UNDERSTANDING AND IMPROVING HEALTHCARE USING ENVIRONMENTAL LIFE CYCLE ASSESSMENT AND EVIDENCE-BASED DESIGN

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This dissertation quantifies and analyzes the environmental and human health impacts associated with healthcare through assessment of the physical built environment of a hospital as well as the processes and procedures conducted within the building. Healthcare, especially in the United States, seeks to reduce cost and improve human health in part by reducing waste and improving building design and operational practices. This work shows that sustainability engineering tools help assess the effects of green design considerations in whole hospital performance and can identify areas of high environmental loading in the operating room (OR).

A comparative longitudinal assessment showed the hospital performance impacts of green, holistic hospital design. Following the move into the new, green facility, the Children's Hospital of Pittsburgh of UPMC significantly improved their productivity, quality of care, and staff satisfaction. The utility use per square foot dropped over 50% for electricity, heating energy, water, and sewer, while hospital expenses per patient in bed remained stable. This and other contributions to the field of Evidence-Based Design inform future design decisions which optimize hospital energy use and maximize positive patient outcomes and staff satisfaction.

This research established process and hybrid life cycle assessment (LCA) frameworks to assess hospital operating room procedures. Case studies of infant birth procedures and hysterectomies at Magee-Womens Hospital of UPMC show that production and disposal of single-use materials and devices as well as heating, ventilation, and air conditioning systems have the highest environmental loading within the OR.

The hysterectomy study, in particular, pointed to upstream material manufacturing as an area for large environmental improvements in healthcare facilities. For example, single-use cotton materials such as towels and gauze make up only 9% of vaginal and 11% of abdominal hysterectomy municipal solid waste by weight, but the production of these cotton materials accounts for 55-90% of the total environmental impacts of vaginal and abdominal hysterectomies in nearly all categories analyzed. A Monte Carlo assessment of the hysterectomy LCA showed ranges of environmental impacts based on variability of OR procedures and uncertainty in impact assessment methods.

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NOMENCLATURE

AP	Acidification Potential
ADE	Adverse Drug Event
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
Carc	Human Health: Carcinogenic
CED	Cumulative Energy Demand
Children’s	Children’s Hospital of Pittsburgh of UPMC
CTU(h or e)	Cumulative Toxicity Unit (human or environment) – number of disease cases per kg of chemical emitted
EBD	Evidence-Based Design
EcoTox	EcoToxicity
EIO-LCA	Economic Input-Output Life Cycle Assessment
Eq	Equivalent
EUT	Eutrophication
Gal	gallon
GHG	Greenhouse Gas (emissions)
HDPE	High density polyethylene
HVAC	Heating, Ventilation, and Air Conditioning
kBtu	thousand British thermal units

kWh	Kilowatt hours
LCA	Life Cycle 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 of UPMC
MAR	Medical Administration Record
MCA	Monte Carlo Assessment
MSW	Municipal Solid Waste
NAICS	North American Industry Classification System
NonCarc	Human Health: NonCarcinogenic
ODP	Ozone Depletion Potential
OR	Operating Room
PCT	Patient Care Technician
PIB	Patient in Bed
PP	polypropylene
PPI	Producer Price Index
PVC	Polyvinyl chloride
Resp	Respiratory Impacts
RMW	Regulated Medical Waste
RN	Registered Nurse
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
US EPA	United States Environmental Protection Agency
USGBC	United States Green Building Council

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1.0 INTRODUCTION

1.1 MAKING HEALTHCARE HEALTHY: THE BUILT ENVIRONMENT, HOSPITALS, AND SUSTAINABILITY

The size and cost of healthcare is increasing. Expenses for all personal healthcare services and products in each state have been growing 4.4% to 7.3% per capita annually. In each state, healthcare spending ranges from $5,000 to $10,400 per person per year. Healthcare spending accounted for 17.9% of the US Gross Domestic Product (GDP) in 2011, and 36.3% of those national healthcare expenditures are for hospital care specifically (CMS 2011; Kaiser Family Foundation 2011). In 2011, the healthcare sector employed nearly 12 million people, making up 6.4% to 11.7% of each state's total workforce (Kaiser Family Foundation 2011). Hospitals employ nearly a third of the healthcare sector (BLS 2013).

As environmental sustainability becomes a greater priority for the American public, the healthcare industry, with its relative size, costs, and expected growth, is under pressure to improve its economic, social, and environmental sustainability. With these challenges and growing health concerns in the general population, public healthcare providers are turning towards a preventative model of care, part of which involves environmental health or the healthy interaction of humans with their environment (Fani Marvasti and Stafford 2012). Hospitals, in particular, are called upon to be designed more sustainably and to improve the environmental sustainability of their processes and procedures (Ficca, Chyun et al. 2000; Phelps, Horman et al. 2006; Verderber, Fauerbach et al. 2008; Younger, Morrow-Almeida et al. 2008; Stichler 2009). In order to implement more environmentally sustainable hospital building design and medical practices, healthcare decision-makers need proper tools and information about the industry's current environmental footprint, which aspects of hospital design and function contribute most significantly to environmental and human health impacts, and how changes to the healthcare system might impact its overall sustainability.

1.2 RESEARCH GOALS AND OBJECTIVES

The overarching goal of this research was to analyze and improve the environmental and human health impacts associated with healthcare through analysis of the physical built environment of a hospital as well as the processes and procedures conducted within the building. This research utilized common hospital reporting metrics to compare building performance and health and safety effects of a new, green hospital and its former, traditional facility. By specifically studying green hospitals, this research expands current knowledge on the performance and human-related effects of green buildings (Evidence-Based Design, EBD) and increases our understanding of the impacts of hospital design on employee performance and patient outcomes. This research also applies an environmental sustainability scientific assessment tool, Life Cycle Assessment (LCA), to hospital operating room (OR) procedures, specifically comparing vaginal and cesarean section births as well as four modes of hysterectomy. The use of LCA at the OR scale allows hospital decision-makers to identify areas of performance with relatively high environmental impacts and target those areas as they move towards more environmentally sustainable practices. The objectives of this research, and the specific questions related to each objective are to:

1) Determine the effect of cohesive, green building hospital design on building performance, hospital employees, and patients through a comparative longitudinal assessment of an older, traditional hospital with its new, LEED-certified (Leadership in Energy and Environmental Design) replacement.

- How does sustainable hospital design affect hospital performance?
- How can hospital performance metrics help determine the effects of sustainability initiatives within hospitals?

2) Develop and test a life cycle assessment (LCA) framework specific to hospitals using case study data collected from vaginal births done in labor and delivery rooms (LDR) and cesarean section births performed in operating rooms (OR).

- How can LCA determine environmental sustainability of the healthcare industry?

3) Modify and apply the LCA framework to analyze the environmental impacts of common surgical procedures using four modes of hysterectomies- laparoscopic, robotic, vaginal, and abdominal- as the case study.

- What aspects of hospital operating procedures contribute the most to a procedure's environmental impacts?

4) Identify advantages and limitations of the life cycle human health impact categories when applying LCA to healthcare.

- What are the advantages and limitations of life cycle impact categories such as human health when applying LCA to healthcare issues?

The first three objectives are addressed in Chapters 3, 4, and 5 respectively. Objective 4 is addressed in an extended segment of the literature review found in Chapter 2.

1.3 BROADER IMPACTS

This research brings together a diverse professional team of engineers, nurses, physicians, hospital facility managers, and hospital “green team” members, a majority of whom are women. It advances our understanding of green building performance and healthier hospital design as well as the life cycle impacts of surgical practice. This work verifies the efficacy of managerial and building design decisions in our Evidence-Based Design case study and potentially influences design decisions in future hospital building projects. The Children’s hospital EBD study was disseminated through journal publications and in oral presentations at Engineering Sustainability 2013 and ISSST 2013 (International Symposium on Sustainable Systems and Technology). This research was also presented in poster format in São Paulo, Brazil at SASBE2012 (Smart and Sustainable Built Environments: Emerging economies), a conference hosted by the CIB (International Council for Research and Innovation in Building and Construction) Work Commission 116. The EBD study also led to an additional PhD-level, EBD research project currently being conducted at the University of Pittsburgh in partnership with Magee-Womens Hospital.

The work pertaining to the application of LCAs in hospitals provides a methodology for the industry-expressed need of quantifying environmental impacts of hospital procedures. In doing so, this work aids hospitals in establishing baseline environmental performance measurements and assists in identifying aspects of procedural practice with relatively high environmental impacts. Specifically, the green team at Magee-Womens Hospital is incorporating LCA results of their surgeries into environmentally sustainable policy changes and hospital greening initiatives to target material purchasing and waste disposal.

Two undergraduate students at the University of Pittsburgh and one at the University of Arkansas participated in the data collection and analysis phases of this project, learning about research methods, statistics, and technical writing. One of the students utilized this work to complete her honors thesis for her Bachelor’s Degree. The LCA studies support a growing healthcare sustainability research partnership between the University of Pittsburgh, Arizona State University (ASU), and Northeastern University. Additional collaborations were established with healthcare sustainability researchers at the University of Washington, the Yale University School of Medicine, the University of British Columbia, and the organization Practice Greenhealth. The methodology and results of these Life Cycle Assessments were presented at CleanMed 2011 and 2013, ISSST 2012, Engineering Sustainability 2013, and LCA XII, and were published in peer-reviewed journals and conference proceedings.

Elements of this research and environmental sustainability awareness are now incorporated into training for nurses at the Community College of Allegheny County (CCAC) in Pennsylvania. This research contributed and continues to contribute to a variety of lectures and undergraduate class projects for courses such as Design for the Environment, Green Building Design, Introduction to Life Cycle Assessment, and Engineering & Sustainable Development at Pitt, and the Engineering Projects in Community Service (EPICS) program at ASU. Content is also included in public community lectures and programs at Magee-Womens Hospital and disseminated through the medical community via Practice Greenhealth, a nonprofit organization focused on improving the environmental sustainability of healthcare.

1.4 INTELLECTUAL MERIT

This work advances understanding of green building performance and healthcare sustainability while enhancing existing literature on evidence-based hospital design and the environmental impacts of medical procedures. The hospital metrics used in the EBD study establish an effective methodology for monitoring the performance of green building design and for measuring the overarching human-related effects of hospital design. Our novel application of LCA methodology to the operating room (OR) advances our understanding of OR waste composition and the full range of associated environmental impacts of common surgical procedures. Though significant future research is needed to make broad, lasting changes to healthcare material and resource consumption, this study introduces a scientific, analytical framework to healthcare professionals as a means of monitoring their environmental baseline and assessing the efficacy of policy and programmatic changes.

2.0 BACKGROUND AND LITERATURE REVIEW

This section discusses previous research in healthcare and its environmental impacts. The first subsection focuses on green building performance monitoring and the psycho-social impacts of green building design. It summarizes Evidence-Based Design studies focused on the human health impacts of changes to standard hospital design. Section 2.2 summarizes existing concerns in hospital consumption patterns, such as waste generation, energy use, and wastewater effluent. The third subsection contains an overview of life cycle assessment methodology and studies which have applied LCA methodology to healthcare. Section 2.3 also contains an extensive literature review related to Objective 4: identifying the advantages and limitations of the life cycle human health impact categories when applying LCA to healthcare. For this reason, section 2.3.2 is longer than a standard literature review segment. It covers existing LCIA methodology in LCIA as well as human health measurement methodologies outside of the field of sustainable engineering.

2.1 GREEN BUILDING PERFORMANCE ANALYSIS AND EVIDENCE-BASED DESIGN OF HOSPITALS

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). Building construction and demolition account for anywhere from 25% to 65% of Municipal Solid Waste streams in the US (Beachey 1998; Cascadia Consulting Group 2003; MARC 2009). Beyond that, people spend 90% of their time indoors and are exposed to air pollutant levels 2 to 5 (or more) times higher than outdoor values (EPA 2010). Many studies confirm a connection between safe, walkable community designs and decreased risk of chronic diseases such as asthma and diabetes, improved weight and body mass indices of residents, and increased social engagement (Tester 2009; Feng, Glass et al. 2010; Napier, Brown et al. 2011), but what are the environmental and human health effects of individual buildings?

In 1998 the USGBC released the first green building rating system, LEED (Leadership in Energy and Environmental Design) to incentivize design which more wisely utilizes natural resources and materials (USGBC 2006). Studies began analyzing the environmental impacts of buildings and building products at each stage of a building's life cycle (Citherlet, Di Guglielmo et al. 2000; Peuportier 2001; Junnila and Horvath 2003; Scheuer, Keoleian et al. 2003; Prek 2004; Guggemos and Horvath 2005; Nyman and Simonson 2005; Maydl, Passer et al. 2007; Blengini 2009; Nolan, Hamilton et al. 2009; Sandrolini and Franzoni 2009). Research focused on the energy costs and efficiencies during the use of a building (Sherif and Kolarik 1981; Ucar and Doering 1983; Bourassa and Phillips 1984; Abel 1994; Cole and Kernan 1996; Adalberth 1997; Levin 1997; Suzuki and Oka 1998; Thormark 2002; Yohanis and Norton 2002; Venkatarama Reddy and Jagadish 2003; Sartori and Hestnes 2007; Kofoworola and Gheewala 2008; Pérez-Lombard, Ortiz et al. 2008; Blengini and Di Carlo 2010; Blengini and Di Carlo 2010; Ramesh, Prakash et al. 2010; Aktas and Bilec 2012). Health concerns associated with the indoor environment, such as "sick building syndrome," gave rise to studies on the effects of individual buildings and green design on immediate health and welfare (Au Yeung, Chow et al. 1991; Thirumalaikolundusubramanian, Shanmuganandan et al. 1991). Though the causes of SBS symptoms are not entirely known, researchers believe it is a combination of chemical, physical, biological, and psychosocial factors- meaning it is not only exposure to mold and toxins that can cause SBS, but also a person's psychological interaction with their built environment (Lahtinen, Huuhtanen et al. 1998; Norbäck 2009).

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). To better understand the effects of green buildings, studies have analyzed metrics such as worker productivity, developing surveys or analyzing company-collected data such as employee absenteeism or sick leave (Kats, Alevantis et al. 2003; Ries, Bilec et al. 2006; Seppänen and Fisk 2006; Loftness, Hakkinen et al. 2007; Wiik 2011). Using a questionnaire to monitor occupant health, Breysse, et al. found that green home renovations improved the health of residents (Breysse, Jacobs et al. 2011).

One aspect of green building design in particular, the indoor air and environmental quality (IAQ and IEQ), have been linked to worker health and productivity in multiple studies (Mitchell, Zhang et al. 2007; Singh, Syal et al. 2010; Sundell, Levin et al. 2011). In separate studies, Kosonen, et al. and Seppänen, et al. found a direct correlation between decreased IAQ and decreased worker productivity (Kosonen and Tan 2004; Seppänen and Fisk 2004). Studies also showed that thermal discomfort, either too high or too low an air temperature, also decreased worker productivity and possibly increased perceived stress levels (Seppänen, Fisk et al. 2005; Lan, Lian et al. 2010). Seppänen, at al. found the rate of ventilation and quantity of outdoor air to be directly proportional to employee productivity (Seppänen, Fisk et al. 2006). Other studies have found that natural and sustainable daylighting not only reduces energy demands, but also help employees with perceptual and circadian functions and result in a more positive perception of their work environment (Figueiro 2008; Hua, Oswald et al. 2011).

2.1.1 Environmental Human Health Effects within Hospitals

As a place that serves a vulnerable subset of the population, many reports extol that hospitals, in particular, should be the most rigorous in implementing environmentally sustainable design practices (Phelps, Horman et al. 2006; Vittori and Houghton 2007; Verderber, Fauerbach et al. 2008; Younger, Morrow-Almeida et al. 2008; Stichler 2009). In a survey of design professionals, healthcare professionals, administrators, and patient groups, Cohen and Allison found that perceived critical areas in a hospital setting include patient care issues (addressing clinical, treatment, and recovery problems), patient safety and security (hospital acquired infection, errors, and falls), patient and user satisfaction issues (reducing stress and increasing physical, social and psychological comfort of patients and family), and operational efficiency issues (patient care flow) (Cohen and Allison 2009). Green and sustainable design of healthcare buildings such as hospitals can have a large effect, not only on the building's sustainability performance and energy consumption, but also on these critical areas of patient care and on the productivity and wellbeing of staff within the structure. To what extent building design and sustainability principles contribute to these concerns is not entirely known, but current literature, summarized in Figure 1, begins to assess the effects of aesthetic and functional building design decisions on both patients and staff.

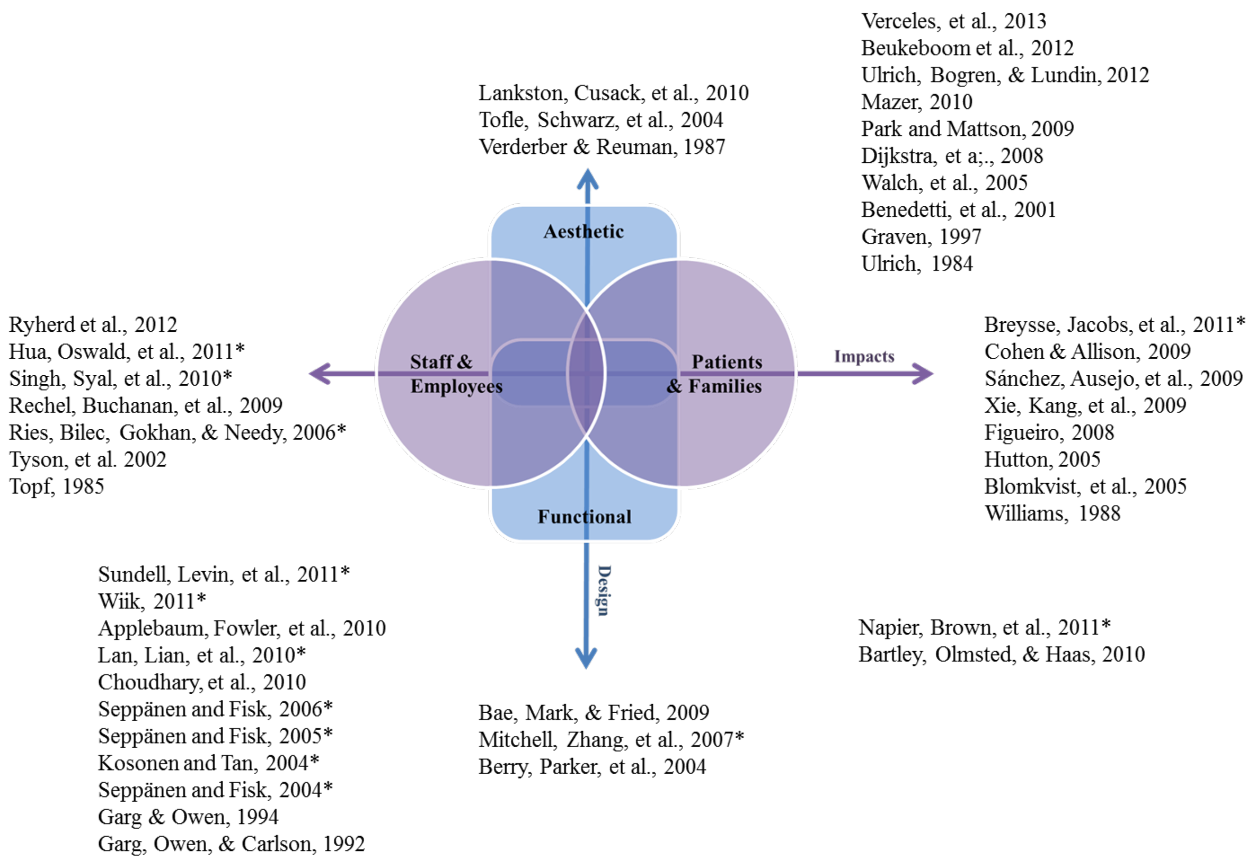


Figure 1: Building Metrics Literature Summary, * = not a healthcare specific study

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). Since then, studies have emerged confirming positive effects of more sustainable medical facility design 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).

Bartley et al. summarized the research done in this area, pointing to strong evidence that access to daylight, appropriate lighting, views of nature, and noise reduction, in addition to single-bed rooms has positive effects on healthcare outcomes for both patients and staff (Bartley, Olmsted et al. 2010). Positive outcomes for staff may be considered an additional benefit for patients, with multiple studies finding correlation between nursing turnover rates and patient falls, patient satisfaction, and rates of medication errors (Trinkoff, Johantgen et al. 2005; Bae, Mark et al. 2010; Hayes, O'Brien-Pallas et al. 2012). These and the following environmental health studies contribute to a growing design methodology called Evidence-Based Design (EBD). EBD in healthcare uses existing research and knowledge to make design decisions in healthcare structures in an effort to improve performance outcomes while simultaneously testing the impacts of design decisions to promote future EBD projects (Cama 2009). Testament to the rising evidence suggesting the benefits of environmental design, the US Green Building Council's new 2011 building design standards for healthcare, LEED for Healthcare, adds points towards green building certification for daylighting as well as noise control (Pradinuk 2009; U.S. Green Building Council (USGBC) 2009; U.S. Green Building Council (USGBC) 2011).

A large portion of existing literature focuses on the effects of noise and lighting within healthcare settings. The next subsection focuses on daylighting and natural views, and subsection 2.1.1.2 focuses on noise-related studies. The final subsection summarizes studies which focus on the effects of other building design characteristics such as indoor air quality, hospital or ward layout, and ergonomic design.

2.1.1.1 Effects of Lighting and Views

Many studies attempt to quantify the psychosocial human health effects of green building design features such as daylighting and natural views. Hua, et al. found that daylighting results in a much more positive perception of a university laboratory work environment (Hua, Oswald et al. 2011). Another study suggested that sustainable lighting not only reduces energy demands, but also helps people with perceptual and circadian functions (Figueiro 2008). Verderber and Reuman confirmed this and found that patients were more negatively affected by lack of accessible windows in rooms than were hospital staff (Verderber and Reuman 1987). Staff, however, and their performance can also benefit from increased lighting. Especially during nighttime shifts, improved lighting is associated with reduced human errors and enhanced nursing care (Rashid and Zimring 2008; Kamali and Abbas 2012).

Studies suggest that in addition to improved circadian rhythms, daylighting can serve as effective light therapy for seasonal affective disorder or other types of depressive illnesses (Benedetti, Colombo et al. 2001). One study found that depressed patients staying on the sunny side of a psychiatric unit were discharges after 16.9 days compared to the patients staying in the other half of the unit who's average length of stay was 19.5 days (Beauchemin and Hays 1996). Additionally, increased daylighting and other evidence-based, stress-reducing hospital characteristics have been found to reduce aggression and the need for physical restraints with psychiatric patients (Ulrich, Bogren et al. 2012) and reduce patients' perceived stress and pain medication rates (Walch, Rabin et al. 2005). Some studies, however, suggest that windows and ambient light conditions might not affect critical care outcomes or sedative use in Intensive Care Units (ICUs) (Verceles, Liu et al. 2013).

Multiple studies conclude that the presence of indoor plants or images of nature in the healthcare environment can reduce stress, anxiety and fatigue and may help control postoperative pain (Dijkstra, Pieterse et al. 2008; Park and Mattson 2009; Beukeboom, Langeveld et al. 2012). Artwork and art therapy in hospitals were found to have a positive impact on healing (Favara-

Scacco, Smirne et al. 2001), though specific colors have not been directly linked to patient or staff mood, and other needs, such as acoustics, temperature, and cleanliness, are considered much more important to emotional well-being than artwork or color (Tofle, Schwarz et al. 2004; Lankston, Cusack et al. 2010).

2.1.1.2 Effects of Noise

Studies indicate that noise levels in hospitals have been increasing over the past 45 years and that no difference exists in daytime and nighttime noise levels (Busch-Vishniac, West et al. 2005; Beyea 2007). Noise levels in hospitals are often above internationally recommended decibel measures (Robertson, Cooper-Peel et al. 1998; Allaouchiche, Duflo et al. 2002; Ryherd, Waye et al. 2008). Multiple studies show a relationship between noise levels in hospitals and the sleep cycles and health effects of patients such as headaches, irritability, prolonged healing, and increased pain sensitivity in some patients (Topf 1985; Biley 1994; Aaron, Carlisle et al. 1996; Topf, Bookman et al. 1996; Graven 1997; Gabor, Cooper et al. 2003; Sánchez, Ausejo et al. 2009; Xie, Kang et al. 2009). Studies also point to noise-induced hearing impairment, adverse physiological effects, and mental health effects (Berglund, Lindvall et al. 1999).

Noise and the hospital acoustic environment were also largely associated with higher stress levels and increased anxiety in hospital staff and patients (Topf 1985; Van Servellen and Topf 1994; Bayo, García et al. 1995; Morrison, Haas et al. 2003; Ryherd, Ackerman et al. 2012). Applebaum, et al. confirmed this in a study comparing noise, perceived stress, job satisfaction, and turnover intention of nursing staff (Applebaum, Fowler et al. 2010). However, in specific hospital environments, such as radiology, noise was found to have a neutral effect on hospital employee performance (McEntee, Coffey et al. 2010).

In general, most reports acknowledge that noise is an issue, especially for patients, and solutions must be employed to monitor and control noise in hospitals (Montague, Blietz et al. 2009; Pope 2010; Salandin, Arnold et al. 2011). Some studies point towards the increased use of music and music therapy as a means of reducing the adverse effects of noise and utilizing the associated benefits of reduced blood pressure, breathing rate, emotional anxiety, and pain (Cabrera and Lee 2000; Mazer 2010). Others suggest the increased need to design or retrofit hospitals with sound absorbing or anti-reflective materials to improve patient outcomes and staff performance and satisfaction (Blomkvist, Eriksen et al. 2005; Hagerman, Rasmanis et al. 2005; Sánchez, Ausejo et al. 2009).

2.1.1.3 Effects of Air Quality, Floor Layout, and Ergonomic Design

Hospital staff and patients are exposed to infectious diseases from airborne and surface contamination, which is why strict ventilation and sterilization standards exist for facilities in most countries (The American Institute of Architects (AIA) 2006; Wirtanen, Nurmi et al. 2012; Fernstrom and Goldblatt 2013). Low ventilation rates are associated with increased infection risk, for example hospital cases involving SARS outbreaks, tuberculosis infection, and nasal inflammation due to *Aspergillus fumigatus* (Menzies, Fanning et al. 2000; Smedbold, Ahlen et al. 2002; Lutz, Jin et al. 2003; Zimring, Joseph et al. 2005). Increased filtration is also associated with better health outcomes and reduced infection rates (Seppänen and Fisk 2006; Balaras, Dascalaki et al. 2007; Khalil 2008; Abdul Salam, Karlin et al. 2010; Campion, Thiel et al. 2012). Proper maintenance of ventilation systems, as well as humidification of hospital air during heating seasons, also positively influences hospital staffs' *perception* of indoor air quality and can have a positive impact on worker health, especially related to sick building syndrome

(Nordström, Norbäck et al. 1994; Nordström, Norbäck et al. 1995; Hellgren, Hyvärinen et al. 2011).

