/LEED/LCA integration would be to analyze the indoor environmental quality (IEQ) of a green healthcare building. IEQ is an established LEED credit category and a significant design focus for EBD, therefore identifying the IEQ LEED credits and synthesizing building occupant satisfaction results could develop a systematic approach for integrating LEED and EBD. Designing a platform that integrates green building characteristics (LEED + LCA) with building occupant satisfaction (EBD) will create a holistic understanding of a sustainable built environment.

APPENDIX A

CHAPTER 3.2: BIRTH CASE STUDY HVAC CALCULATION

Bin Energy Model Setup. The model calculated the energy use for several "bins" representing finite intervals of weather conditions. Equation 2 calculated the energy consumption from the bins modeled.

$$E = \sum_i N_i \frac{Q_i}{\eta}$$

Equation 2: Summation of energy consumption; E is the annual energy use for heating or cooling, N_i is the number of hours for the i^{th} bin, Q_i is the heating or cooling load for the bin, and η is the HVAC efficiency

The model created for the OR (operating room) and LDR (labor and delivery room) used the bin approach while adding some complexity in the form of internal load and humidity calculations. The bins were 1.8 °F intervals from 1.4 to 93 degrees, and in calculations the temperature for each bin was the midpoint and the humidity was the average humidity for hours falling in that bin. The bin frequencies (N_i) and humidities were calculated from hourly weather data for Pittsburgh's typical meteorological year (National Renewable Energy Lab 2011).

The load Q_i for each bin had a heating and a cooling component. The model calculated the cooling load ($Q_{i,AHU}$) on the air handling unit (AHU) to precondition air and the heating load on the reheat box to maintain the temperature set point in the room ($Q_{i,RH}$). The AHU supplies a mixture of outside air and re-circulated return air to reheat boxes throughout the hospital at 52 °F. The load on the AHU that can be attributed to the room was determined using Equation 3.

$$Q_{i,AHU} = \dot{V}(h_{i,MA} - h_{i,SA})$$

Equation 3: Load of the AHU

The volume flow rate ($\dot{V}$) was calculated from the air change rate and room volume provided by facilities staff. The mixed air enthalpy ($h_{i,MA}$) was calculated for each bin as a mixture of outside air at the bin temperature and humidity, and return air at the internal set points. The supply air enthalpy ($h_{i,SA}$) was calculated from the enthalpy of air at the supply set point of 52 °F with moisture content of the mixed air, but limited by an upper set-point. The ratio of outside air to return air was obtained from facilities staff. The AHU economizes from 40 to 50 °F, meaning that it brings extra outside air in to reduce the cooling load, and this was accounted for in the model. The air handling unit has only a cooling load even in the coldest weather because of the high fraction of re-circulated return air.

The second part of the load was the heating provided by the reheat box, which was purely a heating load from the natural gas powered boiler plant. To maintain the temperature set point, the cold supply air is reheated using thermostat control in the room. The reheat box heating load ($Q_{i,RH}$) was determined by solving an energy balance (Equation 4) for the air in the room for each bin.

$$0 = Q_{i,RH} + \dot{V}(h_{i,SA} - h_{SP}) + Q_{i,ENV} + Q_{IL}$$

Equation 4: Energy balance for the air in each room

The heat introduced by the reheat box ($Q_{i,RH}$) was found by setting the sum of the heat flows into and out of the room equal to 0, which must hold true for steady-state conditions in the room. The heat removed by the ventilation system was $\dot{V}h_{SP}$. Heat added was represented with terms for the supply air ($\dot{V}h_{i,SA}$), internal energy gains (Q_{IL}) from people and equipment, and heat gain through the windows and walls ($Q_{i,ENV}$). The latter was calculated for each bin as the external to internal temperature difference for the bin divided by the thermal resistance of the external wall. Only the LDR rooms have an external wall.

For a summary of the HVAC and input variables, see Table 19. The heating and cooling loads were summed separately, because the heating source is a gas boiler and the cooling source is an electric chiller plant. The total annual consumption value was normalized using the number of hours the OR and LDR are in use per year to determine the energy consumption per procedure.