Building design decisions should incorporate the needs of the people who occupy the space and the work patterns of the environment, particularly for the highly specialized hospital environment. Pierce, Rogers, et al. show that appropriate pharmacy layouts improve work flow, reduce waiting times, and increase patient satisfaction (Pierce, Rogers et al. 1990). Another study found new psychiatric ward design correlated with improved behavior in nursing staff and decreased burnout (Tyson, Lambert et al. 2002). Nurses appear to prefer single-occupancy patient rooms as they result in better privacy and accommodation for family members and reduced risk of dietary or medicinal errors (Chaudhury, Mahmood et al. 2006). Sufficient space around patient beds potentially reduces the risk of patient falls and infection transmission though not enough empirical evidence exists to confirm the exact amount of space required (Hignett and Lu 2010). Designers should employ workspace design principles in order to assess staff and patient needs to create a safe and functional work environment (Carayon, Alvarado et al. 2003).

For many doctors, nurses, and healthcare providers, the aesthetic components of design are secondary to design factors which impact safe and efficient care delivery. These include design elements which increase ease of maintenance and cleaning, reduce noise level, increase thermal comfort, and give caregivers easy access to patient wards (Mourshed and Zhao 2012). Patient perspective, however, is somewhat shifted, but no less important. A survey of adolescent patients found that patient-focused ward design in which the needs of all users are incorporated (in this case: the inclusion of private space, locations for extended cell phone use, and access to kitchens) could result in less stress and anxiety for the patients (Hutton 2005). A survey of advanced cancer patients suggested multi-bedded ward design and increased contact with the outdoors might improve quality of life for that patient-group (Rowlands and Noble 2008).

Job satisfaction of nursing staff has been of particular interest to researchers, given the importance of nurses in patient care and safety. Some research focuses on the relationship between the hospital ward or unit layout and the amount of time nurses spend walking, as previous studies indicate nurses may spend over a quarter of their work time walking (Burgio, Engel et al. 1990). Short travel time for nurses and increased nurse-patient interactions are associated with effective and efficient care (Seelye 1982). Nurse's visibility of patient rooms, the presence and location of nursing substations, and the location of medications are all factors of building design which can reduce walking for nurses (Choudhary, Bafna et al. 2010; Seo, Choi et al. 2011). The physical layout of a hospital is thought to have an effect on nursing satisfaction and patient outcomes, but may be dependent on the patient case-types typically treated at the hospital (Devlin and Arneill 2003).

Garg and Owen conducted multiple studies of manual patient lifting techniques conducted by nurses in nursing homes as this often results in physical injury or stress in the staff. Ergonomic interventions to prevent physical stress in nursing staff, such as incorporating patient-handling devices and modifying the toilets and shower areas, decreased the incident rate for staff back injuries by nearly 50% in their study facility (Garg, Owen et al. 1992; Garg and Owen 1994). Ergonomics and its integration into hospital safety hazard identification policies and special hospital teams have reduced employee injury rates and also reduced hospital waste (Evanoff, Bohr et al. 1999; Missar, Metcalfe et al. 2012; Selis, Vanacker et al. 2012).

2.2 ENVIRONMENTAL CONCERNS OF HEALTHCARE PRACTICES

Environmental impacts of healthcare should focus not only on the effects of building design, but also on the operations and processes conducted within the building. When assessing the sustainability of healthcare, many studies focus on the impacts of medical waste disposal (Townend and Cheeseman 2005; Mohan, Spiby et al. 2006; Shaner-McRae, McRae et al. 2007). A 1992 study estimates that US hospitals generate about 6,670 tons of waste per day (Rutala and Mayhall 1992). A majority of this waste appears to be generated from disposable or single-use medical supplies which could be replaced with reusable or multi-use materials (Souhrada 1988; Gilden, Scissors et al. 1992). Further studies maintain that American health facilities are responsible for the landfilling and incineration of over 3.4 billion pounds of waste annually (EPA 2005; DiConsiglio 2008).

Regulated Medical Waste (RMW), otherwise known as “red bag” or infectious waste must be disposed of either by incineration or sterilization and landfilling. A 1988 study of RMW waste found that polyvinyl chloride or PVC plastic accounted for nearly 10% of the waste stream which, when incinerated would lead to a release of dioxins and other chemicals hazardous to human health (Marrack 1988). With this risk, many hospitals have been treating RMW through non-incineration alternatives such as autoclaving and landfilling waste (Sattler 2002). However, a recent LCA-based study suggests that incineration, especially with energy capturing, may be a better option than sterilization and landfilling (Zhao, Van Der Voet et al. 2009; James 2010). Alternately, the use of ash from hospital waste in concrete production and new methods of incineration could offset the carbon-based environmental impacts of the disposal method (Genazzini, Zerbino et al. 2003; Liu, Ma et al. 2006).

Though the disposal method itself has implications on environmental impacts, multiple studies analyzed the recycling or diversion potential of RMW. Tiesczen and Gruenberg sorted through surgical trash in 1992 to analyze the composition, and they estimated that by using reusable linens and implementing recycling programs, waste could be reduced 73% by weight (Tieszen and Gruenberg 1992). Wong and Narasimhan found in 1994 that 32% of red bag waste was plastic, 24% was paper, and 35% was cotton (Wong, Narasimhan et al. 1994). McGain, et al. found that though anaesthetic waste is less than 10% of the OR waste, as much as 30% of it is recyclable and less than 10% would be considered infectious (McGain, Hendel et al. 2009). In 2002, an analysis of the recyclability of medical plastics, found that 60% of OR wastes were recyclable plastics, but due to its designation as RMW, this waste must be treated according to law (Lee, Ellenbecker et al. 2002). Laws, however, give a vague definition of RMW, which leaves its designation open to interpretation (Mühlich, Scherrer et al. 2003).

Currently in the US, each state mandates proper disposal of medical waste with guidelines from the US Environmental Protection Agency (EPA) as established through the Medical Waste Tracking Act (MWTA) of 1988 (United States Environmental Protection Agency 1988). For example, in Pennsylvania, medical waste management is regulated through the PA Department of Environmental Protection’s Bureau of Waste Management, which uses definitions for infectious or medical wastes and proper disposal techniques as established by the EPA. Pennsylvania has also created the Infectious and Chemotherapeutic Waste (ICW) Disposal Law, Act 93 of 1988 which requires an ICW disposal plan to review of ICW incinerators or issuance of disposal permits (Casey 1988). Other states have set up similar management structures; for example, the Colorado Department of Public Health and Environment established the Hazardous Materials and Waste Management Division to ensure compliance with state regulations on proper handling and treatment of infectious wastes. Though proper caution should be used to handle and treat truly infectious waste, guidelines with a clearer definition of RMW could result in significant monetary savings, as estimated by Ponka, et al. (Pönkä, Kaski et al. 1996).

Much of this waste generation is the result of advances in technology and plastics manufacturing, increasing ease of use and disposal of products, and a focus on reducing short term costs which lead to increased purchase of disposable and single-use materials (Greene 1986). Reuse and reprocessing of surgical supplies, though having a greater perceived risk of contamination, have positive implications for environmental and economic impacts of hospitals. In an assessment of disposable and reusable trocars, scissors, and Veress cannulas used in surgical procedures, Adler, et al. found that disposable instruments cost 19 times more than the reusable and perhaps also result in greater environmental impacts (Adler, Scherrer et al. 2005). Though proper sterilization techniques need to be enforced, the reprocessing of single-use medical devices could result in monetary and environmental savings for hospitals (De Oliveira and Lucas 2008; DiConsiglio 2008; Jacobs, Polisena et al. 2008; Barnett and Rios 2009; US Food and Drug Administration (FDA) 2009; Kwakye, Pronovost et al. 2010; Plisko 2010; Kwakye, Brat et al. 2011).

Some studies also point to the un-needed waste in operating rooms with the required disposal of unopened or unused materials (Weinger 2001; Esaki, Macario et al. 2009). Other reports suggest changes to purchasing practices can improve environmental outcomes (Kaiser, Eagan et al. 2001; Kumar, DeGroot et al. 2008; Brusco and Ogg 2010). Messelbeck and Whaley believe that the healthcare industry has the ability to collectively pressure materials suppliers into better environmental performance (Messelbeck and Whaley 1999), while in a study of disposable and reusable materials within the NHS, Ison and Miller conclude that analysis of environmental impacts throughout a product's life cycle has potential as a supportive tool for material purchases (Ison and Miller 2000).

While waste is a relatively well-covered topic of hospital sustainability, other aspects of healthcare impacts also have considerable impact. Though not often addressed in scientific literature, Heating, Ventilation, and Air Conditioning (HVAC) demands for a hospital must meet building codes, but generally account for a large portion of energy requirements in a building's life cycle (Junnila and Horvath 2003; Khalil 2008; Saporta, Ellis et al. 2008; Ruparel 2010). As shown in Figure 2, the energy consumption and intensity per square foot of healthcare buildings is much larger than other commercial buildings (US Energy Information Administration 2003). Large hospitals, or buildings over 200,000 sf, consumed 458 trillion Btus from all major fuel sources in 2007, or about 5.5% of the total energy used in the commercial sector that year (US Energy Information Administration 2012).

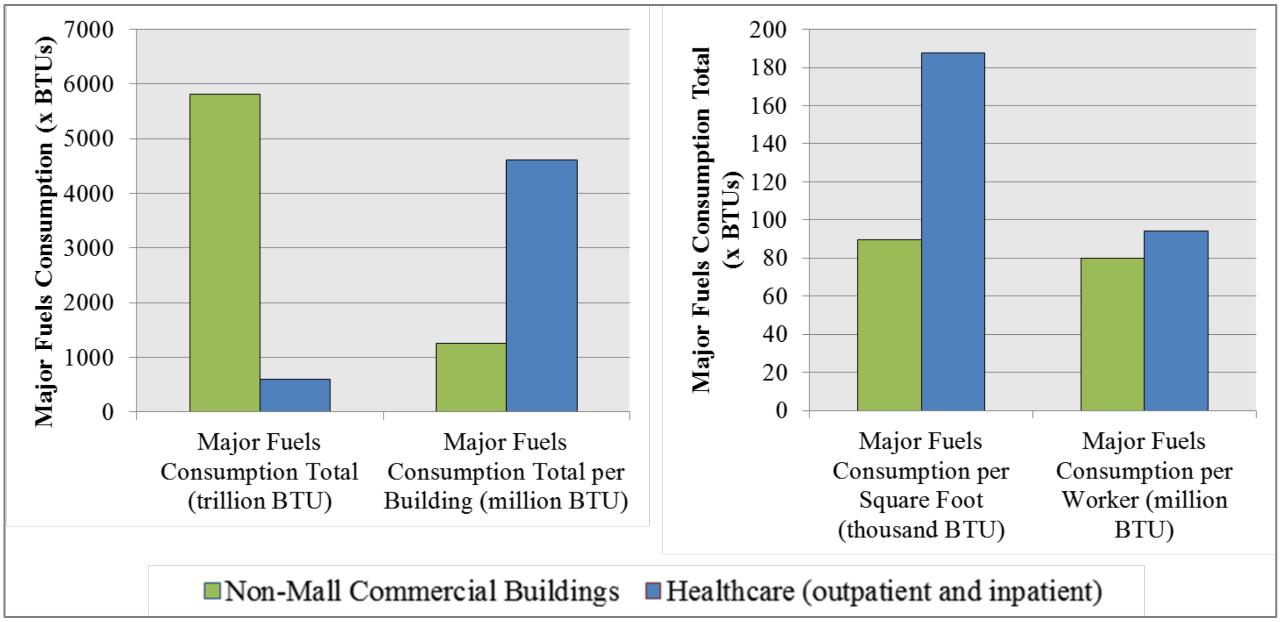


Figure 2: Energy Consumption of Healthcare Buildings Relative to Commercial Building Sector, (US Energy Information Administration 2003)

Direct hospital effluents can represent unique challenges in healthcare as well. Jolibois and Guerbet tested the genotoxicity of hospital wastewater and found that 82% of samples contained at least one of the tested chemical compounds (Jolibois and Guerbet 2006). A 2010 study of hospital effluent in Taiwan found high occurrences of controlled drugs such as methamphetamine, codeine, and ketamine (Lin, Wang et al. 2010). Hospital and pharmaceutical manufacturing effluents are associated with an increase in antibiotic resistant bacteria found in sewage (Guardabassi, Petersen et al. 1998). Additionally, cleaning products and pesticides used within and around a hospital structure can have adverse health effects on cleaning staff, hospital employees, and patients (Wilding, Curtis et al. 2009; Gilden 2010).

While many studies begin to focus on the human health and environmental impacts associated with healthcare, there is still a great void in the literature relating to the sustainability of hospital facilities (Pierce and Kerby 1999). More data is needed to provide meaningful information to practitioners and policy makers within the healthcare industry. One tool used to quantify multiple environmental impacts of a system is Life Cycle Assessment. This tool has many potential applications within the field of healthcare, and proper use of LCA results could greatly improve the sustainability of medical practices.

2.3 LIFE CYCLE ASSESSMENT

Life Cycle Assessment (LCA) quantifies 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. Sectors such as manufacturing, building construction, biofuel production, and waste management use LCA to analyze their environmental impacts. Life cycle thinking has been applied to healthcare based studies, but the healthcare system has a distinct need for data relating to its environmental impacts (Weinhold 2001; Velagaleti and Burns 2007; Kwakye, Pronovost et al. 2010; Kwakye, Brat et al. 2011). There are three basic approaches for conducting an LCA. They include process LCA, Economic Input-Output LCA (EIO-LCA), and hybrid LCA.

Process LCA follows guidelines set forth by the International Organization for Standardization (ISO 14040 and 14044) and are conducted in four stages as shown in Figure 3 (International Organization for Standardization 1997). Stage one includes establishing the boundary conditions of the system and defining a functional unit for the system. This stage standardizes LCA 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. LCA practitioners generally use professional product databases to help identify inventory input and output data for each inventory item.

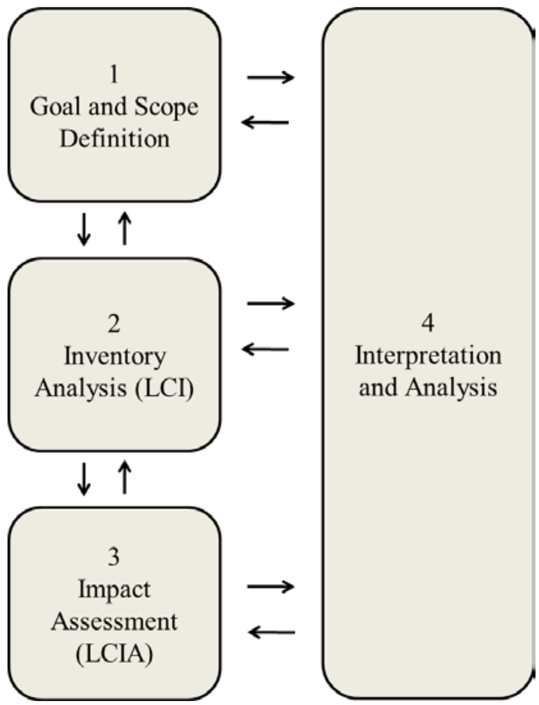


Figure 3: Stages of Life Cycle Assessment as Defined by ISO 14040

Stage three, Life Cycle Impact Assessment (LCIA), is the stage where the environmental emissions of the inventory data are aggregated and translated into impact categories (e.g. ecotoxicity and global warming potential). Several tools and models are available to aid in calculating LCIA results. One commonly used, US-based tool is TRACI (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) developed by the US Environmental Protection Agency (EPA) (Bare, Norris et al. 2003). More details on the LCIA stage can be found in Section 2.3.2. The fourth and final stage is called interpretation. This iterative stage analyzes the accuracy and suitability of all previous stages and also identifies areas of the life cycle or subsystems that have relatively high environmental impacts.

Process LCA is limited by the quality of available data, the accessibility of data, the definition of system boundaries, and time constraints associated with data acquisition. Such limitations have led to criticism of the suitability of process LCA for analysis of complex systems (Wong 2004). Another limitation of process LCA is inclusion of Scope 3 emissions, or the emissions downstream from product production and manufacture (i.e. use and disposal) (Ranganathan, Corbier et al. 2004; Huang, Weber et al. 2009).

Economic Input-Output LCA (EIO-LCA) was developed partially to make up for the shortcomings of process LCA. EIO-LCA uses aggregated data from economic sectors and attributes an environmental loading associated with the production of a product based on how much each sector purchases from other sectors (Rosenblum, Horvath et al. 2000; Suh, Lenzen et al. 2004; Hendrickson, Lave et al. 2006; Carnegie Mellon University Green Design Institute 2011). Limitations to EIO-LCA appear during detailed analysis as a result of the aggregation of economic sectors and uncertainty of data, and so it is better suited for high level analysis (Lenzen 2000; Bilec, Ries et al. 2006; Lenzen 2006; Bilec 2007). Hybrid-LCA is the combination of both process and EIO-LCA, each of which serves to make up for the other methods' limitations. Hybrid-LCA has been used to analyze building construction and service industries and will be applied to some of the work in this thesis (Suh, Lenzen et al. 2004; Bilec, Ries et al. 2006; Junnila 2006; Suh 2006).

2.3.1 Life Cycle Assessment Methods Applied to Healthcare

As global warming and carbon emissions have become a focus, some hospitals and healthcare systems have adopted carbon and ecological footprinting tools as a means to analyze the environmental impact of their operations and facilities. An ecological footprint study titled *Material Health* found that the National Health Services (NHS) in England and Wales consumed 1.3 million tonnes of products, generated 385,000 tonnes of waste, and released 3.18 million tonnes of emissions to air (J. Barrett 2004). *Material Health* does not include the extraction of raw materials or the manufacturing of those materials, instead focusing on consumption of resources and waste generation. Citing methodology from the *Material Health* study and other ecological footprints of hospitals, the Global Health and Safety Initiative released guidelines for conducting environmental footprints of hospitals (Germain 2002; Berg, Lapinski et al. 2009).

In a 2007 EIO-LCA study focusing on the carbon footprint of the US Healthcare Sector, Chung and Meltzer found that healthcare activities account for 8% of total US greenhouse gas emissions and 7% of US carbon dioxide emissions (Chung and Meltzer 2009). Power, et al. calculated the annual CO_2 emissions of the US's minimally invasive surgeries (MIS) to be 355,924 metric tons per year, which would make it 189th on the United Nation's 2008 list of annual carbon emissions of individual countries (Power, Silberstein et al. 2012; United Nations (UN) 2012). Global use of anesthetics gases was found to be a major contributor to healthcare's carbon footprint, with *annual global warming potential equivalent to CO_2 emissions from one coal fired power plant* (Sulbaek Andersen, Sander et al. 2010).

Using UK-based Carbon Trust methodology Blanchard, et al. conducted a carbon footprint of two North American emergency medical services, finding that nearly 40% of carbon emissions were the result of diesel fuel use and 23% was due to electricity (Blanchard and

Brown 2009). Karlsson and Ohman developed a life cycle based carbon assessment tool for Region Scania health center in Sweden, enabling the hospital to strategize their CO_2 reduction efforts (Karlsson and Öhman 2005). The study determined that 41% of Region Scania's CO_2 emissions were related to material consumption (Karlsson and Pigretti-Ohman 2005). Environmental footprints are useful for locating sources of carbon dioxide (CO_2) emissions within a system, but they do not analyze other environmental impacts, such as effects to human health or ecotoxicity.

Full process LCA methodology has been used to analyze individual products within the healthcare industry. A 1999 LCA comparison of single use and reusable surgical drapes found that single use drapes produced more clinical waste while reusable drapes resulted in more total energy consumption, water use, and CO_2 emissions (Dettenkofer, Grießhammer et al. 1999). McGain, et al. found in 2010 that reusable plastic anaesthetic drug trays cost less and emitted less CO_2 than single-use trays (McGain, McAlister et al. 2010). A study on reusable and disposable surgical scissors found that the reusable stainless steel scissors were the more "eco-efficient" choice (Ibbotson, Dettmer et al. 2013). Similarly, a 1996 comparative study of the life cycle inventory of reusable and disposable laparotomy pads found the disposable pads had a larger impact on the environment than reusable pads (Kümmerer, Dettenkofer et al. 1996). (Kümmerer, Dettenkofer et al. 1996). A 2012 special issue of Anesthesia and Analgesia reported on a number of life cycle based studies comparing the life cycle environmental impacts of reusable and single use laryngeal mask airways, perioperative textiles, and central venous catheter insertion kits (Eckelman, Mosher et al. 2012; McGain, McAlister et al. 2012; Overcash 2012). These studies identify impacts associated with individual products, but more research is needed to describe the current situation in healthcare at a larger scale so that decision makers can make better overarching decisions related to environmental performance of medical operations.

2.3.2 Current Limitations to the Use of Life Cycle Assessment in Healthcare Settings: Human Health Impact Categories

Most LCIA tools, such as TRACI, contain impact categories related to human health impacts. The accuracy of LCIA methodology of human health impact categories are still debated today, and their resultant units are not easy to translate into practical application, especially when reporting to medical professionals (Owens 1998; Hauschild, Huijbregts et al. 2008; Reap, Roman et al. 2008; Thiel, Campion et al. 2012). Correlation exists between the various emissions at each stage of a product's life cycle and the emissions' effects on human health, morbidity, and mortality. However, actual effects vary based upon exposure pathway, duration, and biological factors, thus limiting the accuracy of causal statements. Regardless of the final reporting units, when analyzing the human health effects resulting from operations within the medical field, it is critical to understand the underlying calculations.

This section of the literature review explores existing methodologies to analyze human health impacts within LCA and in other fields. This section addresses Objective 4 of this thesis and answers the research question 'What are the advantages and limitations of life cycle impact categories such as human health when applying LCA to healthcare issues?'

2.3.2.1 Life Cycle Impact Assessment Methodology

As seen earlier in this literature review, Life Cycle Impact Assessment (LCIA) is the third of four stages in conducting a LCA (ISO 1997). The LCIA translates and aggregates inventory input and output data from the LCI stage into impact categories to help stakeholders assess the environmental impacts of a product or process. LCIA is similar to risk assessment; however, LCIA does not determine *absolute* risk. The models used within LCIA allow LCA practitioners to calculate potential harm or damage, or the probability of human health or environmental impacts, whereas risk assessment traditionally focuses on a single chemical in a given location and time frame which results in more certain predictions of health and environmental risks (Margni and Curran 2012). As seen in Figure 4, the impact assessment stage of LCA contains following components according to ISO 14042: category definition, classification, characterization, and valuation/weighting (ISO 1997).

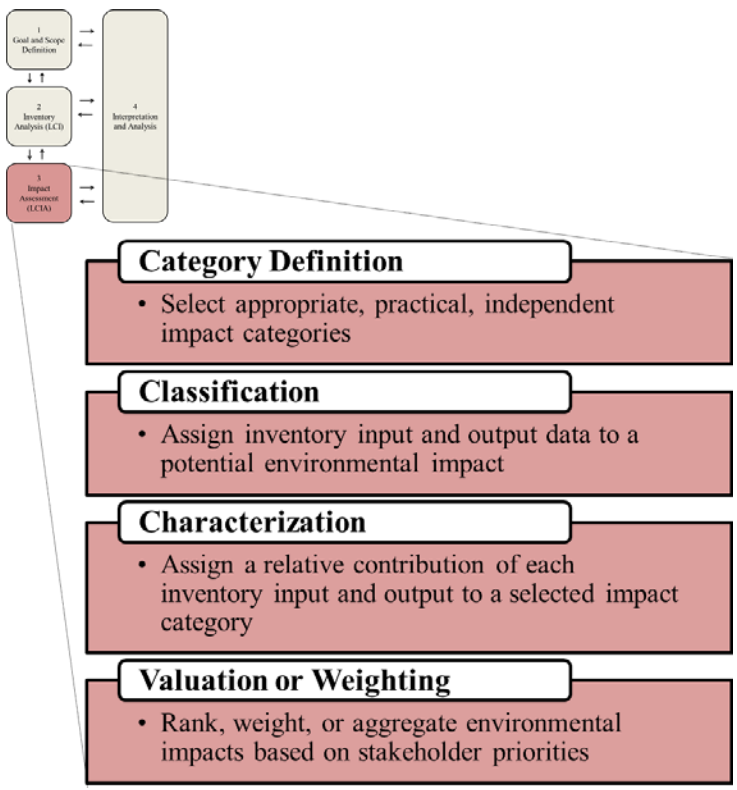


Figure 4: Components of the Life Cycle Impact Assessment Stage of LCA

Impact categories are defined and considered for inclusion in the LCA during the category definition stage. Many environmental impact categories exist, and some LCIA methodologies have standardized categories, which will be further discussed below. Category selection should be consistent with the study's goal and scope and should consider completeness (include all relevant environmental issues), practicality (prioritize necessary categories), independence (avoid double counting dependent impacts), and relation to the characterization step (choose impact categories that relate to available characterization methods) (Jensen, Hoffman et al. 1998).

The classification stage assigns inventory input and output data to potential environmental impacts, i.e. specific impact categories. This qualitative assignment does not consider issues such as potency or environmental persistence, which are accounted for in the next LCIA stage (ISO 1997; Jensen, Hoffman et al. 1998). Some of the inventory data may be assigned to multiple impact categories, in which case "double counting" needs to be monitored and avoided. During the classification stage, impacts may be analyzed on geographical scales, such as global impacts, regional impacts, and local impacts. The assignment of geographic scale can be related to the method of exposure (ie global exposure) and certain impacts are more strongly correlated with a specific geographic scale (ie global warming potential). Time scales must also be considered for certain impact categories. For example, global warming potential is often analyzed on either a 20 year or a 100 year time scale and this affects the characterization factors of each of the inventory input and output data. There is currently no consensus on a single list of impact categories (Jensen, Hoffman et al. 1998; Finnveden, Hauschild et al. 2009).

The characterization stage of LCIA models impact categories in terms of indicators (or characterization factors, CFs) and usually provide a basis for aggregating the input and output data assigned to each category. The indicator or CF assigns the relative contribution of each input and output to the selected impact category. Various models or methods exist which specify the relationship between the inventory input and output data and the indicator, and these methods can have a large effect on the results of the LCA (Dreyer, Niemann et al. 2003; Finnveden, Hauschild et al. 2009). Spatial and temporal compatibilities between the impact category and the inventory data affect the accuracy of each method, but each characterization factor's relationship to the inventory data is based on quantitative, scientific information with a few simplifying assumptions. For some impact categories, the characterization factors are more accepted and standardly utilized across the LCA community (for example, global warming potential). However, impact categories such as land use and resource depletion have not gained consensus in appropriate characterization factors.

The valuation or weighting stage of LCIA aims to rank, weight, and aggregate the results of different LCIA categories to simplify analysis of the relative importance of total results. The weighting process uses a variety of scientifically-based analytical techniques and approaches; however, it is generally based on the subjective priorities of the stakeholders and can complicate further analyses of the LCA (Jensen, Hoffman et al. 1998). This LCIA stage is optional.

The overall goal of LCIA is to help assess environmental significance by providing additional information about a product's or processes' emissions. Since LCIA does not determine absolute risk, proper interpretation of LCIA results is crucial, especially as results are reported in absolute values which might suggest greater certainty (Margni and Curran 2012). A variety of LCIA models and methodologies have been developed and commonly utilized since 1984 as seen in Figure 5 from Margni and Curran, 2012.

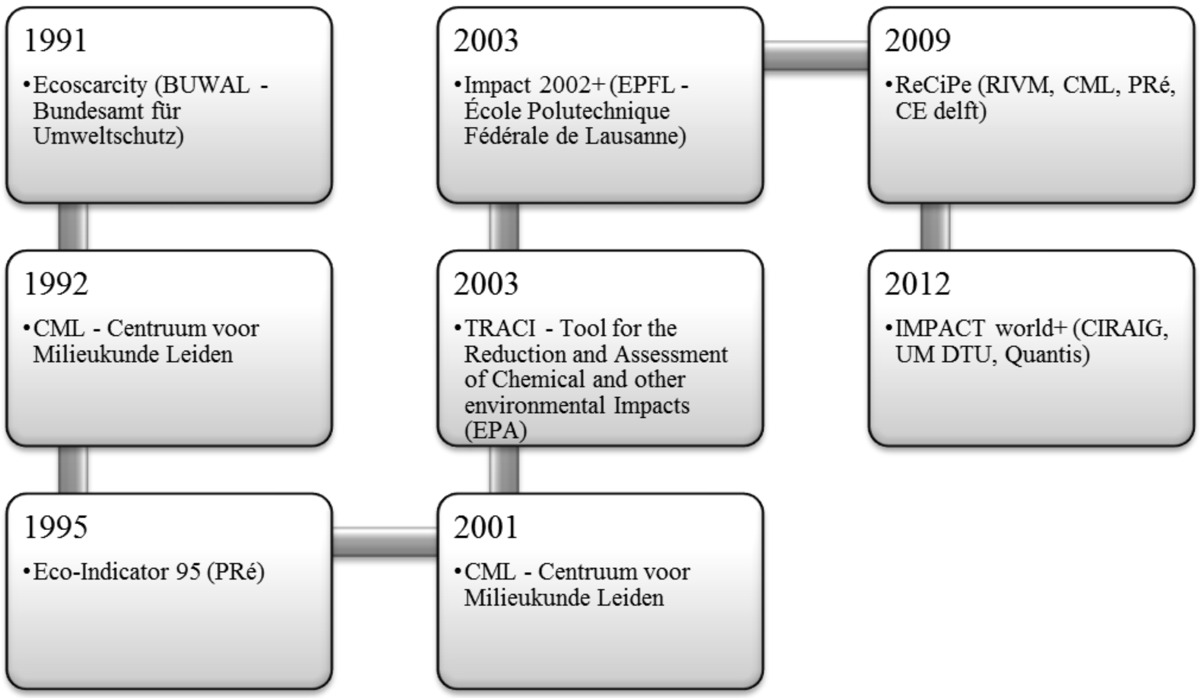


Figure 5: Timeline of Most Common LCIA Methodologies by Introduction Date from (Margni and Curran 2012)

2.3.2.2 Impact Midpoints versus Endpoints

Within the LCIA stage, the impacts of inventory inputs and outputs can be reported at various points in the chain from source to effect. A midpoint, or "intermediate variable" in Europe, represents a point in an impact category's cause-effect chain at which characterization factors can be used to directly calculate the relative importance of the LCI inputs and outputs. The uncertainty in midpoint valuation is kept within an acceptable range (Haes, Jolliet et al. 1999; Bare, Hofstetter et al. 2000; Finnveden, Hauschild et al. 2009). An endpoint, or "damage level," reports the effects of inventory inputs and outputs on society, or the resulting effects further down the chain of correlated, cause-effect impacts. For example, midpoint categories might include concentrations of toxic substances, but not their impact on human health, while endpoint categories might include incidence rate of illnesses, species extinction estimates, etc., as seen in Figure 6.

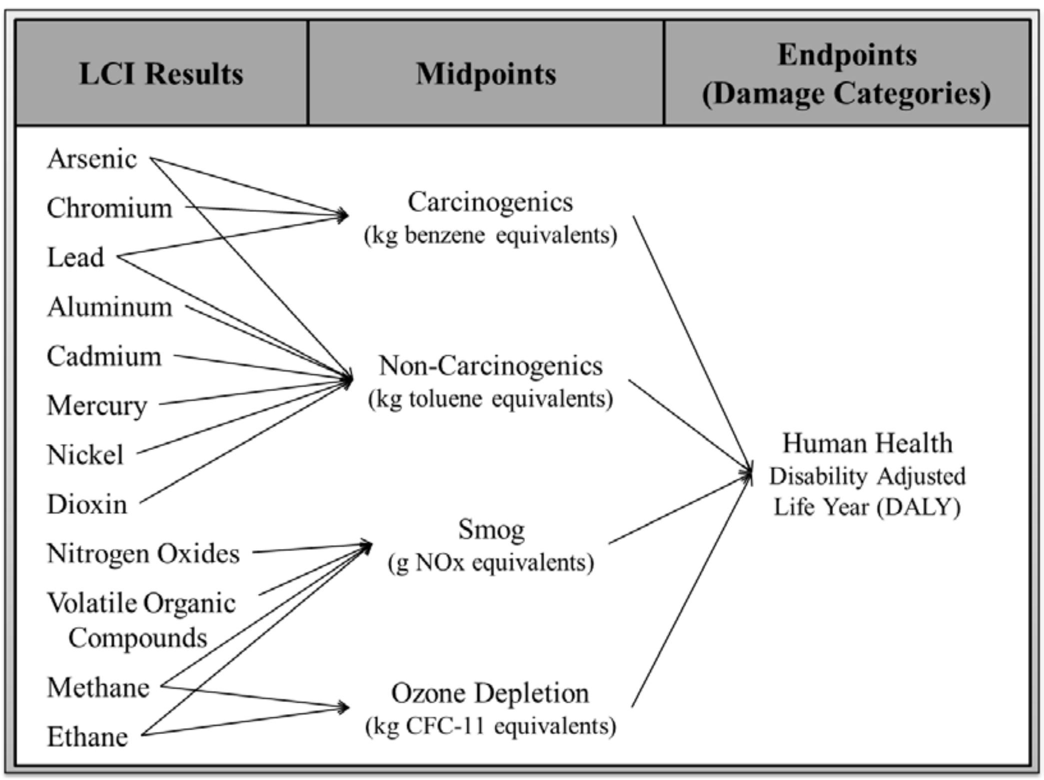


Figure 6: Midpoint to Endpoint LCIA Example

Endpoints facilitate a more informed weighting structure across impact categories. For example, the effects to human health of chemical exposure, global warming, and smog formation can be compared using a common unit such as Disability Adjusted Life Years, making it easier for a stakeholder to analyze and interpret LCA data and results (Margni, Gloria et al. 2008). Opponents to the use of endpoints in LCA assert that extending LCIA models to endpoints reduces their accuracy and thus comprehensiveness. Endpoint models are generally based on unsubstantiated assumptions, and the uncertainties beyond well-characterized midpoints are too high to make endpoints a valuable reporting metric (Bare, Hofstetter et al. 2000; Finnveden, Hauschild et al. 2009). Uncertainty, though present in all forms of impact or risk assessment, can be difficult to meaningfully and clearly present to the general public, and it is best kept to a minimum where possible (Johnson and Slovic 1995).

2.3.2.3 Current Life Cycle Impact Assessment Methods for Analyzing Toxicological Human Health Impacts

In terms of impact categories, human health impacts can be one of the most difficult and most delicate to model. For this thesis work, which focuses on the environmental impacts of healthcare facilities and procedures, human health is one of the more interesting and compelling measurements of environmental impacts for a number of our stakeholders. In commonly-used LCIA methodologies, human health impact categories center on two components- toxic effects of chemical exposure and respiratory impacts due to particulate matter. This section will focus on LCIA methods related to toxic exposures, as characterization models for respiratory effects have greater levels of acceptance by LCA practitioners and are more easily understood by diverse audiences (Hauschild, Goedkoop et al. 2013).

Toxicity impact categories focus on cancerous and non-cancerous effects related to direct exposure to chemicals, and do not include health effects from other agents or effects already allocated to other impact categories (Crettaz, Pennington et al. 2002). For example, impacts from fine particles are included in impact categories such as “respiratory impacts,” and the health effects of noise exposure are often unanalyzed within LCA. Human health effects due to fine particles, tropospheric ozone, and radiation use comparable effect indicators, however, and similar methodologies are applied to those impact categories.

The mechanisms of interaction and the effects of toxic chemicals on organisms differ drastically based on the chemical in question. Toxicologists create chemical effect designations based on local or systemic effects (for example acid burns vs. lead poisoning) and acute, repeated, or chronic exposures. Different organisms, and even unique individuals within a species, respond to toxic chemicals differently. Sensitive groups include those with asthma or existing illnesses, the old, and the young, and toxic chemicals can have a more severe impact on these groups. Thus, a single designation or impact category for toxic effects is difficult to justify, yet has been developed by government and industry for use in risk management and is the basis for the LCIA of human health (Hertwich and Hammitt 2001).

For cancer- and non-cancer-related human health impacts, the chemical fate, the exposure, the likelihood (potency), and the consequences (severity) of toxicological effects (shown in Figure 7) must all be considered when creating characterization factors for LCIA (Crettaz, Pennington et al. 2002; Krewitt, Pennington et al. 2002). Environmental health impacts are calculated as the product of the emission rate of a chemical, the Intake Fraction (iF), and the toxicity. Intake fraction is a metric defined as the total mass of the chemical inhaled or ingested divided by the total mass of the chemical emitted. It is a function of a given chemical’s fate and exposure, from Figure 7. Intake fraction is unit-less and can be used to evaluate individual or population exposures over short or long durations (Marshall and Nazaroff 2006). Typically, iF accounts for inhalation or ingestion exposure, but usually does not include dermal exposure as this route lacks toxicological data and is commonly thought to be negligible (Krewitt, Pennington et al. 2002). Most LCIA methods assume chronic exposure rather than acute toxicity effects (Rosenbaum, Huijbregts et al. 2011).

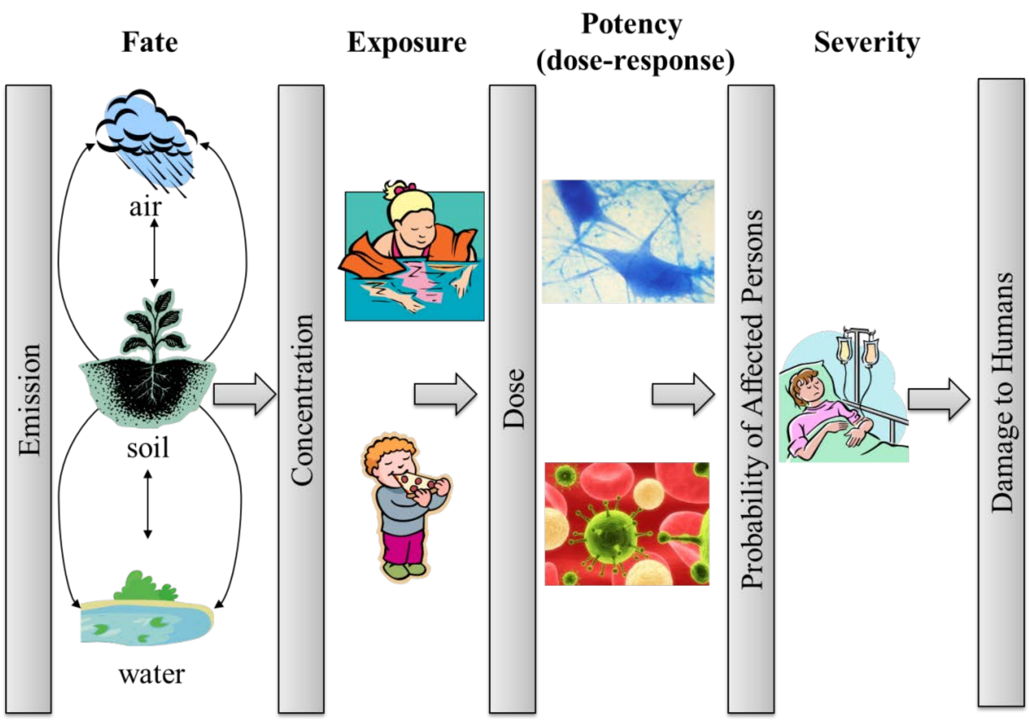


Figure 7: Stages Used to Calculate the Toxicology Effect of Chemicals on Human Health

In LCIA, the potency of a chemical is derived from toxicological data. For carcinogens or cancer-causing chemicals, likelihood of adverse effects is measured off of a slope factor based on risk per unit dose of a given effect (Krewitt, Pennington et al. 2002). Toxicity assessment for cancer effects of chemicals first determines whether a chemical does or does not cause cancer in humans. A toxicity assessment then elucidates the carcinogenic potency of an alleged carcinogen by quantifying the increases in the number of cancers in exposed populations (animals and humans) with increased dosage of the chemical. This creates a dose-response curve for the cancer effects of a chemical, with an assumption that there is no dose threshold below which the risk of cancer is negligible. The cancer-related potency of a chemical is the slope of this dose-response curve, called Slope Factor (SF), which is measured in "risk of cancer per unit dose". The slope is generally linear until high doses are encountered, so in risk assessment, the EPA uses the upper 95% confidence limit of the slope as the SF to increase the margin of safety in risk estimates (US EPA 2013). LCIA methods generally assume that the SF and dose-response curve have "no threshold" and are linear, but this eliminates considerations of background (or existing) concentrations of a given chemical at a specific site (Krewitt, Pennington et al. 2002).

In LCIA for non-carcinogenic chemicals, the likelihood of adverse health effects (or potency) is based on the dose-response gradient of that chemical (Pennington, Crettaz et al. 2002). All chemicals have adverse health effects if a person is exposed with a high enough dose, so the risk of non-cancerous effects is calculated via threshold doses. These thresholds generally include the highest dose that does not produce an observable adverse effect (the No Observed Adverse Effect Level, NOAEL or No Observed Effect Level, NOEL) and the lowest does which does produce an effect (the Lowest Observed Adverse Effect Level or LOAEL). Doses below the threshold value are considered safe in standard risk assessment while doses above the threshold are likely to cause an effect. Conservative risk evaluations will use an Acceptable

Daily Intake (ADI) or a Reference Dose (RfD) value to estimate the adverse effects over a lifetime of daily exposures (Krewitt, Pennington et al. 2002). RfD is calculated by dividing the NOAEL by an uncertainty factor which can span an order of magnitude, but the uncertainty factor ensures that the RfD value contains a margin of safety for describing the risk of adverse health effects (US EPA 2013).

Some LCIA methodologies utilize only these potency-based indicators to describe and aggregate the risk of potential health effects due to a related chemical emission, but the relative severity of health effects due to multiple emissions is not considered. To make up for this limitation, some LCIA methodologies assess the damage to human health both in terms of potency-indicators and severity-indicators (Burke, Doull et al. 1996; Krewitt, Pennington et al. 2002; Huijbregts, Rombouts et al. 2005).

Potency-based indicators reflect the probability, likelihood, or risk of people to be potentially affected by an emission. Toxicology potency factors are based on test data such as No Observed Effect Levels (NOELs) which are determined in laboratory studies of rodents and extrapolated to human measures (Krewitt, Pennington et al. 2002). In LCA, these characterization methods are based on policy thresholds such as reference dose (RfD), acceptable daily intake (ADI), and tolerable daily intake (TDI) (Pennington, Crettaz et al. 2002).

Severity-based indicators or "damage indicators" build on potency-based indicators to include the likelihood and expected severity of the human health effects (Pennington, Crettaz et al. 2002). In that sense, they are analogous to endpoint reporting in LCIA. Severity-based indicators usually express effects in terms of Years of Life Lost (YOLL), Disability Adjusted Life Years (DALY) and Quality Adjusted Life Years (QALY) (Krewitt, Pennington et al. 2002). Severity-based indicators make up for the limitations of potency-based indicators by incorporating the differences between potential consequences of human health effects. Damage indicators also provide a more relevant idea of the resultant hardships and societal concerns of chemical releases for decision makers.

2.3.2.4 Human Health Impact Categories for Commonly Utilized LCIA Methods

Many methodologies exist to assess the risk and damage to human health as the result of toxic chemicals. Table 1 summarizes commonly used base models, such as eco-indicator and USEtox. Table 2 lists common LCIA methodologies and tools and specifies their human health impact assessment models. Discussion in this section will focus on the Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) from the US Environmental Protection Agency (US EPA), as this is the accepted LCIA method for North America and the LCIA tool used for the analyses in chapters 4.0 and 5.0 of this dissertation.

Some Life Cycle Impact Assessment tools, such as older versions of TRACI, present midpoint categories in terms of a reference unit such as kg of benzene equivalents for cancerous impacts and kg of toluene equivalents for noncancerous impacts. Benzene is an organic chemical compound (C_6H_6) naturally found in crude oil. Inhalation and ingestion of benzene is associated with increased risk of cancer and other illnesses. Toluene is a benzene-derived solvent whose inhalation is associated with neurological problems such as weakness, nausea, hearing and vision loss, unconsciousness, and death. Toluene, however, has very little carcinogenic potential (Dees, Askari et al. 1996; National Library of Medicine 2011). While a reference unit is useful in assessing the relative health impacts of a variety of substances, its meaning can be lost on those unfamiliar with the substance itself.

Table 1: Commonly-Used Human Health Toxicological Impact Assessment Base Models

	LCIA Method	***Release Year***	***Release Organization***	***Human Health Impact Category (unit)***	***Endpoint or Midpoint***	***Geographic Scale***	***Number of Substances***	***Reference***
Toxicological Impacts Base Models	***USEtox***	2010	USEtox Team, Task Force on Toxic Impacts UNEP/SETAC Life Cycle Initiative	Human Health Cancer & Noncancer (Comparative Toxic Units human, CTUh)	Midpoint	regional	> 3000	(Hauschild, Huijbregts et al. 2008; Rosenbaum, Bachmann et al. 2008; Henderson, Hauschild et al. 2011; Rosenbaum, Huijbregts et al. 2011)
	USES-LCA 2.0 *(Uniform System for the Evaluation of Substances 2.0)*	2006	Netherlands Center For Environmental Modeling	Damage to Human Health (Disability Adjusted Life Years, DALY)	Midpoint and Endpoint	regional	3393 (potency) / 1192 (damage)	(Huijbregts, Rombouts et al. 2005; Huijbregts, Struijs et al. 2005; van Zelm, Huijbregts et al. 2008)
	Impact 2002+	2003	Swiss Federal Institute of Technology (EPFL)	Damage to Human Health (Disability Adjusted Life Years per person per year, DALY/pers/yr)	Midpoint and Endpoint	regional, global	769	(Jolliet, Margni et al. 2003; Humbert, Margni et al. 2005)
	Eco-indicator 99	1999	PRé Consultants	Damage to Human Health (Disability Adjusted Life Years, DALY)	Endpoint	local, regional	52	(Goedkoop, Effting et al. 2000; Goedkoop and Spriensma 2001)

Table 2: Commonly-Used Impact Assessment Models and Methodology and the Human Health Toxicological Impact Categories

	LCIA Method	*Release Year*	*Release Organization*	*Human Health Impact Category (unit)*	*Endpoint or Midpoint*	*Geographic Scale*	*Reference*
Toxicological Impact Assessment Tools	***ReCiPe 2008 v 1.08*** *(USES-LCA base)*	2012	RIVM, CML , PRé Consultants, Radboud Universiteit Nijmegen and CE Delft	Damage to Human Health (Disability Adjusted Life Years, DALY)	Midpoint and Endpoint	local, regional, global	(Goedkoop, Heijungs et al. 2009)
				Human Toxicity (1,4-dichlorobenzene equivalents)			
	TRACI 2.1 *(USEtox base)*	2012	USEPA	Human Health Cancer & Noncancer (Comparative Toxic Units human, CTUh)	Midpoint	regional, global	(US EPA 2012)
	TRACI *(CalTOX from California EPA base)*	2003	USEPA	Human Health Cancer (benzene equivalents)	Midpoint	regional	(McKone 1993; Maddalena, McKone et al. 1995; Bare, Norris et al. 2003; Bare and Gloria 2006; Bare 2011)
				Human Health Noncancer (toluene equivalents)			
	BEES 3.0 *(TRACI 1.0 base)*	2003	US regional Institute for Standards and Technology (NIST)	Potential Human Health Effects (toluene equivalents)	Midpoint	regional	(Curran and Lippiatt 2002)
	CML 2001 *(USES-LCA base)*	2001	Institute of Environmental Sciences, Leiden University, The Netherlands	Human Toxicity (1,4-dichlorobenzene equivalents)	Midpoint	local, regional, global	(Frischknecht, Jungbluth et al. 2007)

Studies recommend USEtox as a preferred LCIA model for calculating human cancer and non-cancer impacts, as it is most up-to-date, offers the largest selection of chemical characterization factors, and allows for geographic scaling from global to urban effects (Hauschild, Goedkoop et al. 2013). USEtox utilizes Human Toxicity Potential (HTP) per kilogram of chemical as the unit for the characterization factor for each of its chemicals. HTP is the product of Intake Fraction (iF) and Human Effect Factor (EF). The iF ($kg_{intake}/kg_{emitted}$) is the product of chemical fate and human exposure from Figure 7, while the EF (Comparative Toxic Unit for humans, CTU_h/kg_{intake}) is the product of the dose response or potency and the severity (Rosenbaum, Huijbregts et al. 2011).

The reported Comparative Toxic Unit (CTU_h) for human health is an estimate of the increased morbidity as a result of the emissions of a product or process and can be thought of as the disease cases per kg of chemical emitted (Rosenbaum, Bachmann et al. 2008). Effect factors of substances in the USEtox database vary by up to ten orders of magnitude increasing the uncertainty associated with potential human health impacts (Rosenbaum, Huijbregts et al. 2011). As seen in Table 2, the US EPA previously used CalTOX, a California EPA chemical toxicology assessment model, as the base for human health cancer and noncancer impact analyses in TRACI (McKone 1993). The US EPA currently utilizes USEtox in TRACI 2.1, the most recent version of the EPA's impact assessment methodology (US EPA 2012).

2.3.2.5 Limitations of Current Human Health Characterizations in LCIA

Because LCA inventory input and output data are reported in total mass for each chemical emission, the location and timing of each emission are not often given. The integration of the temporal and spatial exposure differs from traditional health and risk assessments which analyzes risk for a given location and point in time. It may be, for example, that the chemicals released over the lifetime of a product meet regulatory requirements for exposure levels at each point in the product's life cycle (eg. emissions do not exceed regulations during the manufacturing stage, or during transport or during use), but when aggregated and removed from spatial considerations, an LCA may suggest damaging health consequences from a given product (Crettaz, Pennington et al. 2002). This is especially important because while many commonly-used LCIA human health impact models utilize existing quantitative methods of health risk assessment, they do not present actual risk but rather the relative potential or probable risk (Burke, Doull et al. 1996; Margni and Curran 2012). LCIA methods are also unable to account for background or existing environmental sources of chemicals, which may increase the local human health risks of relatively small emissions from the analyzed product.

Additionally, experimental toxicological data is only available for a small percentage of the chemicals currently and previously used (Krewitt, Pennington et al. 2002). In 1998, the US EPA estimated that of the roughly 3000 chemicals imported or produced at over one million pounds per year, only 7% have complete basic toxicity profiles and 43% have no testing data whatsoever (US EPA 1998). In addition, most experiments which assess the toxicological risk of chemicals are conducted on species other than humans, and many of those test protocols are not standard between chemical types (Owens 2002). This results in large factors of uncertainty in available data.

Beyond the limitations inherent in current LCIA methodology are limitations in meaningfully reporting adverse health outcomes to a diverse audience or healthcare professionals (Thiel, Campion et al. 2012). Some professionals suggest an impact category such as "cancerous effects" is too arbitrary, as there are multiple types of cancers with various rates of aggressiveness. In traditional medicine, health indicators vary by medical specialty. For example, a urologist will be most interested in those chemicals or emissions affecting the function of the kidney, bladder and reproductive organs. An overarching concern within the profession is mortality or death. However, there is obvious analytical and political complexity in attaching a designation such as “mortality” to the *potential* impacts within life cycle assessment. Some expert panels believe that aggregating different toxic effects into a single category, such as mortality, is “inherently impossible on a scientific basis” (Owens 1998) yet aggregation may be necessary to yield meaningful data for the healthcare field. Additionally, most LCIA methods overlook other, non-toxicological human health impacts such as quality of life or individual and community autonomy. While more difficult to quantify, these social sustainability metrics may be equally valuable when talking about overall or long-term impacts to human health.

2.3.2.6 Approaches to Improving Human Health Impact Assessment

Given the general limitations of human health impact assessment methodology, what can be done to improve the impact assessment phase to make life cycle assessment more meaningful in a healthcare setting? This subsection outlines potential approaches which exist in literature. It is not a complete assessment of improvement options, but rather points to pathways which might be worth pursuing. The first part highlights Health Impact Assessment methods, a policy-based human health assessment method from outside the field of LCA. The second part focuses on a position paper from SETAC-Europe (Society for Environmental Toxicology and Chemistry) which identified qualitative and quantitative approaches to incorporate severity into existing LCIA methods. Finally, the third part highlights a thrust in risk assessment to incorporate more human-based studies from epidemiology, and the potential impact of green chemistry to the effectiveness of LCIA methods.

Measuring Health Consequences of Projects and Policies through Health Impact Assessment

Following the form of Environmental Impact Statements established by the National Environmental Policy Act of 1969, Health Impact Assessments (HIA) analyze the unintended health consequences of major projects and policies (Collins and Koplan 2009). Though specific definitions vary, an HIA is a decision-making tool designed analyze the potential effects of a policy on the health of a population and the distribution of those effects (WHO 1999). It is intended to be a catalyst to engage policymakers, academics, and affected populations in participatory strategic planning (Krieger, Northridge et al. 2003), and follows other forms of risk and impact assessment such as health risk assessment, environmental impact assessment, integrated environmental health impact assessment, social impact assessment, and economic assessment (Mindell and Joffe 2003; Briggs 2008; Negev, Levine et al. 2012).

The first step of an HIA is screening, where it is determined if a HIA will be conducted on a proposed policy or project. No standardized criterion for policy selection exists. The second step of HIA is scoping and assessment where the potential health impacts are identified and literature is reviewed for evidence related to health impacts. In this stage, key stakeholders and experts from a variety of fields are consulted and results are tabulated to indicate possible or probably health impacts. The final step is policy modification and evaluation where the proposed project is modified to maximize positive health effects and minimize the negative (Lock 2000; Parry and Stevens 2001).

Lack of standardization in the selection and application of HIA remains a limiting factor in its effectiveness. The assessment of potential or probable health impacts is subject to inaccurate information and personal biases which reduce the validity of health impact predictions. Similar to LCA, HIA reports health risks of chemicals in cause-effect chains for emissions and impacts, sometimes utilizing toxicological data as in LCIA, which makes HIA equally ineffective with short exposures to chemicals (Krieger, Northridge et al. 2003). HIA includes other human health determinants, however, such as community cohesion, job security, and quality of life, which can portray a more complete picture of human health impacts (Negev, Levine et al. 2012). Like LCA, HIA encounters difficulties in quantifying other health and social effects such as discarded syringes or graffiti in a community, though through the feedback of proper focus groups throughout the analysis, the relative importance of such factors within a community becomes more visible (Parry and Stevens 2001; Briggs 2008).