Table 19: Bin Energy Model Input Variables

Input Variable	Description	Unit	OR Data	LDR Data
Wall Construction[a]	Wall area	ft^2	-	86
	Wall U-value (ASHRAE 2004)	W/m^2K	-	0.36
Occupancy	Average number of people in room	people	9	5
Equipment Heat Load	Electricity consumption of machines and lighting	Watts	9231	3429
Air Changes	Number of air changes in the room per hour (ANSI 2010a))	Air changes/hour	20	10
Flow Rate/ Room Volume	Volume of the room	ft^3	4200	3200

Table 19 (continued)

Inside Temperature (avg)	(ANSI 2010a)	°F	66-70	68-73
Air Temperature Prior to room Entrance	Air temperature in circulating air before it is heated at room entrance	°F	52	52
Outside Temperature (avg)	Yearly average from local weather station (National Renewable Energy Lab 2011)	°F	Pittsburgh Weather	Pittsburgh Weather
Humidity Set Point	(ANSI 2010a)	%	45-60	30-60
Chiller Efficiency	Specific to hospital chiller	%	80	80
Boiler Efficiency	Specific to hospital boiler	%	80	80
Duration	Single year, 24 hours/day	Hours	8765.8	8765.8

Bin Energy Model Results and Discussion. In order to assess which components had the greatest effect on the HVAC bin model, individual variables were isolated and their values incrementally increased and decreased. These values relative to the consumption of both gas and electricity (in kWh) are shown in Figure 49. When air changes per hour is increased 10%, for example, the overall energy consumption increases 12% (to 200,000 kWh) in the OR and nearly 12% (to 90,000 kWh) in the LDR.

Decreasing the value of some variables, such as equipment loading and number of people in the room, actually results in a minor increase in the HVAC system's energy demand. For example, when the electrical loading of the equipment within the LDR is decreased by 20%, there is only a 2% rise in the HVAC's annual energy consumption. Similarly, if the number of people in the OR decreases by 30%, there is only a 3% increase in the energy demand of the HVAC system.

These results are due to the structure of the hospital HVAC system. Air entering the OR needs to be heated (reheat), therefore, reducing the electrical loading of the machines means more reheat needs to be added to the incoming air, resulting in higher energy demands. This model also shows that if that supply air temperature were increased 10% (from 11.1°C to 12.2°C), the energy demand of the LDR would drop 19% (to 68,000 kWh per year). A similar increase in the supply air temperature in the OR, however, would lead to only a 1.5% rise in annual HVAC energy demand since the ORs must run at a lower temperature according to regulated standards.

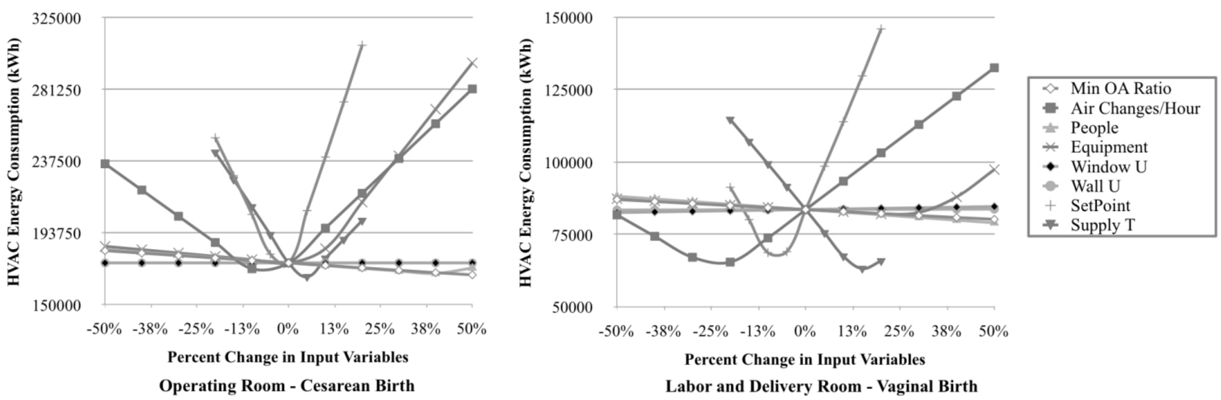


Figure 49: Effect of Input Variables on HVAC Annual Energy Consumption

Figure 49 suggests that the variables having the most impact on the energy consumption are temperature set point, equipment loading, air changes per hour, and supply temperature. Since the temperature set point, air changes per hour, and supply temperature are regulated within a very narrow range, improvements to this system may require more efficient HVAC developments or changes to hospital regulations.

APPENDIX B

CHAPTER 4 STAFF OCCUPANCY SURVEY

Introduction. Magee-Womens Hospital of UPMC completed a green addition, as certified by the US Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) rating system. The benefits of green buildings are often discussed, but further study is needed to quantify their significance, especially from a healthcare perspective. Researchers from the University of Pittsburgh's Department of Civil and Environmental Engineering are conducting a research study that looks at the connection between the proposed benefits to occupants and green buildings.

These researchers have created this survey, which you are about to complete, to assist in understanding the benefits of green buildings. Participation is voluntary and there is no compensation associated with this survey. The survey is anonymous and there is no way to track the submission to a specific individual. Participants can withdraw from the survey at any time. There are no foreseeable risks associated with this project. This study is being conducted by Dr. Melissa Bilec and her Sustainable Healthcare research group. Should you have any questions, please contact Dr. Bilec at mbilec@pitt.ed.