Health Impact Assessment can have meaningful results for a community policy or project and incorporates health effects outside of toxicology. However, HIA is still subject to the limitations of toxicological interpretation as in existing LCIA methodologies.

Creating Finer Detail in Existing Human Health LCIA

Rather than aggregating human health toxicological impacts into a single group, health impacts could be reported in more meaningful subcategories. A position paper for SETAC-Europe identified three subcategories of human toxicity impacts based on general severity-irreversible or life-shortening effects, maybe reversible or life-shortening, and generally reversible or non-life-shortening (Krewitt, Pennington et al. 2002). Possible endpoints for the irreversible or life-threatening effects include cancer, reproductive and teratogenic effects, acute fatal effects or acute severe effects. This sub-categorization, though somewhat based in value judgment, would increase the relevance of results for decision-makers. Sub-categorization has some issues, namely concerns with double counting individual chemicals and not having detailed enough information about each chemical to make a subcategory designation. The limitations of toxicology and risk assessment create challenges for effective or meaningful life cycle assessments.

Incorporating Epidemiology and Green Chemistry in Risk Assessment to Reduce Uncertainty and Broaden Chemical Scope

The data behind human health risk assessment include a variety of research fields, such as toxicology, epidemiology, clinical medicine, mode of action studies, molecular studies, and environmental exposure studies. Epidemiological studies, however, provide evidence of health impacts based on studies of human populations, which reduces the large uncertainties associated with extrapolating health effects of individual chemicals from cross-species laboratory experiments. Proper evaluation and integration of epidemiological study results greatly enhance risk assessment, risk management, and, therefore, life cycle assessment, especially for assessments of known human carcinogens (WHO Working Group 2000; Swenberg, Moeller et al. 2013). Unfortunately, epidemiological studies vary in consistency, making it difficult to extract meaningful causal inferences of the risk of exposures to chemicals and pollutants. Groups, such as the World Health Organization and the Johns Hopkins Risk Sciences and Public Policy Institute, are creating recommendations for improving consistency in reporting and interpreting epidemiological data (White, Fox et al. 2013).

Conducting extensive studies of each individual chemical as it enters the market is not an efficient method of assessing toxicological human health impact (US EPA 1998). The field of green chemistry analyzes potential carcinogenicity of chemicals based off of molecular structures and other molecular properties (Fjodorova, Vračko et al. 2010; Rusyn, Sedykh et al. 2012). This predictive modeling allows chemical and drug developers to avoid potentially carcinogenic molecules and identifies classes of chemicals already in use which should be better monitored and analyzed (Judson, Richard et al. 2009; Benigni, Bossa et al. 2013), though research needs to focus more on the unknown chemicals rather than on the well-studied, “hot topic” substances (Grandjean, Eriksen et al. 2011). Improvements to these fields will lead to improvements in life cycle assessment, though the static nature of LCA requires incremental updates to LCI databases and LCIA methodology as external data become better.

The methods behind LCIA and their inherent limitations are important to bear in mind when presenting and interpreting LCA data for a healthcare audience. Life cycle impact assessment allows hospitals to identify and better understand the environmental and human health impacts of their existing and potential consumption patterns, but proper utilization of results depends on understanding the assumptions and methodologies inherent in the tool. The advantages and limitations of LCIA methods were shown in this chapter, in fulfillment of research Objective 4. As LCA and the fields supporting LCIA continue to improve and develop, the use of LCA in the healthcare setting will become more valuable.

3.0 EFFECTS OF HOLISTIC, GREEN DESIGN ON PERFORMANCE OF HOSPITAL FACILITY

The research presented here addresses research Objective 1. Specifically, it answers the questions ‘How does sustainable hospital design affect hospital performance?’ and ‘How can hospital performance metrics help determine the effects of sustainability initiatives within hospitals?’

3.1 INTRODUCTION

The design and aesthetics of a medical treatment facility impact not only the energy consumption of the hospital but also the performance of the staff and the recovery of the patient receiving treatment within the facility. As a place that serves a vulnerable subset of the population, reports assert that hospitals should be the most rigorous in implementing environmentally sustainable design practices and environmental stewardship (Ficca, Chyun et al. 2000; Phelps, Horman et al. 2006; Verderber, Fauerbach et al. 2008; Younger, Morrow-Almeida et al. 2008; Stichler 2009). Many studies point to sustainable and Evidence-Based Design (EBD) as a method of improving hospitals’ performance and healthcare outcomes. However, continued investigation is needed to show the relationship between health and building design and to monitor the actual performance of green buildings, especially green healthcare facilities (Ries, Bilec et al. 2006; Loftness, Hakkinen et al. 2007).

For the past 7 years, researchers worked with the Children's Hospital of Pittsburgh of UPMC (Children's) to quantify the effects of holistic, sustainable building design on the function and performance of a children's healthcare facility. Using a range of standard hospital reporting metrics in this longitudinal comparative analysis, data was collected to compare the old Children's hospital to their new, LEED-certified facility (Leadership in Energy and Environmental Design) (Bilec, Geary et al. 2010). With metrics of hospital expenses, productivity, quality of care, staff satisfaction, and utilities, researchers show the actual performance of a green hospital as well as the effects of green building design and managerial practice on the health and safety of the building's occupants.

3.1.1 Green Hospital Design

The benefits of green buildings can be difficult to quantify, and it is unknown if green buildings are performing as intended, especially in regards to health concerns associated with the indoor environment (Needy, Gokhan et al. 2007). To better understand the effects of green buildings, studies have analyzed metrics such as worker productivity, developing surveys or analyzing company-collected data such as employee absenteeism or sick leave (Kats, Alevantis et al. 2003; Ries, Bilec et al. 2006; Seppänen and Fisk 2006; Loftness, Hakkinen et al. 2007; Wiik 2011). One aspect of green building design in particular, the indoor air and environmental quality (IAQ and IEQ), has been linked to worker health and productivity in multiple studies (Mitchell, Zhang et al. 2007; Singh, Syal et al. 2010; Sundell, Levin et al. 2011). Other studies have found that natural and sustainable daylighting not only reduces energy demands, but also helps people with perceptual and circadian functions and results in a more positive perception of the work environment (Figueiro 2008; Hua, Oswald et al. 2011).

Studies confirm the positive effects of sustainably-designed medical facilities by analyzing changes in 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; Bartley, Olmsted et al. 2010; Huisman, Morales et al. 2012). Two design aspects in particular, noise control and natural or appropriate lighting, have been well-studied and are associated with increased staff satisfaction and performance, and improved patient outcomes including reduced stress, shorter hospital stays, and reduced pain medication rates (Topf 1985; Verderber and Reuman 1987; Biley 1994; Graven 1997; Benedetti, Colombo et al. 2001; Walch, Rabin et al. 2005; Sánchez, Ausejo et al. 2009; Hua, Oswald et al. 2011; Ulrich, Bogren et al. 2012). This growing field of Evidence-Based Design uses existing research and knowledge to make design decisions in healthcare structures in an effort to improve performance outcomes. These outcomes are monitored, tested, and reported to promote future EBD projects (Cama 2009).

In 2007, the United States Green Building Council (USGBC) partnered with the Green Guide for Health Care (GGHC) to create a green building standard and certification program specifically for healthcare facilities. The LEED 2009 for Healthcare (Leadership in Energy and Environmental Design) standards are based on LEED for New Construction and awards points for location and public transportation accessibility, water efficiency, energy performance, the reuse of existing buildings and materials, and reduction in building materials containing certain chemicals to improve indoor human health (Weinhold 2001). LEED for Healthcare also issues points for design features like natural daylighting, acoustic control, and thermal comfort control

(Pradinuk 2009; U.S. Green Building Council (USGBC) 2009; U.S. Green Building Council (USGBC) 2011). LEED for Healthcare aims specifically to provide nurses, doctors, and hospital staff with a safe and comfortable working environment which is “vital both to their health and to the health of their patients” (Holowka 2007).

Research Question

Children’s 2005 decision to build a brand-new, LEED certified facility created a unique opportunity to examine the actual performance of green buildings and the effects of green design on hospital users and occupants. The aim of this study was to measure and analyze the performance of this green hospital as a whole, relative to its previous, traditional counterpart. This study also evaluated the factors contributing to changes in patient outcome and employee performance and satisfaction metrics (Bilec, Geary et al. 2010). In summary, the overarching research question was how much impact do green building design features have on the intended outcomes?

3.1.2 Children’s Hospital of Pittsburgh of UPMC Case Study

Built in 1926, the original Children’s Hospital of Pittsburgh of UPMC (Children’s) was located in the Oakland neighborhood of Pittsburgh, Pennsylvania. After multiple renovations, it was decided the 260-bed, 400,000 square foot hospital would be replaced entirely with a new facility in Pittsburgh’s Lawrenceville neighborhood as shown in Figure 8. The new Lawrenceville campus was built using an existing healthcare structure and features nearly 1.5 million square feet of hospital and administrative space, 296 patient beds, and the 300,000 square foot John G. Rangos Sr. Research Center. The large increase in size was due to expansion needs, private patient rooms, and large waiting areas containing distraction techniques and technologies (Koller and Goldman 2012).

Figure 8: Children's Hospital of Pittsburgh of UPMC Pre-Move, Traditional Structure and Post-Move, Green Structure

With features such as a green roof and healing garden, individual patient rooms, mobile nursing stations, and daylighting in every room, the new facility became one of the first LEED-certified (version 2.1) pediatric hospitals in the US and an ideal case study to better understand the impacts of hospital design decisions on the hospital's performance. The new hospital was a critical component in fulfilling Children's values: patients and families first, responsibility, innovation, dignity and respect, and excellence (Children's Hospital of Pittsburgh of UPMC 2011).

3.2 METHODS

In order to perform this comparative longitudinal assessment of the two Children's facilities, metrics were collected, statistically analyzed, and validated with hospital staff via the methods described in this section.

3.2.1 Comparative Longitudinal Assessment

In 2006, researchers collaborated with Children's executive management team to identify a host of metrics to monitor in the study. Metrics were sorted into the following categories: Expenses, Productivity, Quality of Care, Staff Satisfaction, and Utilities. These metrics, a sampling shown in Table 3 and full definitions listed in Appendix A, were chosen for multiple reasons. Children's already collected these data for management and reporting purposes, which minimized time and cost concerns for data collection and retrieval, and enabled retrospective data collection and analyses (Powell, Davies et al. 2003). The use of standard hospital metrics also made the study methodology easily applicable to similar studies at other healthcare facilities. Additionally, these data analyzed the costs and benefits of green building design in a more tangible sense, directly influencing green economic methodology (Bilec, Geary et al. 2010).

Table 3: Hospital Metrics Used to Compare Children's Old, Traditional Hospital Design with New, Green Hospital Design

	Metric
Utilities	Gas/Steam (kbtu)
	Electric (kWh)
	Water (kgal)
	Sewage ($)
Expense	Salaries and Wages
	Total Labor Expenses per PIB
	Medical / Surgical Supply Expense per PIB
	Total Operating Expenses by PIB
Staff Satisfaction	Tenure
	Time to Fill
	Turnover - Number of Employees
	Turnover - Years of Service
	Vacancy - Number of Openings
	Vacancy - Average Postion Age
	Admissions
	Total Patients in a Bed
	Average Daily Census
	Vancancy Rate RN
	Turnover Rate RN
	Human Resources Turnover Rate RN
	RN Reassigned Hours

	Metric
Productivity	Regular Hours (all staff)
	Overtime Hours (all staff)
	Total Direct Care Hours per PIB
	RN Productivity
	Patient Care Technician Productivity
	Total Direct Care Productivity
	Total Paid Hours per PIB
Quality of Care	Average Length of Stay
	Doses Dispensed per Hour
	Adverse Drug Events (ADEs)
	Non-ADEs
	Medical Administration Record (MAR) Corrections
	Significant Prescribing Errors
	Blood Stream Infection Rate
	Case Mix Index
	Actual Mortalities
	Expected Mortalities
	Mortality Rate
	Mortality Index

PIB = Patient in Bed
RN = Registered Nurse

Children's Hospital generally provided researchers with data in the identified metrics from July 1999 until November 2012. The hospital reported data on a monthly, quarterly, and yearly basis, depending on the metric, as seen in Table 17 of Appendix A. Data prior to May 2009 were considered "pre-move" or old hospital data, data from May 2009 to present were considered "post-move" or new, green hospital data.

Some data, due to changes in collection methods or facility size and function, needed to be normalized to ensure an even comparison. All expenses and monetary data were normalized to the value of the 2009 US dollar. Utility data was collected for functionally equivalent spaces in the two Children's facilities. For example, the main hospital in the old Children's campus contained space for administration, standard hospital care, and testing laboratories. Equivalent space in the new, green facility and the utilities consumed in that space were included in the comparison as seen in Table 16 of Appendix A.

Children's former facility was not conditioned in every space and was functioning under older hospital codes. The new, green facility is performing beyond current hospital operation codes in terms of air ventilation and filtration, which complicates an even comparison of the two facilities. Additionally, heating methods changed between the two Children's facilities. The old, Oakland campus purchased steam generated from a nearby plant which utilized coal and natural gas. The new, green campus generates heating on-site using natural gas. The quantity of coal and natural gas used to generate the steam purchased by Children's was converted into energy units and compared to the energy consumed through natural gas heat generation at the new Children's hospital.

All utility data was normalized using a number of factors including: heat degree days, cooling degree days, number of patient beds, floor area, and number of patients in a bed (PIB) during a month-long period. In collaboration with Children's Facilities Maintenance, it was determined that the most significant normalization was floor area. This also enabled comparison with national statistics related to energy consumption in hospitals. If data were available in finer detail, interesting normalizations could be made based on individual spaces- for example, comparing the energy and water consumption of the old and new hospitals' administrative spaces or operating rooms. Other suggested normalizations, if possible, might include per inpatient, total number of patients, or total number of building occupants.

3.2.2 Statistical Analysis

Metrics were separated into two populations. One set of data represented the old facility or data collected before May 2009 and was labeled "Pre-Move." Data collected after May 2009 was labeled "Post-Move" and represents the new, LEED-certified hospital's performance. Two sample t-tests with a 95% confidence interval were conducted to compare the populations' means. Where population distributions were non-normal, the variances unequal, or where sample sizes were less than 10, a Mann Whitney test with a 95% confidence interval was conducted to compare sample populations' medians. Distributions were considered non-normal when the Anderson Darling value for normality was less than 0.05. Equality of variance in the two populations was determined using an F-Test (for normal distributions) or a Levene's Test (for non-normal variance).

Figure 9 shows which test was used on select study metrics, as well as the significance or percent change in each metric between the old facility and the new, green hospital. A full list of study metric results and the statistical tests used on each can be found in the Supplemental Information.

3.2.3 Data Considerations and Validation

Researchers held in-person meetings with Children's staff to validate the consistency of data collection and calculations throughout the project period and to identify influences to study metrics. Any outliers and sudden, time-based variations for a study metric were identified and reviewed with appropriate Children's staff to determine the cause.

As this was a longitudinal study, the seven-year study period encompassed shifts in staffing and management policies. With the move to a new facility, Children's modified their hiring practices, requiring potential employees to complete a survey which tests the individuals' alignment with Children's overall mission and vision. Changes to staff satisfaction metrics could be affected by Children's new recruitment model, which shifted most hiring from posting job announcements and waiting for responses to headhunting. Children's also updated management and accountability standards, putting a cap on the amount of time in which a manager could review position applicants.

Additionally, and perhaps most significantly, in 2012, Children's earned *Magnet* recognition from the American Nurses Credentialing Center (ANCC) an honor shared with only 6% of hospitals nationwide. *Magnet* status recognizes the hospital's dedication to quality patient care, nursing excellence, and a collaborative, empowering nursing environment (American Nurses Credentialing Center (ANCC) 2012). To be initiated in the Magnet Recognition Program, hospitals must develop an organizational culture and strategic plan which empowers the professional development of nurses, and transform managerial policies and structure to encourage nursing leadership. *Magnet* status is associated with higher rates of specialty certification of nursing staff, reduced adverse drug events for patients, and lower patient mortality (Boyle, Gajewski et al. 2012; McHugh, Kelly et al. 2012). Children's new, innovative hospital environment aided in their drive towards *Magnet* distinction, but the organizational and managerial changes required to achieve *Magnet* status also influenced the changes observed in the study metrics.

3.3 RESULTS

This section discusses results of the study according to metric categories: utilities, expenses, productivity, staff satisfaction, and quality of care. The limitations and applicability of this study are highlighted at the end of this section. A summary of significant results can be seen in Figure 9, and a complete listing of results as well as metric definitions can be found in Appendix A.

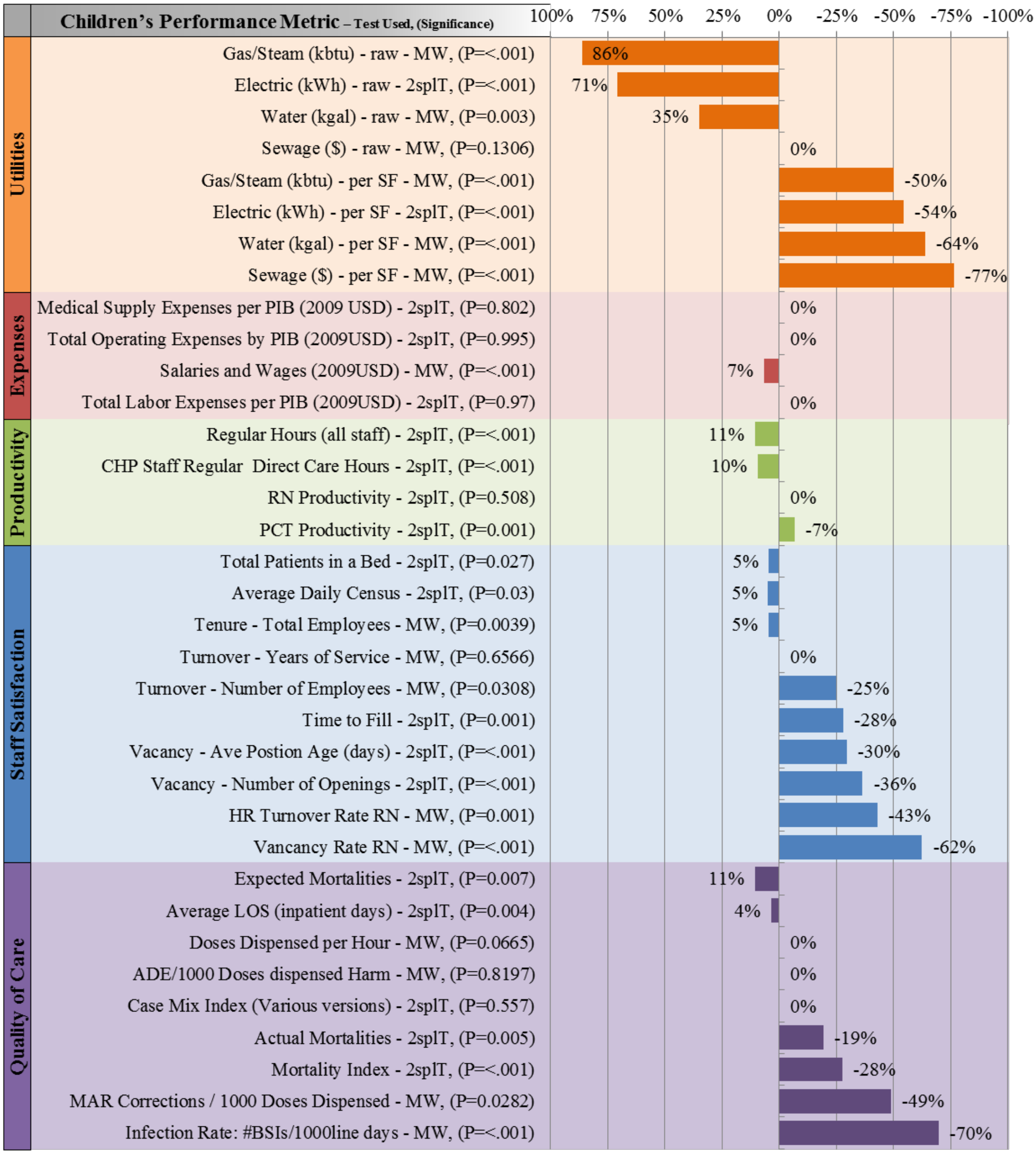


Figure 9: Selection of Significant Changes in Children's Hospital Performance Metrics from the Old Hospital (Pre-Move) to the New, Green Hospital (Post-Move)

3.3.1 Utilities Energy and Water Intensity Improve Substantially in New, Green Building on a Comparative Square-Foot Basis

Children’s raw electricity consumption increased by about 70% ($P<0.001$), but with the addition of over 1 million square feet of functionally-equivalent space (a nearly 300% increase in size), Children’s electricity consumption per square foot was actually reduced approximately 50% to 2.9 kWh/sf ($P<0.001$) as seen in Figure 10. Other utilities at Children’s follow a similar pattern. While total usage of water at Children’s increased by 43% ($P<0.001$), their usage per square foot decreased more than 60% to 2.9 gallons of water per square foot ($P<0.001$). Sewage data are measured in expenses rather than quantity; however, as seen in Figure 11, sewage closely correlates with water usage, as expected. Following the move to the new facility in June 2009, there were some errors in the water and sewage metering resulting in a deficit. The error was found and corrected in the December 2009 billing cycle, resulting in the visible peak in Figure 11. The dotted lines represent an average of that 8 month period for water and sewage consumption. The statistical comparison included original data from this 8 month period in the Post-Move category.

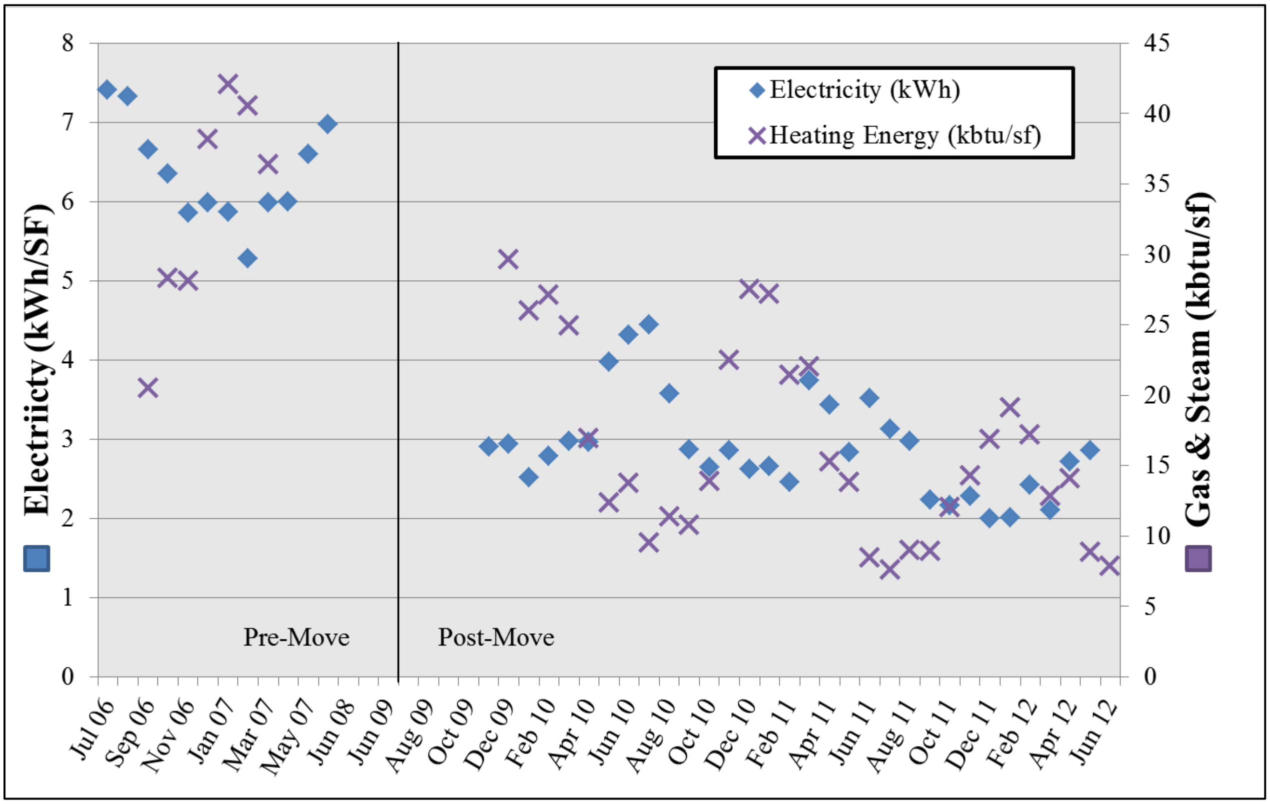


Figure 10: Electricity and Energy Consumption of Traditional (Pre-Move) and Green (Post-Move) Children's Hospital on a per square foot basis

Heating production at Children's varied between the old, Oakland campus hospital and the new, green hospital. The old hospital purchased steam for heating from a nearby steam generation plant. The new hospital utilizes natural gas to produce heat on-site. Using data from the steam generation facility, this study converted the amount of coal and natural gas used in Children's steam generation to estimate the amount of energy Children's required for heating. A comparison of Children's energy consumption shows an 86% increase in the total kBtu's consumed monthly (P<0.001) but a 50% decrease in energy consumption per square foot (P<0.001) to 16.2 kBtu/sf as displayed in Figure 10.

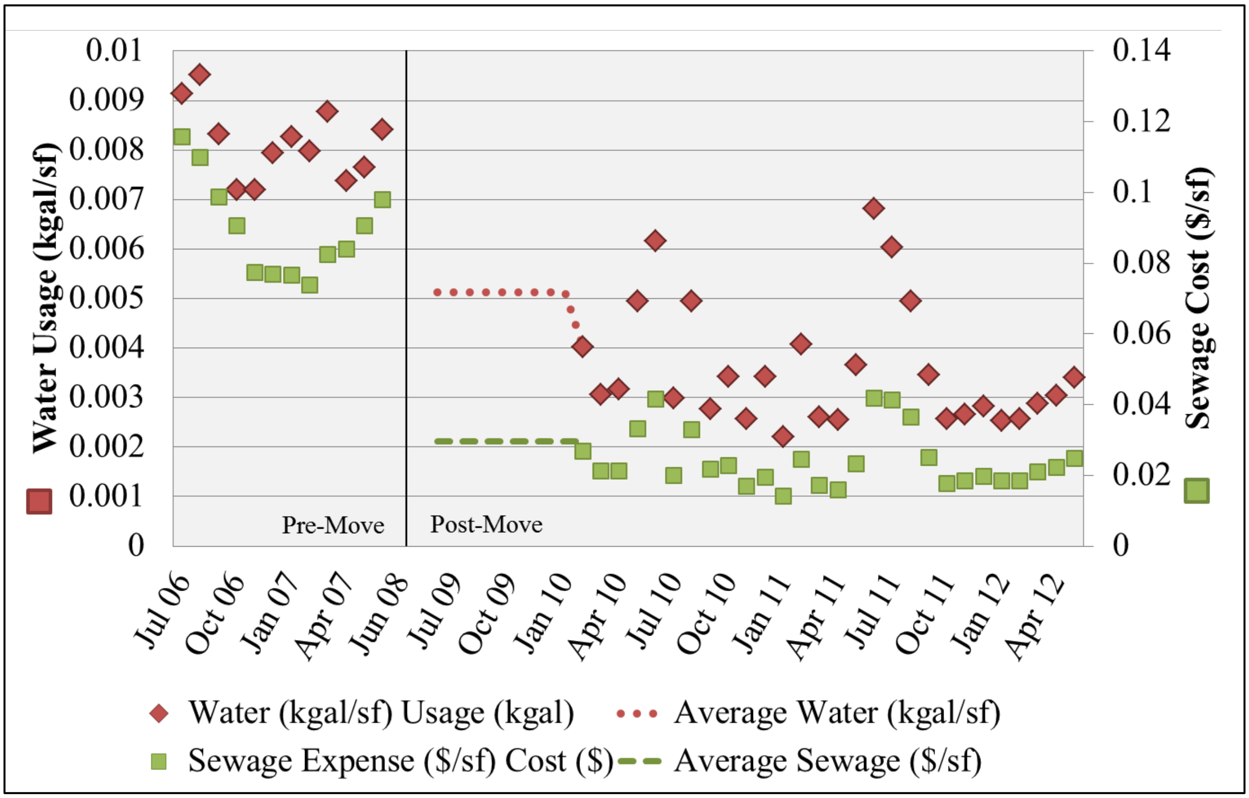


Figure 11: Water and Sewage Consumption of Traditional (Pre-Move) and Green (Post-Move) Children's Hospital on a per square foot basis

A US Energy Information Administration (EIA) report using 2007 data shows that large hospitals, or hospital buildings with more than 200,000 sf, consume an average of 234.1 kBtu of energy per square foot from all major fuel sources in a year and hospitals in the northeast region of the US have an average energy intensity of 241.9 kBtu (Lewis, Swenson et al. 2012).

Through the move to their green building, Children's combined energy consumption from all major fuel sources was reduced over 50% to 252.5 kBtu/sf in Fiscal Year (FY) 2012. As a portion of total energy consumption, Children's reduced their electricity needs from 76.8 kWh/sf-year in FY 2007 to 30.4 kWh/sf-year in FY 2012, nearly matching the EIA's reported average of 29.1 kWh for large hospitals.

The increase in overall, absolute utility consumption is due in part to the expansion of the hospital, but also to the updates in mechanical systems. The old Children's hospital functioned under older building codes and regulations. As such, not all rooms were conditioned. The new hospital not only performs beyond current hospital building codes, but also utilizes energy-efficient HVAC systems in all areas of the hospital, indoor air quality monitors, and an integrated building management system.

3.3.2 Expenses per Patient in Bed Remain Unchanged

Despite a three-fold increase in hospital size and nearly 15% increase in patient capacity, no statistically significant changes were found in Children's medical and surgical supply expenses per patient in bed (P=0.802) or total operating expenses per patient in bed (P=.995). Additionally, this study found a statistically significant rise in the patient length of stay based on inpatient day; however, the change represents only a 4% increase in a 5.4 day average.

Due to programmatic shifts, Children's reduced the number of "agency" hires or temporary hires, thus resulting in significantly decreased spending in purchased personnel metrics and an increase of about 7% (P<0.001) in total, non-normalized staff salaries and wages. These staffing policy changes offset each other in Children's expenses, as seen by the total labor expenses per PIB metric which had no significant changes between the old facility and the new (P=0.970).

3.3.3 Productivity Improves as Direct Care Hours Increase

Children's productivity metrics are calculated by dividing the number of hours required (based on patient acuity and nursing workload data) by the number of hours employees provided. Productivity levels in hospitals should be close to 100%. Levels in excess of 100% may signify greater employee efficiency but might also imply staffing shortages. Productivity of Children's RNs remained the same (approximately 100%) in both facilities (P=0.508) while patient care technicians (PCT) productivity dropped from 115% to 107% (P<0.001). The drop in post-move PCT productivity reflects an increased staffing capacity due to reductions in vacancy and turnover rates as seen in the *Staff Satisfaction* section below.

Children's staff experienced an 11% increase in regular hours with no change in overtime hours (P<0.001 and 0.280, respectively). With the significant decreases in purchased personnel metrics mentioned in the *Expenses* section above and a slight increase in the number of patients, this change was expected. The number of direct care hours, or the amount of time spent directly with patients, increased 10% in the new, green facility (P<0.001). An increase in the direct care hours, especially for RNs, has been shown to reduce adverse drug events (ADEs) and the risk of hospital-related deaths and failures to rescue (Needleman, Buerhaus et al. 2002; Kane, Shamliyan et al. 2007). This relationship is reinforced in the *Quality of Care* section below.

3.3.4 Staff Satisfaction Increases as Seen in Reduction in Turnover and Vacancy Rates

Indicators of staff satisfaction show a 5% increase in employee tenure (P=0.004) and a 25% reduction in general employee turnover (P=0.031). Additionally, the number of position vacancies and the average age of open staff positions have decreased by over 30% (P<0.001 for both). During the study period, the number of patients served increased. Metrics of patient in a bed and of average daily census of patients increased by 5% (P=0.027 and 0.030 respectively).

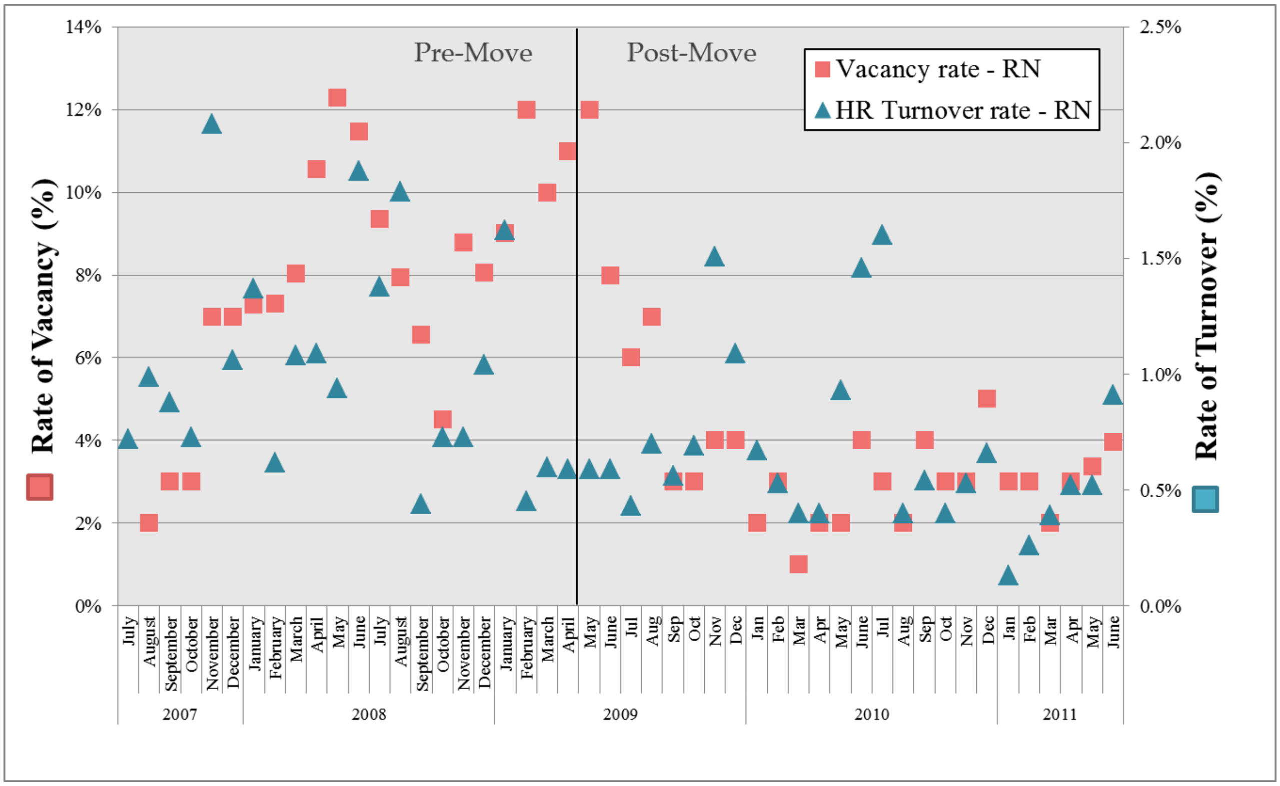


Figure 12: Turnover Rate and Vacancy Rate for Registered Nurses (RN) at the Traditional (Pre-Move) and Green (Post-Move) Children's Hospital

Specific to nursing, Figure 12 shows the average vacancy rate for registered nurse (RN) positions decreased over 60% (P<0.001) and the average RN turnover has decreased 43% (P=0.001) to just 9.5%. This is less than the average turnover rate of 10.9% in other 201-300 licensed bed *Magnet* designated hospitals (American Nurses Credentialing Center (ANCC) 2012). Studies show that reduction in nursing turnover has a positive effect on patient satisfaction and reduces the likelihood of medical errors, as seen in the following *Quality of Care* section (Bae, Mark et al. 2010).

3.3.5 Quality of Care Shows Reduced Error Rates and Improved Mortality Index

This study found a 70% decrease in the blood stream infection rate at the new Children's hospital ($P<0.001$) and a 49% reduction in the number of corrections to the Medication Administration Record (MAR) per 1000 doses dispensed ($P=0.028$). No statistical changes were detected in the number of medication doses dispensed per hour. Low sample sizes in some of the quality of care metrics prevented a more rigorous analysis of adverse drug events and prescribing errors, which previous studies show to be common and costly in hospitals with increased potential to harm pediatric patients (Kaushal, Bates et al. 2001; Fortescue, Kaushal et al. 2003). However, the Mortality Index indicates substantial achievements in Children's new green facility.

The *expected* mortality rate, or the number of critically-ill patients not expected to survive, increased 11% ($P=.007$) due to an increase in the severity of patient cases drawn to the new facility. However, the actual mortality rate at Children's decreased almost 20% ($P=.005$), a metric confirmed by the Mortality Index, which decreased nearly 30% for Children's ($P<.001$) as seen in Figure 13. The mortality index is the actual mortality divided by the expected mortality where a number less than 1 is a hospital's goal. In their new facility, Children's index average is 0.59.

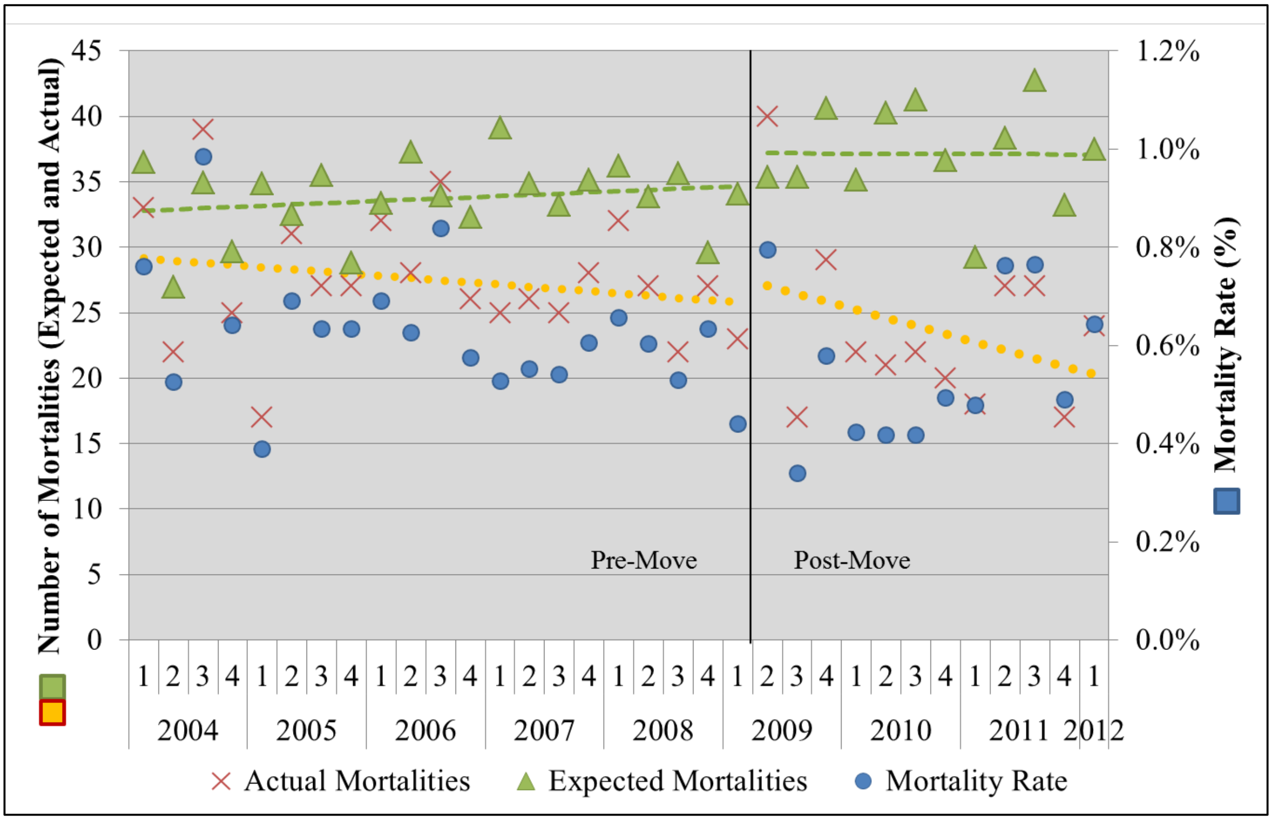


Figure 13: Expected and Actual Mortalities of a Traditional (Pre-Move) and Green (Post-Move) Children's Hospital

3.3.6 Study Limitations and Applicability

Changes in energy and utility efficiency are directly attributable to changes in hospital design and improvements to mechanical systems. However, the length of the study period reduces the ability to isolate metric changes influenced solely by building and design-related sources.

Children's leadership, policies, and programs have changed, most notably with the achievement of *Magnet* nursing status, and these changes inherently also effect this study's metrics.

According to a senior administrator in nursing, who has worked at Children's for nearly twenty years, the physical prominence of this green structure is thought to have catalyzed and reinforced managerial and programmatic changes. They believe Children's unusual commitment to breaking the status quo in hospital design cannot be excluded from the improvements to staff satisfaction, employee productivity, and quality of patient care identified in this study. For future studies, researchers recommend the additional analysis of data such as employee and patient surveys or focus groups to better understand the perceived and psycho-social impacts of the structure's design, as well as additional modeling which might better predict the relative importance of leadership, policy, and green building design changes.

3.4 SUMMARY AND CONCLUSIONS

Following the move into a new, LEED-certified facility, Children's Hospital significantly improved their productivity, quality of care, staff satisfaction, and utility use per square foot while their expenses per patient in bed remained stable. Energy and electricity use per square foot decreased 50% ($P<0.001$ for both) in the new, green facility and water consumption per square foot decreased 64% ($P<0.001$). The amount of time that Children's staff spend directly with patients increased 10% ($P<0.001$) in the new hospital, while vacancy rates dropped 30% ($P<0.001$) and turnover dropped 25% ($P=0.031$). Blood stream infection rates dropped 70% ($P<0.001$) in the new, green hospital and while expected mortalities increased 11% ($P=0.007$), actual mortalities decreased 19% in the new facility ($P=0.005$).

The length of this longitudinal assessment limited the ability to separate the impacts of green building design from the effects of managerial and programmatic changes to the hospital. Over the study period, organizational and individual changes related to *Magnet* nursing designation and modified hiring practices greatly affected Children's hospital performance metrics. The relative effect of behavioral and organizational changes or green building design decisions is unknown, but there may also be a reinforcing symbiosis between the two elements in regards to improved employee performance and patient outcomes. Since *Magnet* designation required significant cultural change for Children's, the new, green hospital may have helped catalyze or foster those changes. Green hospital design and new, more efficient technologies, however, directly influenced the improvements to utility-related metrics.

Children's continues to improve their quality of care and the environmental sustainability of their services through green purchasing and alternative cleaning products, and they credit the building with increased safety, improved staff satisfaction, and reduced patient and parent stress (Children's Hospital of Pittsburgh of UPMC). Children's new, green campus is emblematic of their dedication to being a model of environmental sustainability and health for the Pittsburgh community and other hospitals nationwide.

4.0 EVALUATING ENVIRONMENTAL IMPACTS OF MEDICAL PROCEDURES: LIFE CYCLE ASSESSMENT OF BIRTHING AN INFANT

The work presented in this chapter addresses research Objective 2 and the question 'How can Life Cycle Assessment determine environmental sustainability of the healthcare industry?' This work was published in *Science of the Total Environment* as "Life Cycle Assessment Perspectives on Delivering an Infant in the US" (Campion, Thiel et al. 2012).

4.1 INTRODUCTION

Healthcare represents a rapidly growing economic sector in the United States, accounting for 17% of the total US GDP in 2009 (Bureau of Economic Analysis 2009). In 2008, US hospitals employed over 5.3 million people and spent nearly $320 billion on goods and services from other businesses (AHA 2011). To support this level of activity, the healthcare sector is estimated to consume 73 trillion kWh of electricity annually, and its hospital facilities are the second most energy-intensive facility type per square foot in the US (US DOE 2009; Esmaeili, Jahromi et al. 2011). The emissions from this electricity use alone result in estimated tens-of-thousands of adverse health effects (AHA 2010; National Research Council (U.S.), Committee on Health et al. 2010). In addition, medical facilities face unique infection control challenges that have led to increasing use of disposable materials and escalating waste production. Consideration of the effect on the environment, and potential subsequent health effects, is an important consideration.

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 2009). 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 (CO2 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 CO2 eq. Approximately 80% of the GWP in the healthcare sector is attributed to carbon dioxide (CO2), which is one-tenth of the total CO2 emissions in the US (Chung and Meltzer 2009; Patrick 2011). 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. In this study, we will introduce Life Cycle Assessment (LCA) as a tool that can analyze healthcare sustainability using multiple environmental impact categories.

4.1.1 Background on Process Life Cycle Assessment

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. Process LCA follows guidelines set forth by the International Organization for Standardization (ISO 14040 and 14044) and is conducted in four stages (ISO 1997; ISO 1997). 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 relatively high environmental impacts.

4.1.2 Case Study: Delivering a Baby

This research uses 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. Our 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 delivery.

4.2 METHODS

The complexities and challenges of combining life cycle assessment with the healthcare industry required that the project framework be well established. The first step was to develop collaborative partnerships between engineers and hospital staff. The second step was to establish the process LCA framework, which included data collection, LCI database selection, and LCIA results.

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.

4.2.1 Life Cycle Assessment Framework

4.2.1.1 Goal, Scope, and System Boundaries

The functional unit of this study was the birth of one baby. The boundaries of the study (Figure 14) 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).

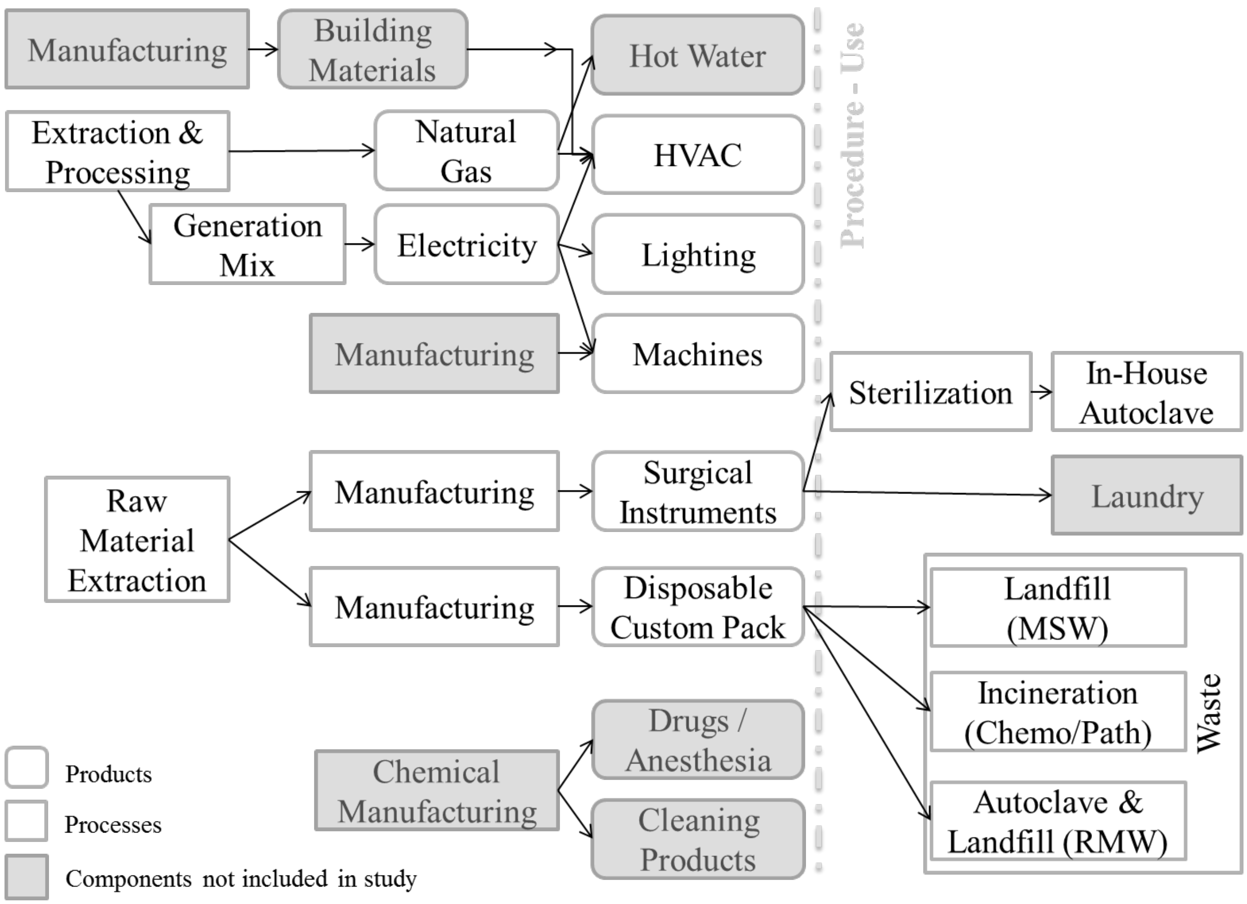


Figure 14: Data Flowchart for Cesarean Section and Vaginal Births

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 approximately 15,000 healthy, full term births performed over 8 years at a single institution, 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). We assumed a ratio of women having their first birth to women who have previously given birth of 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.

4.2.1.2 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. As mentioned in Section 1.2, the LCI stage compiles the inputs and outputs of a product or 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.

The following section is divided into two parts: LCI materials and LCI energy consumption. LCI materials describes the methods used to account for the production and end of life of the disposable custom packs and the reusable surgical instrument packs for both the cesarean section and vaginal births. The LCI energy consumption section explains methods used to determine electrical loading of machines and the energy consumption due to HVAC in both the OR in the case of cesarean section births and the LDR in the case of vaginal births.

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 4. If a product was comprised of more than one material, then the total weight of the product was divided evenly 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.

Table 4: Disposable Custom Pack; RNA = North American geographical code; RER = Europe geographical code; S = system process; a = (Moreno, Weidema et al. 2011); b = (IDEMAT); c = (NREL 2010); d = (Lalive 1996)

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]	X90CrCoMoV 17 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	-

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 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 4. 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 births at Magee did not generate waste for disposal in other waste streams such as recycling, hazardous waste, and electronic waste.

Items in a reusable surgical instrument pack for both a cesarean birth and a vaginal birth were weighed and summarized, results shown in Table 5. 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 5: Reusable Surgical Instrument Pack Data; RNA = North American geographical code; RER = Europe geographical code; a = (NREL 2010); b = (IDEMAT)

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]	X90CrCo MoV17 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

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, 2 *Amsco* 3043 vacamatics and 1 *Steris Amsco Century* V160H prevac steam sterilizer, 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, which can be seen in Table 6 and Table 7.

Table 6: Machine Information for Operating Room (Cesarean Section)

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

Table 7: Machine Information for Labor and Delivery Room (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

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 is not being constantly 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, see Table 8. 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, see Table 9.

Table 8: Machine and Lighting Information

	OR	LDR	Data Source
Number of Machines	17	10	Observation
Machine Load (watts)	7889	3738	Machine Specifications
Number of Lights	10	11	Hospital Specifications
Lighting Load (watts)	1942	507	Hospital Specifications

Table 9: Pennsylvania Power Generation Mix from (USEPA 2007)

Electricity Mix	PA %
Hydro	0.6
Nuclear	22.3
Oil	0.3
Gas	2.9
Coal	72.9
Non-hydro renewables	0.5

4.2.1.3 Bin Energy Model Setup

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 model calculated the energy use for several "bins" representing finite intervals of weather conditions. The energy consumption from the bins was summed by the Equation 1:

$$E = \sum_i N_i \frac{Q_i}{\eta}$$ **Equation 1**

Where 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 and LDR 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 2.

$$Q_{i,AHU} = V^{Y}(h_{i,MA} - h_{i,SA})$$ **Equation 2**

The volume flow rate (V^Y) 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 3) for the air in the room for each bin.

$$0 = Q_{i,RH} + V^{Y}(h_{i,SA} - h_{SP}) + Q_{i,ENV} + Q_{IL}$$ **Equation 3**

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 $V^Y h_{SP}$. Heat added was represented with terms for the supply air ($V^{Y}h_{i,SA}$), 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 10. 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 10: Bin Energy Model Input Variables

Input Variable	Description	Unit	OR Data	LDR Data
Wall Construction[a]	Wall area	ft²	-	86
	Wall U-value (ASHRAE 2004)	W/m²K	-	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 2010)	Air changes/hour	20	10
Flow Rate/ Room Volume	Volume of the room	ft^3	4200	3200
Inside Temperature (avg)	(ANSI 2010)	°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 2010)	%	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

a. Because the OR has no exterior walls, wall construction was not used in bin calculations.

4.2.2 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. 2003). Impact categories analyzed and reported include global warming, acidification, carcinogenics, non-carcinogenics, respiratory effects, eutrophication, ozone depletion, ecotoxicity, and smog.

4.3 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 (see Figure 15). This was due to the production and consumption of electricity and natural gas required to run the machines, lighting, and HVAC system.