This green building survey should take approximately 15-20 minutes.

You may not be familiar with all of the terms used in the survey. Technical terms are defined the first time they appear in a question on each page of the survey.

Background Questions:

Q: What is your gender? A: Male / Female

Q: What is your age? A: Under 30 years / 31 to 59 years / over 60 years

Q: How would you describe your job? A: Patient care technician / physician / nurse / nurse practitioner / physician assistant / student / technician / administrators / hospital facilities / other

Q: How long have you been working on the Inpatient Oncology Unit (Unit 5800), located in the new addition? As a reminder, the addition opened in June 2012. A: less than 6 months / 6 to 12 months / 1 to 2 years / 2+ years

Q: What shifts do you typically work? Check all that apply. A: Day / Evening / Night

Workspace Use and Layout Questions

Q: During a typical day, what percentage of your time do you spend working in the following locations? This answer should total 100%. A: % in patient rooms / % in patient treatment areas / % in individual workspace (ex. Personal office) / % in shared workspace (nurse station) / % in meeting rooms / % other

Q: How satisfied are you with your individual workspace? A: 5-point satisfaction scale (very dissatisfied / dissatisfied / neutral / satisfied / very satisfied)

Q: How satisfied are you with the patient rooms? A: 5-point satisfaction scale (very dissatisfied / dissatisfied / neutral / satisfied / very satisfied)

Q: How satisfied are you with the patient treatment areas? A: 5-point satisfaction scale (very dissatisfied / dissatisfied / neutral / satisfied / very satisfied)

Q: How satisfied are you with the shared workspace or nurse stations? A: 5-point satisfaction scale (very dissatisfied / dissatisfied / neutral / satisfied / very satisfied)

Q: How satisfied are you with the meeting room? A: 5-point satisfaction scale (very dissatisfied / dissatisfied / neutral / satisfied / very satisfied)

Q: Overall, does the layout of Unit 5800 interfere or enhance your ability to get your job done? A: 7-point scale (Significantly interfere / interfere / somewhat interfere / neutral / somewhat enhance / enhance / significantly enhance)

Q: If you use the Meditation Room, how do you use the Meditation Room? Check all that apply. A: Private conversations with patients and family members / private conversations with other staff / mediation or break / I do not use the Mediation Room / other

Q: Please describe an issues or features related to the layout of Unit 5800 that are important to you.

Aesthetic Questions

Q: How satisfied are you with the overall aesthetics of Unit 5800 (appearance, color schemes, furnishing, etc)? A: 5-point satisfaction scale (very dissatisfied / dissatisfied / neutral / satisfied / very satisfied)

Q: What outside view do you see the most on a typical workday? A: Green roof / Garden Courtyard / City View / Other

Q: How does the outside view interfere or enhance your ability to get your job done? A: 7-point scale (Significantly interfere / interfere / somewhat interfere / neutral / somewhat enhance / enhance / significantly enhance)

Thermal Comfort and Air Quality Questions

Q: Which of the following do you have the ability to personally adjust or control on Unit 5800? Check all that apply. A: Thermostat / adjustable air vent in wall, ceiling or floor / other / none

Q: How satisfied are you with the temperature in patient rooms? A: 5-point satisfaction scale (very dissatisfied / dissatisfied / neutral / satisfied / very satisfied)

Q: How satisfied are you with the temperature in the workspace? A: 5-point satisfaction scale (very dissatisfied / dissatisfied / neutral / satisfied / very satisfied)

Q: How satisfied are you with the air quality in the patient rooms? A: 5-point satisfaction scale (very dissatisfied / dissatisfied / neutral / satisfied / very satisfied)

Q: How satisfied are you with the air quality in the workspace? A: 5-point satisfaction scale (very dissatisfied / dissatisfied / neutral / satisfied / very satisfied)

Q: How does the overall thermal comfort in the workspace interfere or enhance your ability to get your job done? A: 7-point scale (Significantly interfere / interfere / somewhat interfere / neutral / somewhat enhance / enhance / significantly enhance)

Q: How does the overall air quality in the workspace interfere or enhance your ability to get your job done? A: 7-point scale (Significantly interfere / interfere / somewhat interfere / neutral / somewhat enhance / enhance / significantly enhance)

Lighting Questions

Q: Which of the following controls do you have over the lighting on Unit 5800? Check all that apply. A: light switch / light dimmer / window blinds / desk light / other / none

Q: How satisfied are you with the amount of electric light in patient rooms? A: 5-point satisfaction scale (very dissatisfied / dissatisfied / neutral / satisfied / very satisfied)