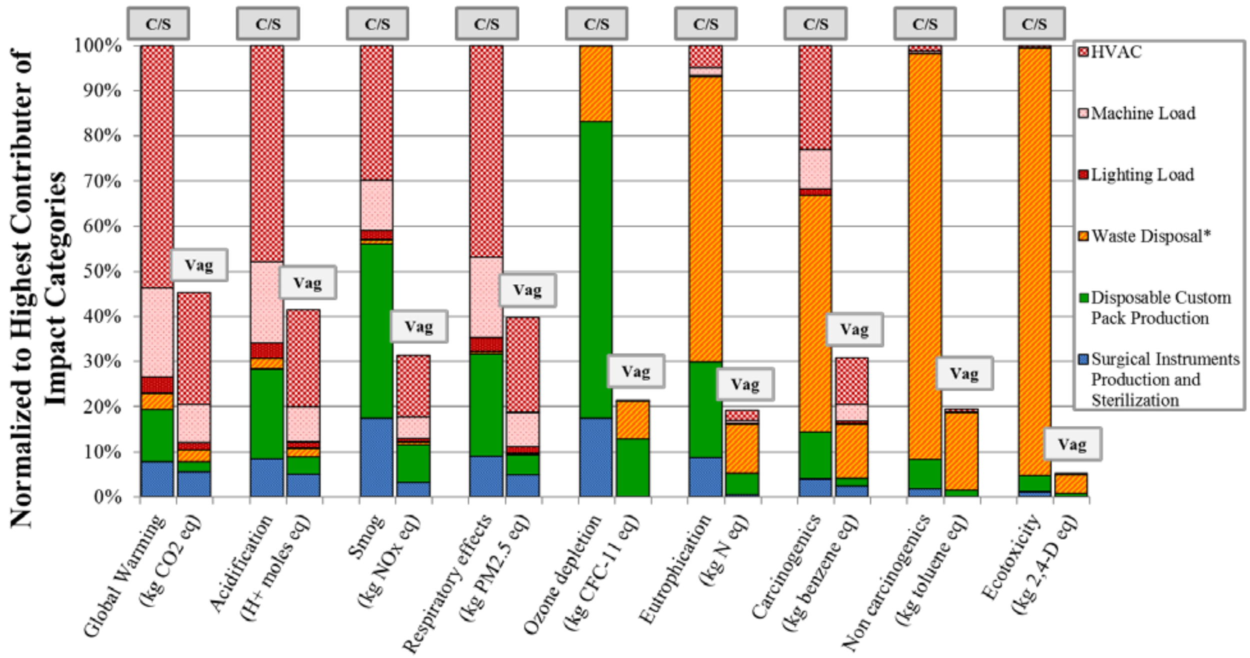


Figure 15: Environmental Impacts of Cesarean Section (C/S) and Vaginal (Vag) Births.

*** Waste calculated for the disposable custom packs and placenta disposal.**

4.3.1 Disposable and Reusable Materials

The production of disposable and reusable materials of both birthing modes is summarized Figure 16. 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.

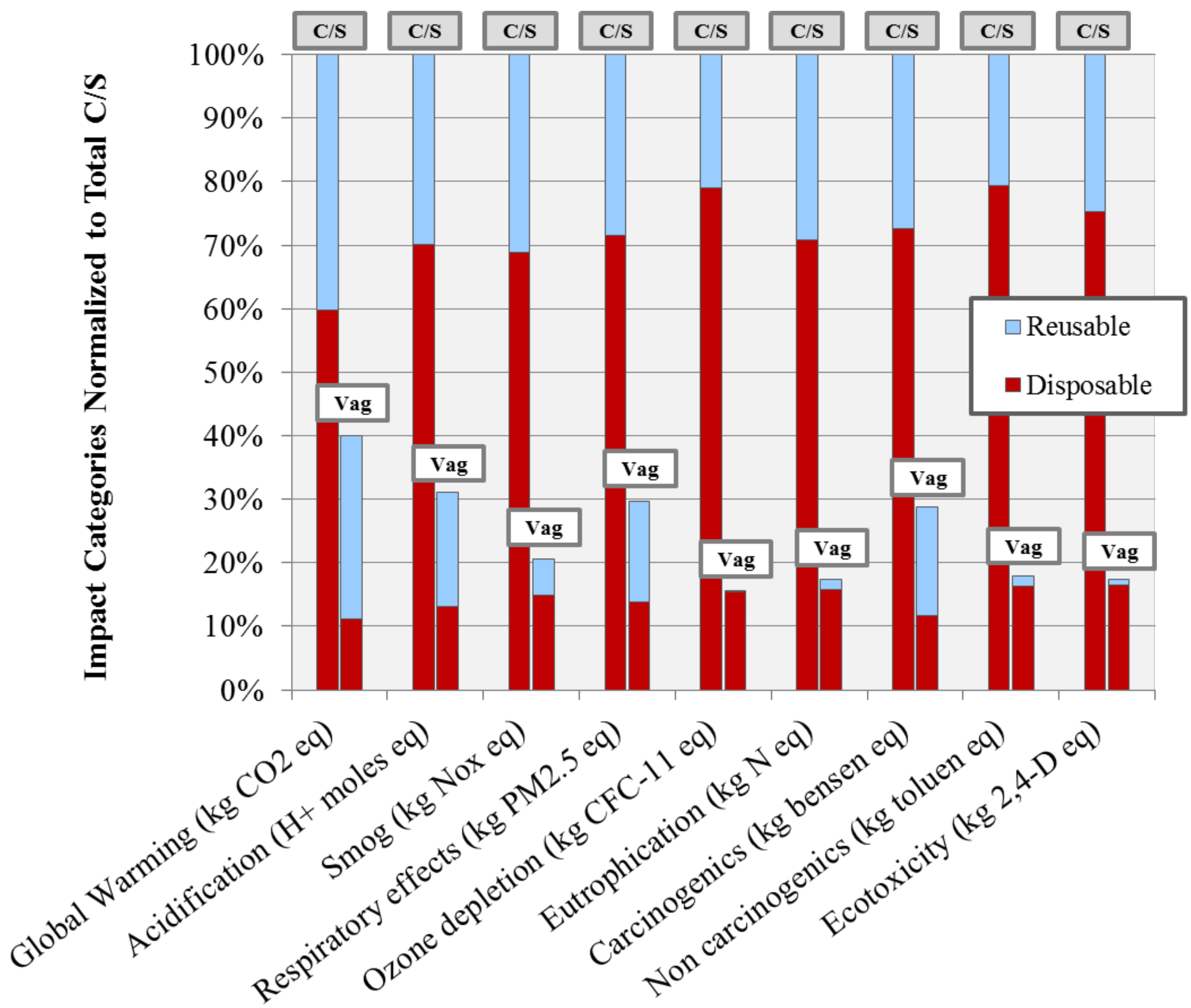


Figure 16: Cesarean Section (C/S) and Vaginal (Vag) Birth Disposable and Reusable Material Impacts

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 as shown in Figure 17. Specifically, 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.

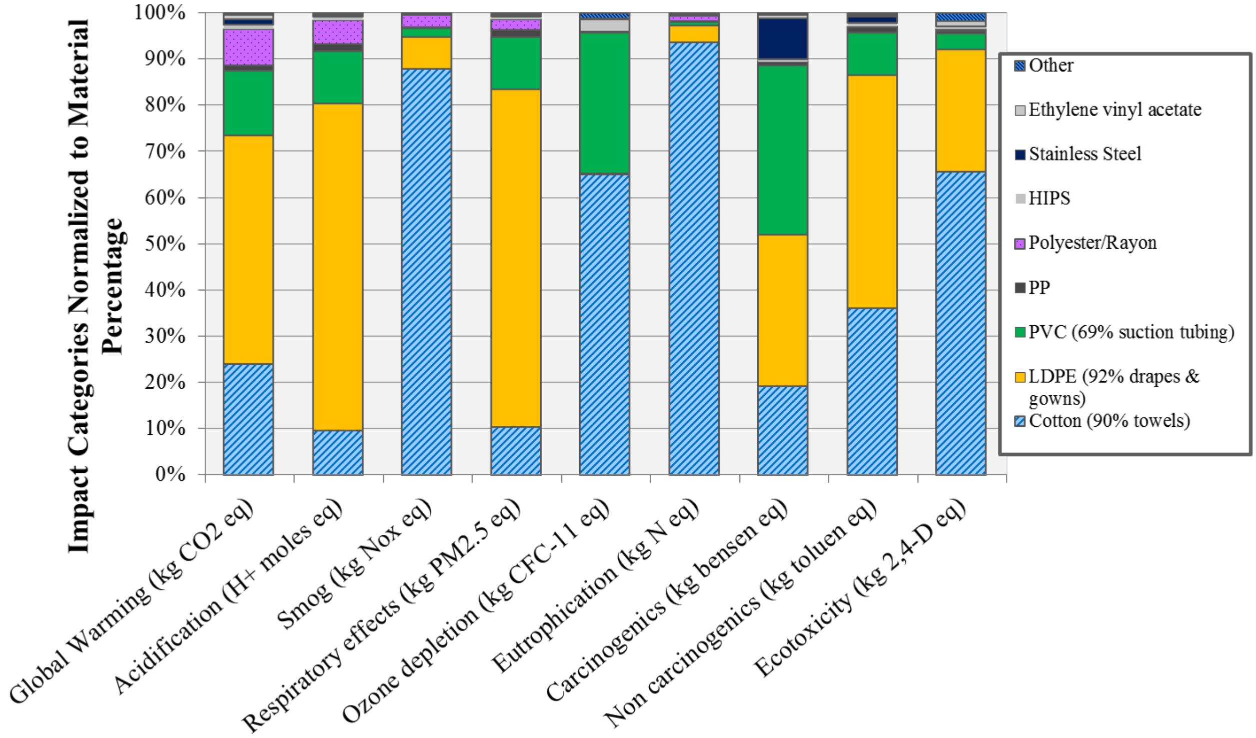


Figure 17: Environmental Impacts for the Production of Cesarean Section Disposable Materials

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.

4.3.2 Waste and Disposal

The total impacts from Figure 15 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 18). 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 18. Transportation of waste does not contribute significantly to the four impact categories examined in Figure 18 as transportation usually results in CO_2 emissions associated with global warming potential and other impact categories not examined.

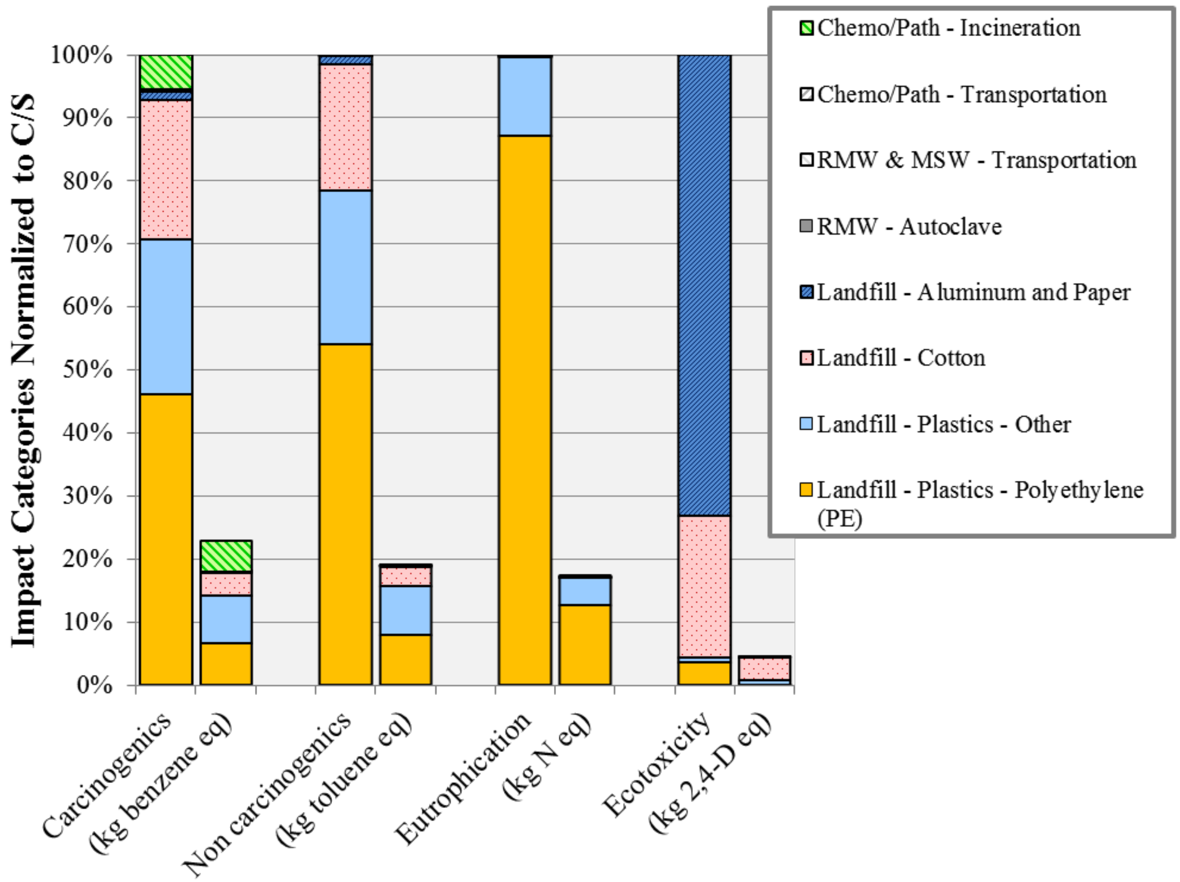


Figure 18: End of Life Impacts for Cesarean Section (C/S) and Vaginal (Vag) Births

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. Additionally, ecoinvent 2.0

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. Available literature may help create more accurate waste disposal models for the US (Barlaz 2006; Gentil, Damgaard et al. 2010).

4.3.3 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. Similarly, implementing occupancy sensors and low energy lighting could reduce the amount of electricity consumed and associated impacts.

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 19. 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.

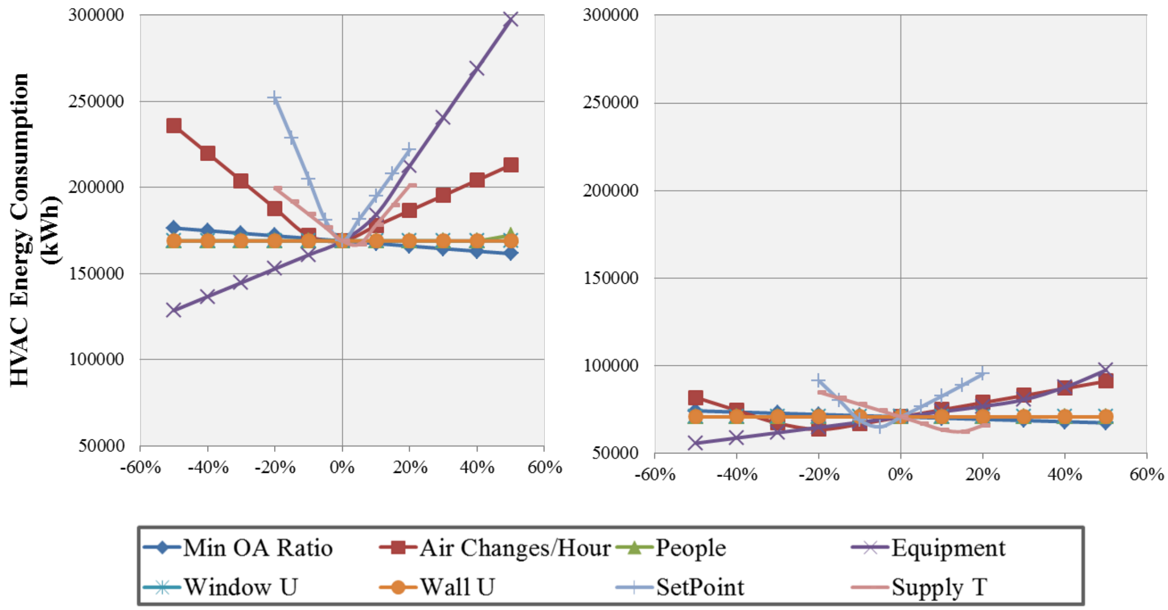


Figure 19: Effect of Input Variables on HVAC Annual Energy Consumption

Figure 19 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.

4.4 SUMMARY AND CONCLUSIONS

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.

5.0 ENVIRONMENTAL IMPACTS OF ADVANCING SURGICAL TECHNOLOGIES: LIFE CYCLE ASSESSMENT OF HYSTERECTOMIES

The research presented here addresses research Objective 3. It seeks to answer the question 'What aspects of hospital operating procedures contribute the most to a procedure's environmental impacts?'

5.1 INTRODUCTION

The size and cost of healthcare is increasing, which increases the environmental and human health impacts of hospital care. Expenses for all privately and publicly funded personal healthcare services and products in each state have been growing 4.4% to 7.3% per capita annually. In each state, spending ranges from $5,031 to $10,349 per person. Pennsylvania's spending on healthcare is $7,730 per resident. Healthcare spending accounted for 17.9% of the US Gross Domestic Product (GDP) in 2011, and 36.3% of those national healthcare expenditures are for hospital care (CMS 2011; Kaiser Family Foundation 2011). In 2011, the healthcare sector employed nearly 12 million people, making up 6.4% to 11.7% of each state's total workforce, with hospitals employing a third of the healthcare workforce (Kaiser Family Foundation 2011; BLS 2013). Yet the size and spending on healthcare has done little to improve the health of the general US population relative to other wealthy countries (Berwick and

Hackbarth 2012). Growing concerns over obesity and related chronic diseases leave healthcare providers seeking new health delivery paradigms, such as the preventative care model, which involves environmental health or the healthy interaction of humans with their environment (Arnrich, Mayora et al. 2010; Fani Marvasti and Stafford 2012).

As environmental sustainability becomes a greater priority for the American public, focus falls on the healthcare industry due to its relative size, costs, expected growth, and status within individual communities (Rich, Singleton et al. 2013). Hospitals, in particular, as large generators of waste and other emissions, are called upon to be designed more sustainably and to improve the environmental sustainability of their processes and procedures (Ficca, Chyun et al. 2000; Phelps, Horman et al. 2006; Verderber, Fauerbach et al. 2008; Younger, Morrow-Almeida et al. 2008; Stichler 2009). Improved environmental performance within hospitals is estimated to reduce healthcare spending. A study commissioned by the Healthcare Research Collaborative estimates that implementing sustainable practices within all US hospitals could save over $5.4 billion in the next 5 years (Kaplan, Sadler et al. 2012). Proper tools and research are needed to establish the healthcare industry's baseline environmental performance at various levels and to measure the impact of sustainability improvement efforts.

This study focuses on the environmental impacts related to a hospital Operating Room (OR), which is one of the most costly and waste-intensive areas of a hospital (Elixhauser A 2010). The materials, energy, and processes required to perform four types of hysterectomies were analyzed using a sustainability analysis tool called Life Cycle Assessment (LCA). Using LCA to identify the elements of an OR surgery which contribute the most to a hospital's life cycle environmental impacts, researchers and healthcare workers can target those elements to maximize environmental benefits.

5.1.1 Life Cycle Assessment

Life Cycle Assessment (LCA) quantifies the environmental impacts of a product or process throughout its life cycle. LCA of an individual product identifies which life cycle stage (i.e.: resource acquisition, manufacturing, use and end of life) has the highest impact and makes recommendations for lowering such impacts. A comparative LCA compares two or more related products and makes a recommendation as to which one is environmentally preferable.

Standards for performing a LCA are defined by the Environmental Protection Agency (EPA), Society for Environmental Toxicologists and Chemists (SETAC), the American National Standards Institute (ANSI), and the International Organization of Standardization (ISO) (Fava, Denison et al. 1991; Vigon, Tolle et al. 1992; UNEP/SETAC 2005; ISO 2006). According to ISO 14040 and 14044, there are four steps to conducting a *process LCA* (ISO 1997; ISO 2006). The first step is setting the study scope, boundaries, and functional unit. The functional unit is often used to define the function of the product or process being analyzed in order to compare it to a functionally-equivalent product or process. Each stage of a product's or process's life cycle is characterized by inflowing resources and energy, as well as outflowing products and by-products. These inflows and outflows are quantified in the Life Cycle Inventory (LCI) step of the LCA. Characterization factors are then applied to the LCI results during the Life Cycle Impact Assessment (LCIA) step in order to convert all material flows to a common unit so that they can be compared. Characterization factors are based on the varying environmental stresses caused by individual materials, emissions and energy flows. The result of the LCIA is a standardized list of environmental impacts in categories such as greenhouse gas emissions, acidification, human health and ecotoxicity. The final step in an LCA is to analyze and interpret the results.

Limitations of process LCA arise due to lack of data quality and accessibility, poorly defined system boundary definitions, and time constraints associated with data acquisition. Such limitations have led to criticism of the suitability of process LCA for analysis of complex systems (Wong 2004). Another limitation of process based LCA is the complication of including Scope 3 emissions, which are the emissions associated with a product downstream of production (i.e. use and disposal) (Ranganathan, Corbier et al. 2004; Huang, Weber et al. 2009).

To make up for the shortcomings of process LCA, researchers developed Economic Input-Output LCA (EIO-LCA). EIO-LCA employs an economic input-output model, combined with environmental data, to give sector-specific energy and environmental impacts associated with the production of a product (Rosenblum, Horvath et al. 2000; Suh, Lenzen et al. 2004; Carnegie Mellon University Green Design Institute 2011). Limitations to EIO-LCA appear during detailed analysis as a result of the aggregation of economic sectors and uncertainty of data, and so it is better suited for high level analysis (Lenzen 2000; Bilec, Ries et al. 2006; Lenzen 2006; Bilec 2007).

Hybrid-LCA is the combination of both process and EIO-LCA, each of which serves to make up for the other methods' limitations (Suh, Lenzen et al. 2004; Bilec, Ries et al. 2006; Junnila 2006; Suh 2006). This research benefits from the use of Hybrid-LCA through detailed product analysis via process LCA and comprehensive process analysis of complex materials by EIO-LCA.

5.1.2 Medical Applications of LCA

Life Cycle Assessments have been used to compare individual single-use and reusable products and materials in the healthcare industry (Dettenkofer, Grießhammer et al. 1999). McGain, et al.

found that reusable plastic anesthetic drug trays cost less and emit less CO_2 than single-use trays (McGain, McAlister et al. 2010). A study on reusable and disposable surgical scissors found that the reusable stainless steel scissors were the more "eco-efficient" choice (Ibbotson, Dettmer et al. 2013). Similarly, a comparative study of the life cycle inventory of reusable and disposable laparotomy pads found the disposable pads had a larger impact on the environment than reusable pads (Kümmerer, Dettenkofer et al. 1996). A 2012 special issue of *Anesthesia and Analgesia* reported on a number of life cycle-based studies comparing the life cycle environmental impacts of reusable and single use laryngeal mask airways, perioperative textiles, and central venous catheter insertion kits (Eckelman, Mosher et al. 2012; McGain, McAlister et al. 2012; Overcash 2012).

Hospitals and healthcare systems have also adopted carbon and ecological footprinting tools as a means to analyze the life cycle carbon-use impacts of their operations and facilities (Karlsson and Öhman 2005). A 2007 Economic Input-Output LCA of the entire US healthcare sector found that healthcare activities account for 8% of total US greenhouse gas emissions (Chung and Meltzer 2009). Power, et al. calculated the annual CO_2 emissions of the US's minimally invasive surgeries (MIS) to be 355,924 metric tons per year, which would rank MIS as 189th on the United Nations 2008 list of countries' annual carbon dioxide emissions (Power, Silberstein et al. 2012; United Nations (UN) 2012). The use of anesthetics gases significantly contributes to the carbon footprint of surgical procedures as a whole. The global warming potential of anesthetic gases used annually worldwide is equivalent to the CO_2 emissions from one coal fired power plant (Sulbaek Andersen, Sander et al. 2010). Carbon footprints are useful for locating sources of potential global warming contributors within a system, but they do not account for other environmental impacts, such as effects to human health or ecotoxicity.

5.1.3 Case Study: Hysterectomies at Magee-Womens Hospital

This research used a hybrid-LCA approach to quantify the environmental impacts of a vaginal, an abdominal, a laparoscopic, and a robotic hysterectomy in the operating rooms (OR) at Magee-Womens Hospital (Magee) of the University of Pittsburgh Medical Center (UPMC). US News and World Reports ranked Magee 5th in the nation for gynecology in 2012 and Practice Greenhealth presented Magee with the *Environmental Leadership Circle* Award in 2013 (US News and World Report 2012; Practice Greenhealth 2013). This case study incorporated Economic Input Output LCA (EIO-LCA) methods into the previous LCA framework developed for analysis of infant birthing procedures (Campion, Thiel et al. 2012). This study additionally developed waste audit methodology and applied Monte Carlo uncertainty and variability assessments to help understand the relative environmental consequences of each component of a hysterectomy.

Hysterectomies were chosen for multiple reasons. As previously stated, the OR is one of the most costly and waste-intensive areas of a hospital (Elixhauser A 2010). While OR waste generation rates vary drastically between individual hospitals, ORs account for between 20-73% by mass of hospital waste streams (Goldberg, Vekeman et al. 1996; U. S. Air Force Institute for Environment Safety and Occupational Health Risk Analysis 2001; Lee, Ellenbecker et al. 2002). Hysterectomies are also the second most common OR procedure for women, with more than 600,000 performed annually in the US (of the nearly 51.4 million total annual inpatient surgeries in the US) (Reynolds and Advincula 2006; Wu, Wechter et al. 2007; Elixhauser A 2010; US CDC 2010). Nearly a quarter of American women will undergo a hysterectomy by age 60 (Brill 2006).

There are four general methods of conducting hysterectomies. Abdominal hysterectomies, or the removal of the uterus through a large incision in the abdomen, remain the most common type of hysterectomy. In 2000, 68% of all hysterectomies in the US were done abdominally (Whiteman, Hillis et al. 2008). By 2010, that number fell to 47%, due to advancing technologies and newer, "minimally invasive" surgeries (MIS) (Wright, Ananth et al. 2013). Removal of the uterus through the vagina, or a vaginal hysterectomy, represented 21-32% of hysterectomies nationally in 2003 (Wu, Wechter et al. 2007). In minimally invasive surgeries, such as laparoscopic and robotic techniques, surgical tools are inserted into the body through small incisions in the abdomen. The primary difference between a laparoscopic and robotic surgery is that surgical tools in a robotic hysterectomy are controlled remotely by a physician.

Laparoscopic hysterectomies represented nearly one-third of hysterectomies in the US in 2010 (Wu, Wechter et al. 2007; U.S. DHHS and CDC 2012; Wright, Ananth et al. 2013). Following approval by the US Food and Drug Administration (FDA), rates of robotic hysterectomies rose from 0.5% of all US hysterectomies in 2007 to 9.5% in 2010, with hospitals who first adopted the new technology utilizing the robot in over 22% of their annual hysterectomy cases (Liu, Lu et al. 2012; Wright, Ananth et al. 2013).

Following the technological trends of medicine, robotic and robot-assisted laparoscopic hysterectomies are becoming more common. Robotic procedures can overcome some of the challenges of laparoscopic surgeries – such as a two dimensional working plane – while maintaining minimally-invasive status (Reynolds and Advincula 2006; Visco and Advincula 2008; Göçmen, Şanlikan et al. 2012). Despite these benefits, the trend towards ever-increasing technology in the operating room is being called into question (Breeden 2013).