Q: How satisfied are you with the amount of natural daylight in patient rooms? A: 5-point satisfaction scale (very dissatisfied / dissatisfied / neutral / satisfied / very satisfied)

Q: How satisfied are you with the amount of electric light in the workspace? A: 5-point satisfaction scale (very dissatisfied / dissatisfied / neutral / satisfied / very satisfied)

Q: How satisfied are you with the amount of natural daylight in the workspace? A: 5-point satisfaction scale (very dissatisfied / dissatisfied / neutral / satisfied / very satisfied)

Q: How does the overall electric lighting quality in Unit 5800 interfere or enhance your ability to get your job done? A: 7-point scale (Significantly interfere / interfere / somewhat interfere / neutral / somewhat enhance / enhance / significantly enhance)

Q: How does the overall natural lighting quality in Unit 5800 interfere or enhance your ability to get your job done? A: 7-point scale (Significantly interfere / interfere / somewhat interfere / neutral / somewhat enhance / enhance / significantly enhance)

Acoustic Quality and Speech Privacy

Q: How satisfied are you with the noise level on Unit 5800? A: 5-point satisfaction scale (very dissatisfied / dissatisfied / neutral / satisfied / very satisfied)

Q: How satisfied are you with the ability to have private conversations without being overheard by others? A: 5-point satisfaction scale (very dissatisfied / dissatisfied / neutral / satisfied / very satisfied)

Q: How satisfied are you with your ability to hear others? A: 5-point satisfaction scale (very dissatisfied / dissatisfied / neutral / satisfied / very satisfied)

Q: How satisfied are you with the level of distraction? A: 5-point satisfaction scale (very dissatisfied / dissatisfied / neutral / satisfied / very satisfied)

Q: How does the overall acoustic quality of Unit 5800 interfere or enhance your ability to get your job done? A: 7-point scale (Significantly interfere / interfere / somewhat interfere / neutral / somewhat enhance / enhance / significantly enhance)

Q: How does the overall speech privacy of Unit 5800 interfere or enhance your ability to get your job done? A: 7-point scale (Significantly interfere / interfere / somewhat interfere / neutral / somewhat enhance / enhance / significantly enhance)

Productivity Questions

Q: How does the thermal comfort of Unit 5800 affect your productivity? A: 7-point scale (strong negative effect / negative effect / somewhat negative effect / neutral / somewhat positive effect / positive effect / strong positive effect)

Q: How does the air quality of Unit 5800 affect your productivity? A: 7-point scale (strong negative effect / negative effect / somewhat negative effect / neutral / somewhat positive effect / positive effect / strong positive effect)

Q: How does the lighting of Unit 5800 affect your productivity? A: 7-point scale (strong negative effect / negative effect / somewhat negative effect / neutral / somewhat positive effect / positive effect / strong positive effect)

Q: How does the outside view of Unit 5800 affect your productivity? A: 7-point scale (strong negative effect / negative effect / somewhat negative effect / neutral / somewhat positive effect / positive effect / strong positive effect)

Unit 2800 Logic Questions (Pre-Move)

Q: Did you work on Unit 2800 (Women's Oncology), prior to the move in June 2012? A: Yes / no

Q: How satisfied were you with your individual workspace? A: 5-point satisfaction scale (very dissatisfied / dissatisfied / neutral / satisfied / very satisfied)

Q: How satisfied were you with the patient rooms? A: 5-point satisfaction scale (very dissatisfied / dissatisfied / neutral / satisfied / very satisfied)

Q: How satisfied were you with the patient treatment areas? A: 5-point satisfaction scale (very dissatisfied / dissatisfied / neutral / satisfied / very satisfied)

Q: How satisfied were you with the shared workspace or nurse stations? A: 5-point satisfaction scale (very dissatisfied / dissatisfied / neutral / satisfied / very satisfied)

Q: How satisfied were you with the meeting room? A: 5-point satisfaction scale (very dissatisfied / dissatisfied / neutral / satisfied / very satisfied)

Q: Overall, did the layout of Unit 2800 interfere or enhance your ability to get your job done? A: 7-point scale (Significantly interfere / interfere / somewhat interfere / neutral / somewhat enhance / enhance / significantly enhance)

Q: Please describe an issues or features related to the layout of Unit 2800 that are important to you.

Final Feedback and Thanks

Q: Do you have any other suggestions for improving Unit 5800? If so, what are they?

Q: Do you have any suggestions for improving this survey? If so, what are they?

Thank you for completing this survey! This research study is being conducted by Dr. Melissa Bilec and her Sustainable Healthcare research group. Should you have any questions, please contact Dr. Bilec at mbilec@pitt.edu.

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