Magee conducts hysterectomies using all four generic surgical methods, which allows this study to analyze the environmental impacts associated with most surgical procedures conducted in ORs in the United States today. This study aims to create baseline measurements of environmental performance in the OR and to identify areas of common surgical procedures where environmental improvements might have large-spread effect.

5.2 MATERIALS AND METHODS

This section is divided into three subsections. It begins by establishing the system boundaries for the hysterectomy LCA and then by describing the data collection methods including waste auditing and energy estimates. The final subsection explains the LCI and LCIA steps utilized during the life cycle assessment and the Monte Carlo methods used to estimate the uncertainty and variability of the study data.

5.2.1 System Boundaries

This study can be thought of as four individual LCAs, one for each generic type of hysterectomy- vaginal, abdominal, laparoscopic, and robotic. The functional unit of this study was one hysterectomy. The boundaries of the study focused on a single hysterectomy including components such as energy consumption, material production, material sterilization, and material disposal. Due to the scarcity of LCI data regarding cleaning chemicals and anesthetics, the use and manufacturing of these items were not included in this study.

Previous LCA studies debate the life cycle importance of a building's construction phase (Hendrickson and Horvath 2000; Junnila and Horvath 2003; Bilec, Ries et al. 2010). Because this study aims to understand the environmental impacts related to surgical procedures and the physical rooms in which they are conducted are nearly identical, the environmental impacts due to the hospital's construction or building materials was not included in this study. Due to limited information on the manufacturing of large machines and equipment within the OR, these impacts were also not included in the study as per previous study methodologies (Campion, Thiel et al. 2012; Morris, Wright et al. 2013).

Unlike previous medical LCAs, this study collected material data through waste auditing and additional boundaries were set around the analysis of collected hysterectomy waste. The audits involved data collection from individual patients' medical cases; therefore, the project team applied for and was granted Internal Review Board (IRB) approval under 45 CFR 46.110.(4) and 45 CFR 46.110.(5 (IRB#: PRO11010250). Potential study participants were limited to those over age 18, undergoing a hysterectomy for non-cancer reasons, and those *not* undergoing any other surgical procedures in addition to the hysterectomy. The study team purposely limited exclusions.

5.2.2 Data Collection Methods

The following sections describe the methodologies utilized in collecting data from the four types of hysterectomies performed at Magee. It is divided into waste auditing, reusable material and tool data collection, and power or electricity data collection. Waste auditing enabled researchers to estimate the environmental impacts from the production and disposal of materials used during a single hysterectomy. Energy auditing assessed the electricity use of the surgical machines and lighting in the OR, and bin modeling, as described in the following section, estimated the energy consumption in an OR due to heating, ventilation, and air conditioning.

5.2.2.1 Material Waste Auditing for Single-Use and Disposable Items

In order to characterize the products and materials entering Magee's municipal solid waste (MSW) and recycling streams, detailed waste audits were conducted. Researchers collected and sorted the waste from 15 cases of vaginal, abdominal, and robotic hysterectomies and 16 cases of laparoscopic hysterectomies (61 total audits). An additional 9 cases were collected but were withdrawn from the study prior to sorting due to changes in surgery type during the procedure or the presence of cancer found during post-surgery pathology reports. The following methodology was used in obtaining and sorting the MSW and recycling from each hysterectomy case.

Using the Preparatory to Research Waiver through the IRB, the project's Research Coordinator reviewed the surgical schedules on a weekly basis to identify eligible subjects, who were approached on the day of surgery and asked to participate in the study. The Research Coordinator explained the study protocol, discussed the risks and benefits of the study, and answered any questions. If the patient agreed to participate in the study, she signed the Informed Consent Form. The Study Coordinator also signed the ICF and gave the patient a copy. A copy of the ICF was sent to Medical Records for incorporation into the subject's medical record, and the informed consent process was documented in the patient's surgical chart.

Once a patient consented to participating in the study, researchers conducted a visual sweep of the OR prior to the surgery to ensure all previously generated waste was eliminated. Immediately following the surgery, the MSW and recycling was collected, labeled with the case identification number, and moved to a secure storage location for sorting. The researcher also verbally collected data from the OR nurses including number of employees in the OR during the procedure, number of linens used, and the number and types of reusable surgical instrument trays used. Following the procedure, information about the patient, such as Body Mass Index (BMI), surgical complications, and uterine weight was recorded. Uterine weight was used to calculate environmental impacts of the chemo and pathogenic waste stream, or the transportation and incineration of the uterus.

Once or twice weekly, a team of trained researchers would physically sort the collected waste from the individual patient cases. Researchers participating in the sorting completed University of Pittsburgh's Environmental Health and Safety Bloodborne Pathogen Training module. All sorters were required to wear personal protective equipment (PPE) in addition to long-sleeve outfit, closed-toed shoes, and hair tie-backs. PPE included face masks with splash shield, surgical gowns, surgical gloves, and shoe covers, as shown in Figure 20.

Figure 20: Researchers conduct waste audit of municipal solid waste and recycling from a single hysterectomy

Before sorting commenced, the total MSW and recycling were weighed on an industrial floor scale. This total weight includes any fluids produced/acquired during surgery. All subsequent weights of individual materials within each waste stream were taken on a digital scale with 30lb capacity and 0.1 ounce accuracy. The recycling was divided and weighed in the following categories: Plastic #5, Plastic #1, Plastic #6, and inappropriate materials or materials which are not actually recyclable but were found in the recycling stream. The MSW was divided and weighed according to the following method, which can also be seen in graphical format in Appendix B.1 Waste Audit Procedures.

Researchers spread a protective cloth on the floor of the waste storage area, removed items from a single case's MSW, and separated the items according to material type. MSW items that were wet or contained fluids were set aside and counted. Locum material weights were taken of dry items and subsequently attributed to each case. This was done to ensure an accurate estimate of the material production impacts during the Life Cycle Assessment. MSW materials which were composed of multiple materials, such as grounding pads, cautery pens, and insuflators, were also counted. Sample "mixed material" items were later dismantled in a controlled laboratory setting and the component materials were weighed to estimate the impacts associated with each case as seen in Figure 21. MSW which was not wet or of mixed material production were sorted into the following material categories: gowns and drapes (SMS PP, Spunbound-Meltblown-Spunbound Polypropylene), cotton, blue wrap, gloves (sorted by color), rubber, hard plastic (generally #5), soft or thin-film plastic, Styrofoam, polyurethane foam or foam rubber, cardboard and paperboard, glass, paper, aluminum, metal (stainless steel), syringes, and wood. Any MSW that was too soiled to be safely removed from the collection bags were labeled as “leftovers,” photographed, and weighed as a whole. Leftovers represent less than 2% of the average total weight of all cases. Waste auditors also noted those cases whose waste contained batteries or metal utensils which should typically be disposed of in other waste streams or reused.

Figure 21: Mixed Material products were disassembled and measured in a controlled laboratory setting

In order to estimate the impacts associated with the “sharps” waste stream, “peel packs” were sorted out of the MSW. These are paper labels affixed to the packaging of electrical tools which are used to cut into the patient. The paper labels are thrown into the MSW stream while the electrical tools themselves are sent into the non-needles sharps waste stream. While the research team was unable to safely assess the sharps stream, counting the number of tools used through representative peel packs gives an accurate estimate of the amount of waste being directed to this stream. As with mixed materials in the MSW stream, locum sharps tools were disassembled in a laboratory setting and weighed according to material type, though it was ultimately decided to base this portion of the LCA off of cost data due to the complexity of the tools. Cost data for these laparoscopic and robotic tools was obtained through Magee's purchasing department and the EIO-LCA methods are described below in Section 5.2.3.1 Life Cycle Inventory and Impact Assessment.

5.2.2.2 Reusable Materials and Instruments

Reusable materials include hospital linens and surgical steel instrument trays. Hospital linens were cotton-based products such as the patient gown, OR sheet, blanket, pillowcase, and under-patient chuck. Blue towels were found in both the MSW, where they were appropriately incorporated into the material waste audits, and in the reusable hospital linens. The number of linen products used during each patient case was collected from the nursing staff during the material waste audits and the weight of a representative linen item was used to calculate the weight of reusable cotton products used on average per hysterectomy type. The lifespan of individual cotton products was estimated by Magee staff and is listed in Table 11. Variability in individual linen lifespans was incorporated into the Monte Carlo Assessment.

Table 11: Estimated weight and lifespan of reusable surgical linens

Linen/Cotton Product	Representative weight (kg)	Estimated Lifespan (Uses)
Patient Gown	0.344	48
Sheet	0.292	50
Blanket	0.698	52
Pillowcase	0.098	32
Under-Patient Chuck	0.51	42
Blue Towel	0.054	10

The name and number of stainless steel surgical instrument trays used in each patient case was recorded during the material waste auditing as seen in Table 12. A representative tray was weighed to estimate the weight and all materials inside were assumed to be stainless steel. The lifespan of surgical instruments was difficult to quantify as each kit contains a wide range of instruments and the individual lifespan of those instruments varies based on its handling and care, its design, its ability to be re-sharpened, and its condition. The lifespan of each kit was therefore estimated at 300 uses based on a 2012 study and variability of this estimate was incorporated into the Monte Carlo Assessment (McGain, McAlister et al. 2012). We did not incorporate impacts due to repairs such as sharpening of stainless steel surgical instruments.

Table 12: Reusable Stainless Steel Surgical Instrument Weight and Quantity per Hysterectomy

Stainless Steel Surgical Instrument Tray Name	Weight (kg)	Abdominal (# trays / 14 cases)	Vaginal (# trays / 16 cases)	Laparoscopic (# trays / 13 cases)	Robotic (# trays / 16 cases)
Cysto Pan Tray	2.032	2	4	0	5
Vaginal Hyst Tray	10.6	0	16	2	0
Book Walter 1	10.7	1	0	0	0
Book Walter Table Post Set	10.7	1	0	0	0
Laparomtoy Tray	11.1	15	0	0	0
Laparomtoy Mayo String	5.0	9	0	0	0
Mini-Laparotomy Tray	9.71	1	0	0	0
Oncology Tray	3.0	5	0	0	0
0 Degree Cysto Scope	0.492	3	0	0	0
Hd Camera	2.132	3	2	10	5
Advanced Laparoscopy	5.7	0	0	13	5
Olympus Operative Laparoscopy	4.732	0	0	13	1
D&C Pan	10.1	0	1	13	2
Morcellator Knife	2.432	0	0	3	0
Karl-Strotz Morcillator	4.132	0	0	4	0
Cysto Pan Tray	2.032	0	0	3	4
Pellosi Uterine Manipulator	2.5	0	0	9	0
Bariatric High Def Scope	2.432	0	0	5	0
0-Degree Bariatric Scope	2.253	0	0	11	0
Abdominal Sacropexy	8.232	0	0	1	0
0-Degree Gyne Scope	2.432	0	0	1	4
Davinci Scope	2.432	0	0	0	16
Davinci General Top	8.7	0	0	0	15
Davinci General Bottom	8.7	0	0	0	16
Rigid Davinci Tray	8.2	0	0	0	3
Average number of trays per case		3	2	7	5
Ave. weight per case allocated over 300 uses		0.064	0.040	0.105	0.088

5.2.2.3 Power and Energy Data from OR Equipment

In order to accurately estimate the electrical consumption of an OR during surgery, an assessment of the machines and lighting was conducted in a single OR at Magee. A table showing the OR machine inventory and estimated wattage of all machines can be found in Table 18 of Appendix B.2 Data Collection and Analysis Tables. Initially, all machines and light bulbs were inventoried and the power ratings from the back of each machine were recorded. From this, a maximum energy load was estimated.

Due to IRB and hospital-based restrictions on placing electrical monitoring devices on medical equipment during surgery, the research team used watt meters to measure the equipment in an unused OR at Magee. This assessment resulted in a 66% reduction of estimated electricity consumption compared to the use of power ratings on the backs of the machines.

In order to further fine-tune the assessment, the team identified machines that run intermittently throughout a surgery. For example, equipment such as the Valleylab Force FXc electrical grounding machine and the Ethicon / Gynecare morcellator constantly draw a low voltage throughout the procedure but are only used during a portion of the surgery, at which time they draw a significantly higher voltage. The electrical draw of these intermittent-use machines was measured using watt meters and a mock surgery during which the tools were tested on raw meat as shown in Figure 22. This test showed that the Valleylab Force Fxc electrical grounding machine draws about 15W in its idle state but while in use can draw as much as 131W. For these machines, the team also monitored two locum surgeries per hysterectomy type to estimate the percentage of time they are used over the course of the entire procedure. The results of this secondary survey show that these machines draw a higher voltage for only about 5% of the total surgery duration, as shown in Table 21 of Appendix B.2 Data Collection and Analysis Tables.

Figure 22: Reading power draw of variable-electricity surgical equipment

The energy consumption due to Heating, Ventilation, and Air Conditioning was estimated using a bin type model which assumed steady-state and calculated heating, cooling, and dehumidification load in the OR. This model is recommended to calculate system loads and sizing and has been used in previous studies (American Society of Heating 2009; Campion, Thiel et al. 2012). Inputs to the model include measured electricity consumption data, average OR occupancy per hysterectomy collected during waste auditing, and boiler and chiller efficiencies as reported by Magee facilities personnel.

5.2.3 Data Assessment Methods

The following subsections describe the Life Cycle Assessment for environmental impacts of hysterectomies and Monte Carlo Assessment methods for variability and uncertainty employed in this study.

5.2.3.1 Life Cycle Inventory and Impact Assessment

The LCI stage of life cycle assessment compiles the inputs and outputs at all life cycle stages of a product or process. Published databases contain the unit processes which correspond to a specific product or process and its associated inputs and outputs. Database selection is important to accurately reflect the environmental impacts of the system. Data collected via the methods described above were translated into appropriate LCI unit processes for both production and disposal of the materials, as shown in Table 19 and Table 20 of B.2 Data Collection and Analysis Tables.

For this study, researchers gave preference first to US based databases, i.e. USLCI (NREL 2010); the most robust database (ecoinvent) was considered second (Frischknecht, Jungbluth et al. 2005); and finally, a different database was selected if unit processes were not available in either USLCI or ecoinvent. All database selections were determined by comparing the physical description and application of the material to the unit process description. Impacts due to the transportation of material wastes were calculated using distances from the hospital facility to the landfill and recycling facilities based on waste hauling quantity data provided by Magee's facility management. All transportation impacts were calculated using ecoinvent processes.

The selection of environmental impact database processes for reusable materials was identical to that of single-use or disposable materials. Allocation of impacts due to production and disposal of reusable materials was allocated based on the estimated lifespan of the materials, as listed in Table 11 for linens and Table 12 for stainless steel. Limited information was available on the environmental impacts of the sterilization process and associated products for reusable materials. In the case of linen sterilization, a quantity of 27.4 g of detergent per kg of cotton laundered and 0.2 kWh of electricity per kg of cotton laundered was assumed based on previous literature, specifically a 1999 study based in Germany (Barrie 1994; Dettenkofer, Grießhammer et al. 1999; Bajpai and Tyagi 2007). Though a US-based literature of domestic laundry estimates the electrical consumption per kilogram of cotton at 0.87 kWh, lower estimates are expected for industrial laundry facilities (Blackburn and Payne 2004). The sterilization of surgical trays was based off of an energy consumption estimate (2.57 kWh per stainless steel surgical instrument tray) of the sterilizing and autoclaving machines at Magee (Campion, Thiel et al. 2012). No estimate was available for the types or numbers of chemicals or solvents used to sterilize the stainless steel surgical instruments.

Certain processes were modified based on literature to more accurately reflect the product or process being represented. The USLCI electricity process was modified to match the energy mix of Pennsylvania (EPA 2007). Disposable gowns, drapes, and bluewrap from the OR are a type of polypropylene fabric also known as spunbond-meltblown-spunbond or SMS. SMS polypropylene accounted for an average of 23% of the MSW by weight for all hysterectomy types as shown in Section 5.3.2 Material Composition of Hysterectomy Cases. Standard LCI databases model the impacts of polypropylene up to its pellet form. In order to account for the impacts due to the manufacture of the textile beyond pelletization of the plastic, the dissertation work of Celia M. Ponder was used to modify the existing PP process within the USLCI database (Ponder 2009).

Hybrid LCA Setup

Certain medical equipment used in laparoscopic and robotic hysterectomies was too complex to be broken down accurately into representative components. To account for the impacts due to the manufacture of these "sharps" items, this study utilized Economic Input-Output LCA (EIO-LCA) (Carnegie Mellon University Green Design Institute 2013). This combination of process LCA and EIO-LCA is called Hybrid LCA and is used to address issues that may be encountered using each method alone as mentioned in previous sections (Lenzen 2002; Bilec, Ries et al. 2006).

The monetary values were evaluated using the purchaser price model in EIO-LCA, as the prices were reflective of what the hospital paid, and not the cost to the manufacturer. The value was assessed using the corresponding sectors designated by the North American Industry Classification System (NAICS). The NAICS classification system is the method for classifying businesses in order to collect and assess data related to the US economy and its performance. For the production of complex medical devices, NAICS sector 339112 *Surgical and Medical Instrument Manufacturing* was selected.

The price paid per unit for each piece of medical equipment was collected from Magee purchasing staff and matched to the number of medical equipment used in each hysterectomy based off of collected peel pack data as seen in Figure 46, Figure 47, Table 23, and Table 24 of Appendix B.2 Data Collection and Analysis Tables. In this manner, a range of disposable medical equipment costs was estimated and incorporated into the Monte Carlo Assessment as described below. The monetary values were converted from 2012 US dollars to 2002 dollars, the basis for the most recent EIO-LCA model, using a percent change of 94.9% for medical instrument manufacturing according to Producer Price Index Industry (PPI) Data from the Bureau of Labor Statistics (BLS 2013). While this monetary conversion is necessary to ensure accuracy, it does not completely exclude EIO-LCA's reliance on historical values where process demands and environmental impacts can change significantly.

The disposal of these devices in Magee's sharps waste stream was also evaluated with EIO-LCA through NAICS sector 562000: *Waste Management and Remediation Services*, which includes the processing of sharps-designated medical equipment. Magee staff reported the cost of this disposal at $0.21/lb in 2012 US dollars, or $0.38/kg in 2002 US dollars, again using PPI data (BLS 2013). The average quantity of non-needle sharps waste generated was estimated using the peel pack data and estimated weights in kg of each peel pack item. The impacts from disposal of these sharps were calculated by multiplying the estimated weight of sharps waste in each case by the EIO-LCA impacts from $0.38 in the NAICS sector 562000.

The EIO-LCA data in these two sectors was analyzed using TRACI 2.1 version 4.00 (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) and the Energy analysis function found on the EIO-LCA online tool (US EPA 2012; Carnegie Mellon University Green Design Institute 2013). Unit conversion was necessary to match the impact categories Acidification, Carcinogenics, NonCarcinogenics, and EcoToxicity with the process LCA results as seen in Table 13. A characterization factor of 50.79 kg SO2 eq / H+ mole was used for acidification potential conversion. EIO-LCA reports human health toxicity impacts (cancer and non-cancer) in benzene and toluene equivalent emissions to air. For this reason, TRACI characterization factors of 2.97e-7 CTUh / kg benzene to air and 5.3e-8 CTUh / kg toluene to air were chosen, where CTUh stands for Cumulative Toxicity Unit for humans. EIO-

LCA reports ecotoxicity as kg 2,4D to continental freshwater, and a characterization factor of 8.60e2 CTUe / kg 2,4D was used, where CTUe stands for Cumulative Toxicity Unit for the environment. For the EIO-LCA portion of this study, the effects of chemicals' fate to soil and water were not considered in the categories related to human toxicity, nor were chemicals' fate to air and soil for ecotoxicity.

Table 13: Impact Category Characterization and Conversion for EIO-LCA and Process LCA

Impact Category	EIO-LCA Units	Process LCA Units (TRACI)	EIO-LCA Impacts per $1US2002 Purchaser	CF (TRACI)	EIO-LCA Impacts per $1US2002 Purchaser (Converted)
Ozone depletion	kg CFC-11e	kg CFC-11 eq	0.000002	1	0.000002
Global warming	kg CO2e	kg CO2 eq	0.403317	1	0.403317
Smog	kg O3e	kg O3 eq	0.000002	1	0.000002
Acidification	kg SO2e	mol H+ eq	0.002117	50.79	0.10752243
Eutrophication	kg Ne	kg N eq	0.000068	1	0.000068
Carcinogenics	kg benzene eq	CTUh	0.000037	2.97E-07	1.0989E-11
Non carcinogenics	kg toluene eq	CTUh	0.023076	5.3E-08	1.22303E-09
Respiratory effects	kg PM10e	kg PM10 eq	0.000698	1	0.000698
Ecotoxicity	kg 2,4D	CTUe	0.000018	860	0.01548
Energy	MJ	MJ	5.87	1	5.87

Environmental impacts from the inputs and outputs of the four types of hysterectomy were calculated using TRACI 2.1 version 4.00 for both process- and EIO-LCA (Bare, Norris et al. 2003). Embodied energy or a summation of all energy used during the material's life cycle, was calculated using Cumulative Energy Demand (CED) version 1.08 developed by ecoinvent version 2.0 and PRé Consultants (Frischknecht R. 2003; Frischknecht, Jungbluth et al. 2007). Impact categories analyzed and reported include global warming potential (or, more appropriately, greenhouse gas emissions), acidification, carcinogenics, non-carcinogenics, respiratory effects, eutrophication, ozone depletion, ecotoxicity, smog, and CED.

5.2.3.2 Monte Carlo Assessment of Variability and Uncertainty

Researchers utilized Monte Carlo Assessment (MCA), or random number sampling, to account for the uncertainty inherent in life cycle inventory data and the variability of material and energy consumption for each type of hysterectomy. The use of MCA allows this study to more accurately depict the range of potential environmental impacts which can result from a typical hysterectomy. A graphical flowchart of the MCA process specific to this project can be found in Figure 48 of Appendix B.2 Data Collection and Analysis Tables.

The material data collected from each hysterectomy allowed researchers to statistically estimate probability distributions for the prevalence of this material in an average surgery using the Anderson Darling Test in an Individual Distribution Identification tool. Distributions of materials in each type of hysterectomy were normal, lognormal, most extreme value as seen in Figure 23. Where Anderson Darling tests showed distributions were not normal, lognormal, or most extreme value, a designation of "no distribution" was given and as shown in Figure 44, Figure 45, and Table 22 of Appendix B.2, and an average value was used in the MCA. Some materials, such as green gloves and Styrofoam, did not have a defined distribution based on the data collected. These were not assigned a distribution and their average was used instead. Because electricity data was collected as an average and not on a per-case basis, the variability in electrical and energy consumption in the MCA was based off of the duration of surgery. During the waste audits, patient and surgery information, including the duration of each surgery in minutes, was recorded and the distributions were determined based off of this collected data.

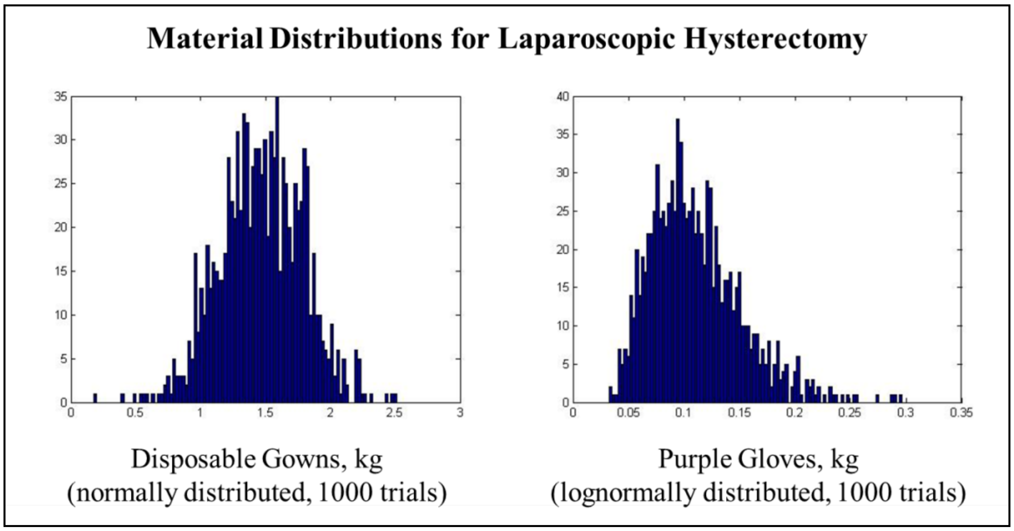


Figure 23: Estimated Material Distributions by Weight for Quantity of Disposable Gowns and Purple Gloves Used during Laparoscopic Hysterectomies

Limits were set on the random values chosen for certain material distributions. For example, no zero or negative numbers were allowed in the random sampling of any materials. An additional lower limit of 50 minutes was placed on the duration of surgery, a lower limit of 50 on the number of reuses of stainless steel, and a lower limit of 5 was placed on the number of reuses of linens, as shown in Appendix B.3 Monte Carlo Scripts for .

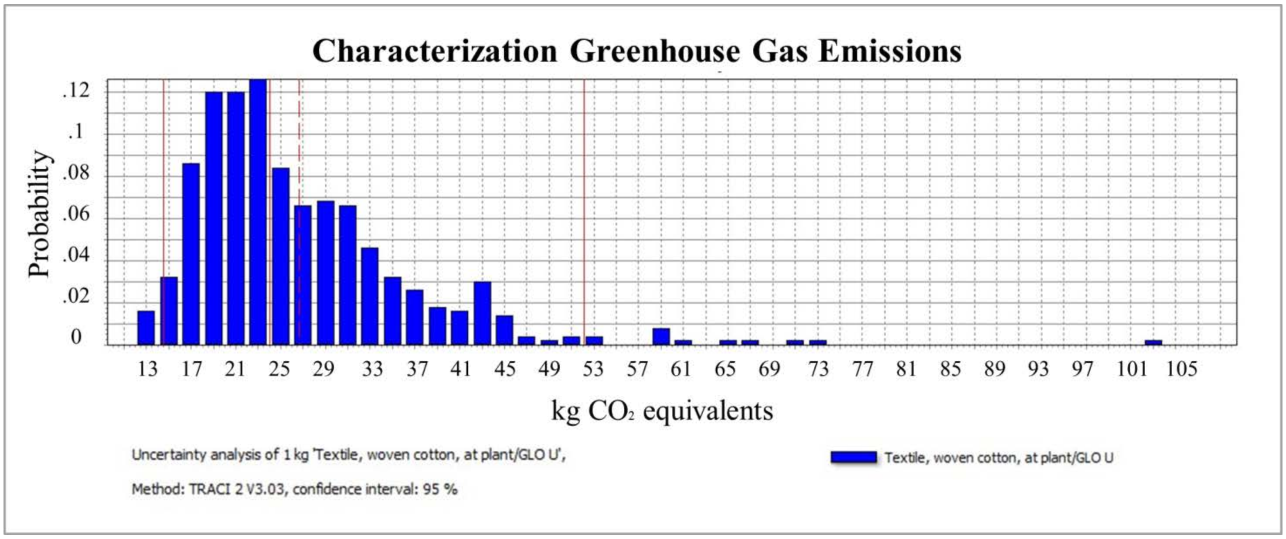


Figure 24: Results of Monte Carlo Assessment (500 trials) of Respiratory Impacts of Cotton Production Process (ecoinvent) in SimaPro 7.3.3 PhD

To account for their uncertainty, individual MCAs of all ecoinvent LCI database processes used in this study were conducted in SimaPro 7.3.3 PhD (PRé Consultants 2011) and were assumed to be lognormal for all impact categories based on the shape of the distribution, as seen in Figure 24. The mean and standard deviation of each LCI process was then converted using Equation 4 and Equation 5 to location and shape parameters for lognormal distributions for use in the overall MCA. Where an impact per unit material had a mean value of less than one (or a lognormal location parameter of less than zero), the MCA failed to produce an identical mean through random number sampling based on the location and shape parameters. To avoid this statistical issue, all the units for each impact category were converted from kilograms into grams, milligrams, or nanograms prior to running the MCA. After the MCA was completed, the units were converted back into their original form.

$$\mu = \ln \frac{m^2}{\sqrt{v + m^2}}$$

Equation 4: Location parameter for lognormal distribution based on mean, m, and variance, v.

$$\sigma = \sqrt{\ln(\frac{v}{m^2} + 1)}$$

Equation 5: Shape parameter for lognormal distribution based on mean, m, and variance, v.

Only the ecoinvent LCI database contains uncertainty data, and therefore, this was the only database for which impact distributions were obtained. The remaining database impacts were incorporated into the MCA as averages. Uncertainty data is not yet incorporated into the EIO-LCA method. Therefore, these LCI data were entered into the MCA as averages and not as distributions. Variability in cost data was estimated for laparoscopic and robotic hysterectomies and was incorporated into the MCA as a triangular distribution, as seen in Table 22 of Appendix B.2 Data Collection and Analysis Tables.

This MCA randomly sampled numbers from the probability distributions of materials and their impacts, resulting in an overall distribution of the impacts of a hysterectomy. The resulting distribution was calculated from 100,000 random samplings (shown as the variable "trials" in B.3 Monte Carlo Scripts for). The 5th, 50th, and 95th percentiles as well as the means and standard deviation for all impact categories were reported for each hysterectomy as a whole and for individual components of each hysterectomy- reusable items, production of disposable items, disposal of disposable items, chemo/pathogenic waste, and energy. The impacts due to recycling, because they were negative, were not included within the MCA, but were incorporated as averages in post-MCA results and error bars. When using the median value rather than the mean of the resulting distribution, the effects of very high-impact trials are eliminated, which skews results upwards. This does, however, minimize the effects of worst-case scenarios.

5.3 RESULTS AND DISCUSSION

Section 5.3 discusses the results of the study, beginning with a general overview of the types of cases from which data were collected. The material composition from the waste audit precedes the subsection related to environmental impacts associated with those materials. Results from the MCA and discussion follow this. Section 5.3 concludes with a subsection of suggested environmental improvements for OR surgeries and a subsection of study limitations and future research opportunities.

5.3.1 Overview of Hysterectomy Cases

A minimum of 15 cases per hysterectomy type was used to assess waste generation. Cases were withdrawn from the study when additional surgical procedures were performed on the patient during the hysterectomy, when the type of hysterectomy was converted during the procedure, or when the surgery was conducted too late in the evening for collection of the surgical waste. Medical complications which did not result in additional procedures or conversion of the type of hysterectomy were included in the study as these accurately reflect standard waste generation from surgical procedures in hospitals.

To see which factors might affect waste generation, a variety of patient data was collected following their procedure according to IRB protocol. The data, shown in Table 14, was compared with the waste generated by weight. Larger uterine weights are clearly correlated with abdominal hysterectomies, which in turn is associated with larger impacts due to the disposal of the uterus. However, no other clear trends emerged between waste generation and surgical duration, patient BMI, or blood loss. The effects of surgical complications and physician or surgical staff were not able to be accurately analyzed due to the small sample size. In general, the more electronic or technological equipment used in a case (ie. robotic hysterectomy), the larger the quantity of MSW generated. A specific breakdown of waste generation can be found in Section 5.3.2 Material Composition of Hysterectomy Cases.

Table 14: Statistics on Hysterectomy Cases Collected During Study; Average (Minimum, Maximum)

	Abdominal	Vaginal	Laparoscopic	Robotic
Total Number of Cases	17	19	19	15
Withdrawn Cases	2	4	3	0
Cases Included in Study	15	15	16	15
Surgery Duration, min	141 (67, 229)	115 (50, 242)	150 (60, 245)	104 (51, 167)
Estimated Bloodloss, ml	384 (50, 1500)	242 (25, 1100)	162 (20, 1000)	50 (20, 150)
Patient BMI	30 (23, 36)	29 (18, 37)	30 (21, 38)	32 (18, 43)
Uterine Weight, g	555 (60, 2729)	168 (36, 570)	290 (86, 1064)	173 (40, 448)
Cases with Complications, not withdrawn from study	1	2	1	0
Weight of MSW, kg	9.2 (5.9, 13.9)	8.5 (5.9, 11.3)	10.6 (6.6, 13.6)	13.7 (9.3, 16.8)
Weight of Recycling, kg	0.8 (0, 2.1)	0.4 (0, 1.2)	0.9 (0, 1.8)	0.7 (0.4, 2.0)
Cases with Unused Materials	10	6	14	9
Cases with Batteries in MSW	2	0	12	11

5.3.2 Material Composition of Hysterectomy Cases

Waste auditing of Magee's abdominal, vaginal, laparoscopic, and robotic hysterectomies determined the average material composition of MSW and Recycling of a hysterectomy.

Robotic hysterectomies produced the largest quantity of waste with an average of 13.7 kg of MSW per case, as seen in Figure 25. Of that quantity, 22% was gowns and other SMS PP material, 50% were gloves and other plastics, 18% was paper and 5% was cotton. Abdominal hysterectomies, the most common form of hysterectomy in the US, had an average total MSW production of 9.2 kg. Abdominal procedures produced the largest amount of cotton waste at 1 kg per average surgery or 11% of the waste material composition. Cotton, composed primarily of blue towels and gauze, is associated with larger environmental impacts during the production phase of the life cycle, relative to the production of other materials. Disposal of cotton ranged between 5 and 11% by weight depending on the hysterectomy type. This variability between hysterectomy types, while relatively small, resulted in a disproportionately large range of environmental impacts, which will be discussed in the following sections.

Across all four surgeries, SMS PP material - or gowns, bluewrap, and drapes - composed 22-35% of total waste material by weight. Gloves were about 4-5% by weight of each surgery's waste stream, and other types of plastics – from thin film wrappers to hard plastic trays – made up 36-46% by weight of the MSW in an average hysterectomy. Paper from package labeling and cardboard varied from 5 to 18% of the MSW depending on the type of procedure.

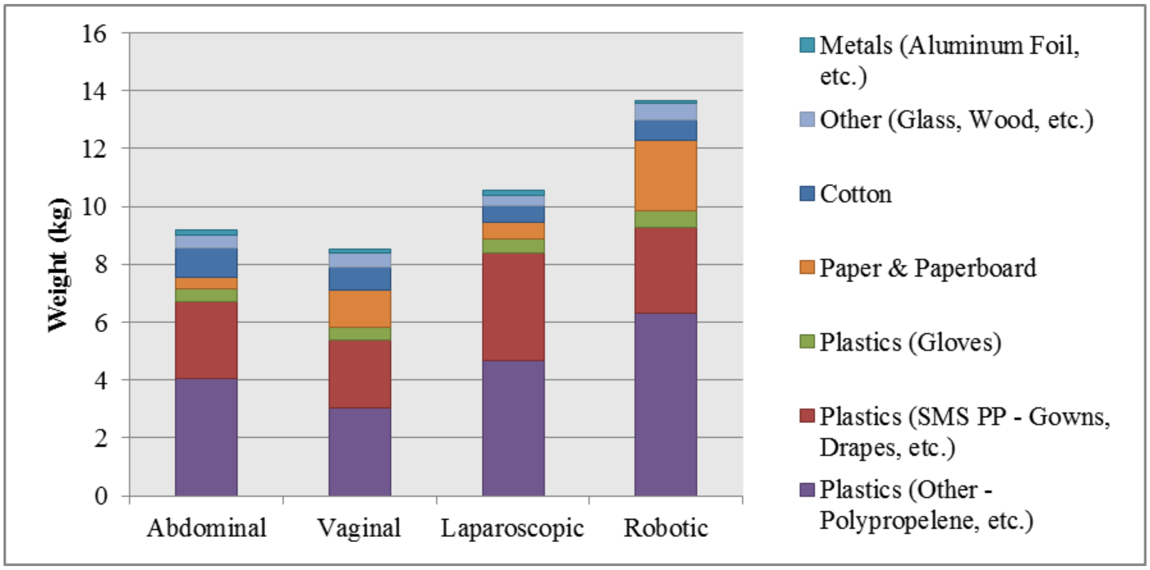


Figure 25: Average Material Composition Municipal Solid Waste from a Single Hysterectomy by Surgery Type

Recycling was variable for each case, as seen in Figure 26. As an average per hysterectomy type, recycling rates ranged from 0.4 kg for vaginal hysterectomies (4% of total material disposal by weight) to 0.9 kg for laparoscopic hysterectomies (8% of total material disposal by weight). Researchers discovered non-recyclable materials in the recycling waste in 1 out of 15 cases for vaginal and abdominal procedures, in 3 out of 16 cases for laparoscopic procedures, and in 6 out of 15 cases for robotic procedures.

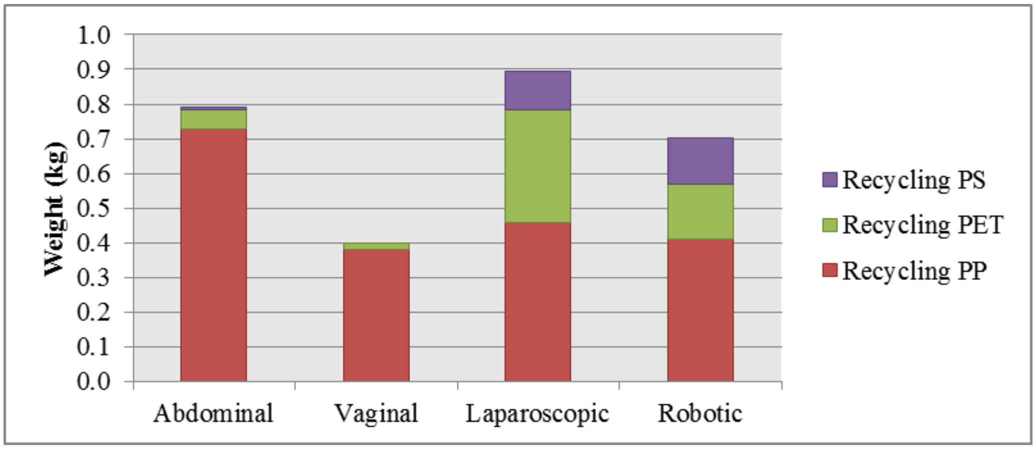


Figure 26: Average Recycling Composition from a Single Hysterectomy by Surgery Type

5.3.3 Environmental Impacts of Hysterectomies

Impacts due to the production of disposable materials made up a large portion of the environmental impacts in every surgery type. The production of disposable materials is associated with at least 40% of the environmental impacts in every category analyzed of all four hysterectomy procedures. Approximately 80% of ecotoxicity impacts, carcinogenic effects, and ozone depletion potential (ODP) are attributed to the production of disposable items as seen in Figure 27. For laparoscopic and robotic hysterectomies, the impacts associated with surgical instruments, which were analyzed using EIO-LCA, dominate in the categories of ODP, greenhouse gas emissions (GHG), acidification potential, respiratory impacts, and cumulative energy demand (CED).

Impacts due to disposal of single-use or disposable materials and tools make up over 40% of the eutrophication potential and nearly 10% of human health non-carcinogenic toxicity impacts in all hysterectomies. In an average hysterectomy, the impacts due to the sterilization and allocated production and disposal of reusable materials accounts for nearly 10% of each impact category. For greenhouse gas emissions, which contribute to global climate change, that number can be as high as 23% due to the burning of fossil fuels used in equipment sterilization and manufacture of reusable instruments.

Impacts due to energy consumption of an average hysterectomy vary between impact categories and hysterectomy types. For example, 40% of greenhouse gas emissions for abdominal and vaginal hysterectomies are the result of energy consumption during surgery, but energy used in robotic and laparoscopic hysterectomies result in only about 10% of the greenhouse gas emissions due to the relatively large impact of surgical instruments. Generally, energy consumption is more significant in the categories of greenhouse gas emissions, acidification potential, respiratory impacts, smog formation, and cumulative energy demand. These categories are largely influenced by emissions resulting from the burning of fossil fuels.

Without accounting for case-by-case variability and impact uncertainty, robotic hysterectomies have the largest relative environmental impact in every impact category, as seen in Figure 28. However, the range of potential impacts due to robotic hysterectomies often overlaps with that of laparoscopic hysterectomies. On average, vaginal hysterectomies have the lowest environmental impact, but the range often overlaps with that of abdominal hysterectomies. The differentiation between hysterectomy types is not as clear for the following impact categories: smog, ecotoxicity, human health carcinogenics, human health non-carcinogenics, and eutrophication. In these categories, a “good” robotic case can overlap with the environmental impacts of a “bad” vaginal case, as can be seen in the error bars of Figure 28.

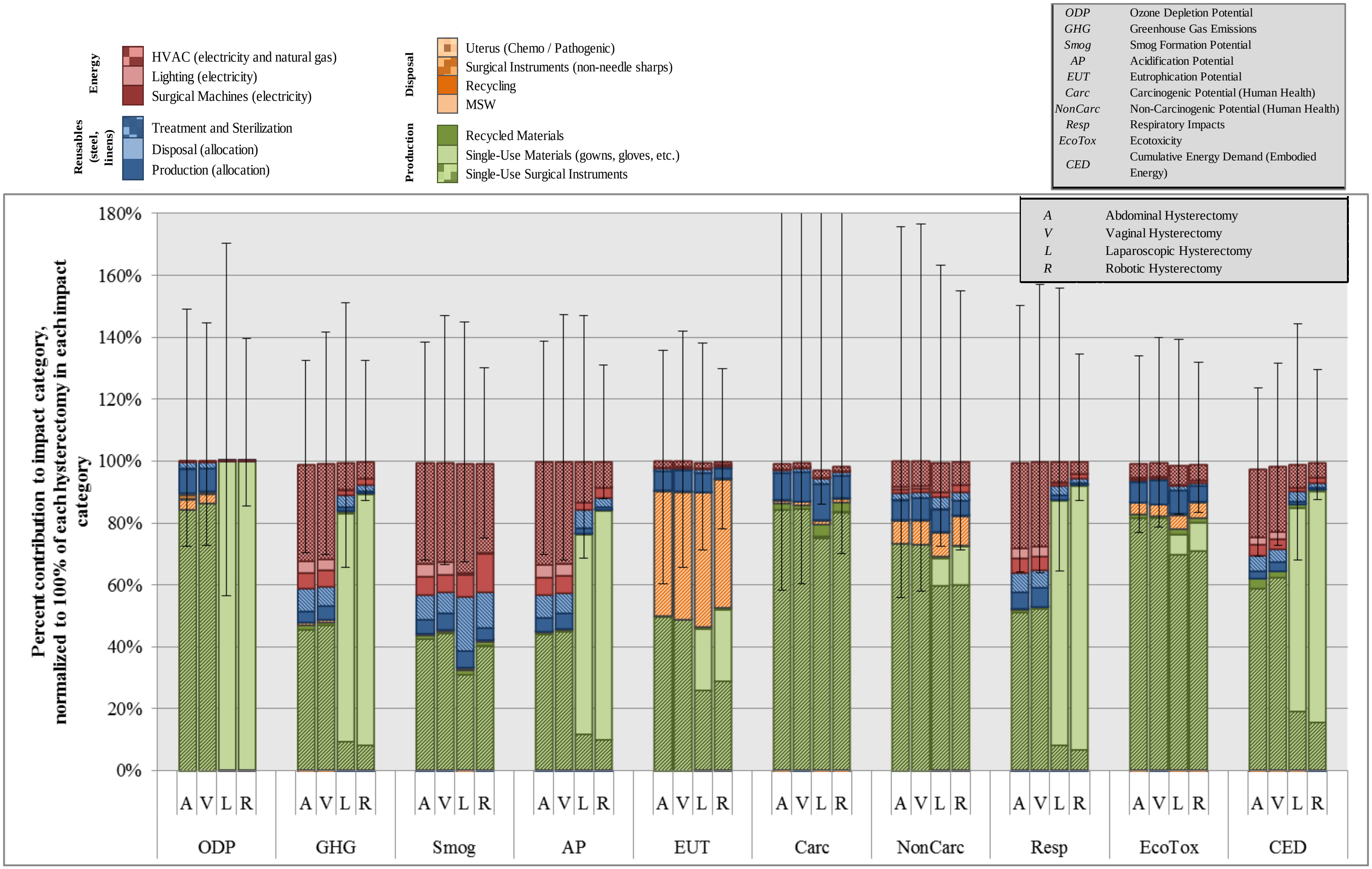


Figure 27: Total Life Cycle Environmental Impacts of an Average Hysterectomy by Surgery Type (normalized to 100% of each hysterectomy in each impact category)

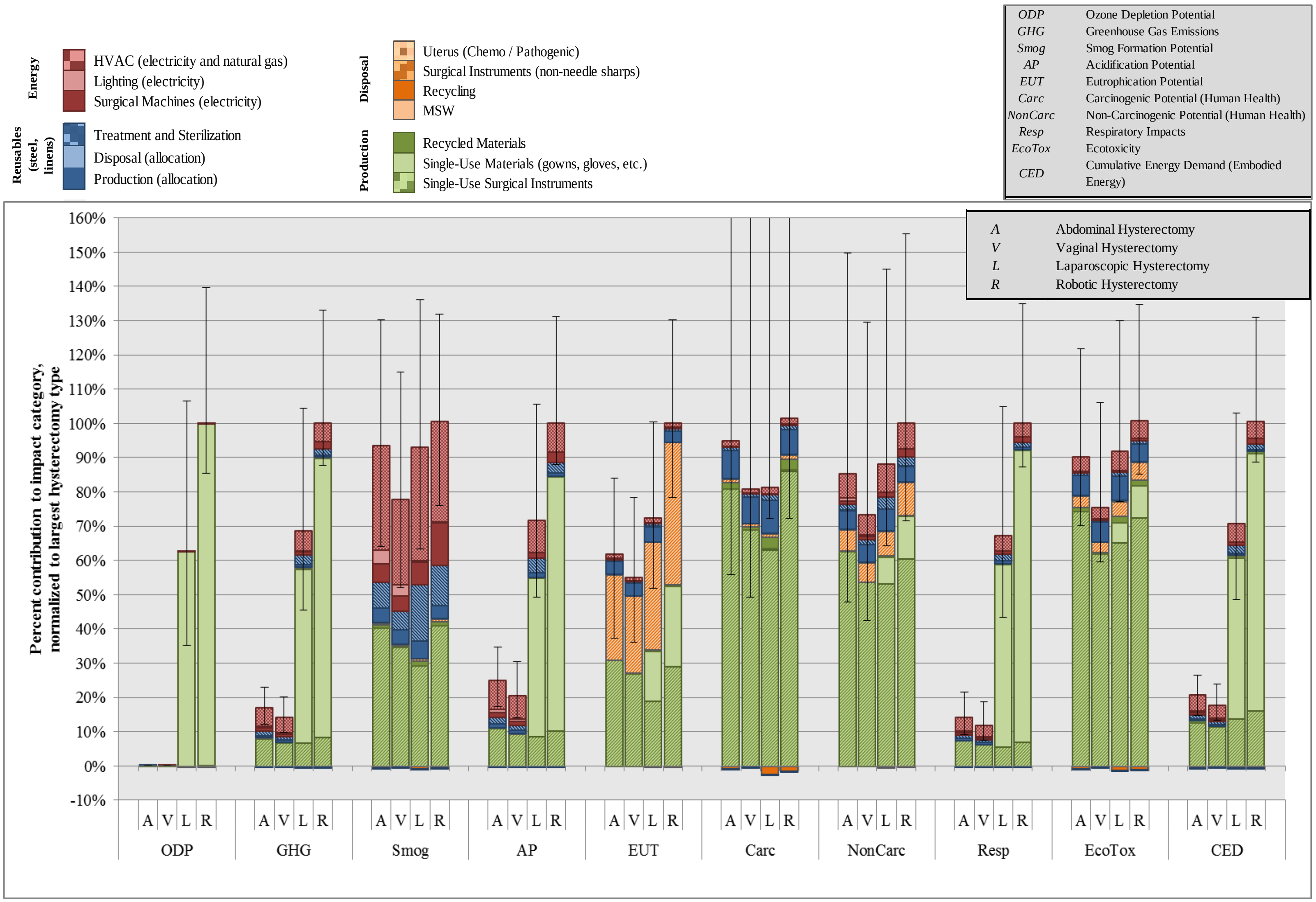


Figure 28: Total Life Cycle Environmental Impacts of an Average Hysterectomy by Surgery Type (normalized to highest hysterectomy type in impact category); negative values reflect positive environmental impacts due to recycling

5.3.3.1 Impacts due to the Production of Disposable Materials

Analyzing only the impacts due to the production of disposable materials reveals that the cotton materials for vaginal and abdominal hysterectomies account for 55-90% of all impact categories except CED, for which cotton production makes up about 25% as seen in Figure 29. Production of SMS PP, the material used for gowns, drapes, and bluewrap, makes up nearly 40% of an abdominal hysterectomy's embodied energy and accounts for 1-20% of all other impact categories. Vaginal hysterectomies follow a similar trend, but with 20% less cotton by weight and roughly 3 times the quantity of paper. The impacts associated with the production of paper products makes up nearly 10% of every impact category for vaginal hysterectomies.

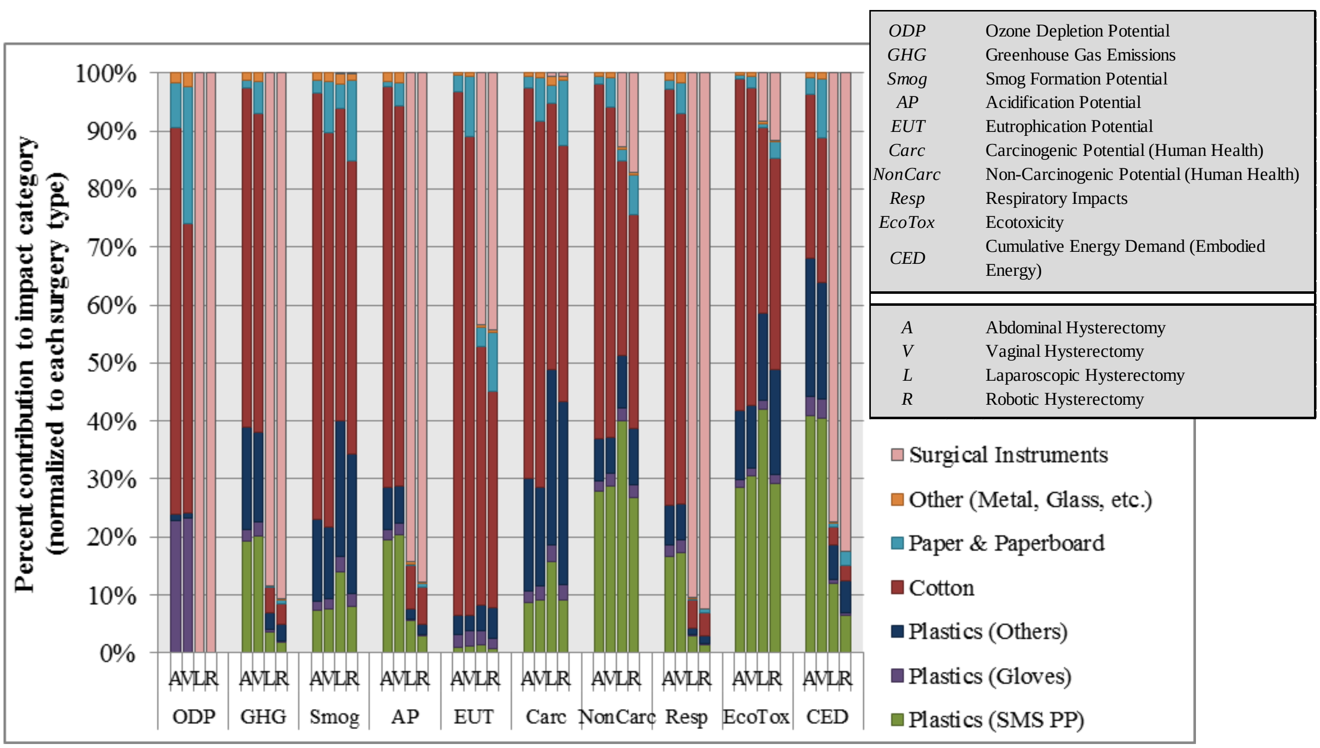


Figure 29: Average Environmental Impacts from the Production of Disposable Materials and Single-Use Tools from a Single Hysterectomy by Surgery Type (Normalized to 100%)

Impacts due to the production of complex surgical instruments dominates certain impact categories for laparoscopic and robotic hysterectomies, accounting for over 80% of these hysterectomies' impacts in ozone depletion potential, greenhouse gas emissions, acidification potential, respiratory impacts, and cumulative energy demand. In impact categories not dominated by surgical instruments, the production of cotton, SMS PP, and other plastics account for over 30% of environmental impacts for laparoscopic and robotic hysterectomies.

5.3.3.2 Impacts due to Transportation and Disposal of Single-Use or Disposable Materials and Tools

Impacts due to the transportation and landfilling of the disposable materials and tools comprise over 40% of the total eutrophication impacts of all hysterectomies, nearly 10% of the total non-carcinogenic human health impacts, and about 5% of the total ecotoxicity potential. Figure 30, a closer analysis of the elements composing the landfilling impacts, shows that the disposal of plastics, including SMS PP (gown and drape material), account for over 40% of the impacts in every category analyzed. The disposal of cotton, unlike its production, account for only about 5% of the impacts for every hysterectomy type.

The disposal of surgical instruments accounts for 7-34% of the smog, acidification potential, and cumulative energy demand and 15-55% of the greenhouse gas emissions and respiratory impacts for abdominal, laparoscopic, and robotic hysterectomies. Due to larger amounts of paper waste in vaginal and robotic hysterectomies, the impacts due to paper disposal compose nearly 15% of the impacts in ODP, smog, acidification, eutrophication, carcinogenics, non-carcinogenics, respiratory effects, and cumulative energy demand for these two surgery types.

Transportation of waste from the hospital to its final disposal site accounts for 10-20% of ODP, smog, acidification, respiratory impacts and cumulative energy demand. Transportation represents only about 5% of greenhouse gas emission impacts due to the relative GHG impacts of surgical instruments. Emissions from the burning of fossil fuels, such as diesel or gasoline, affect these categories.

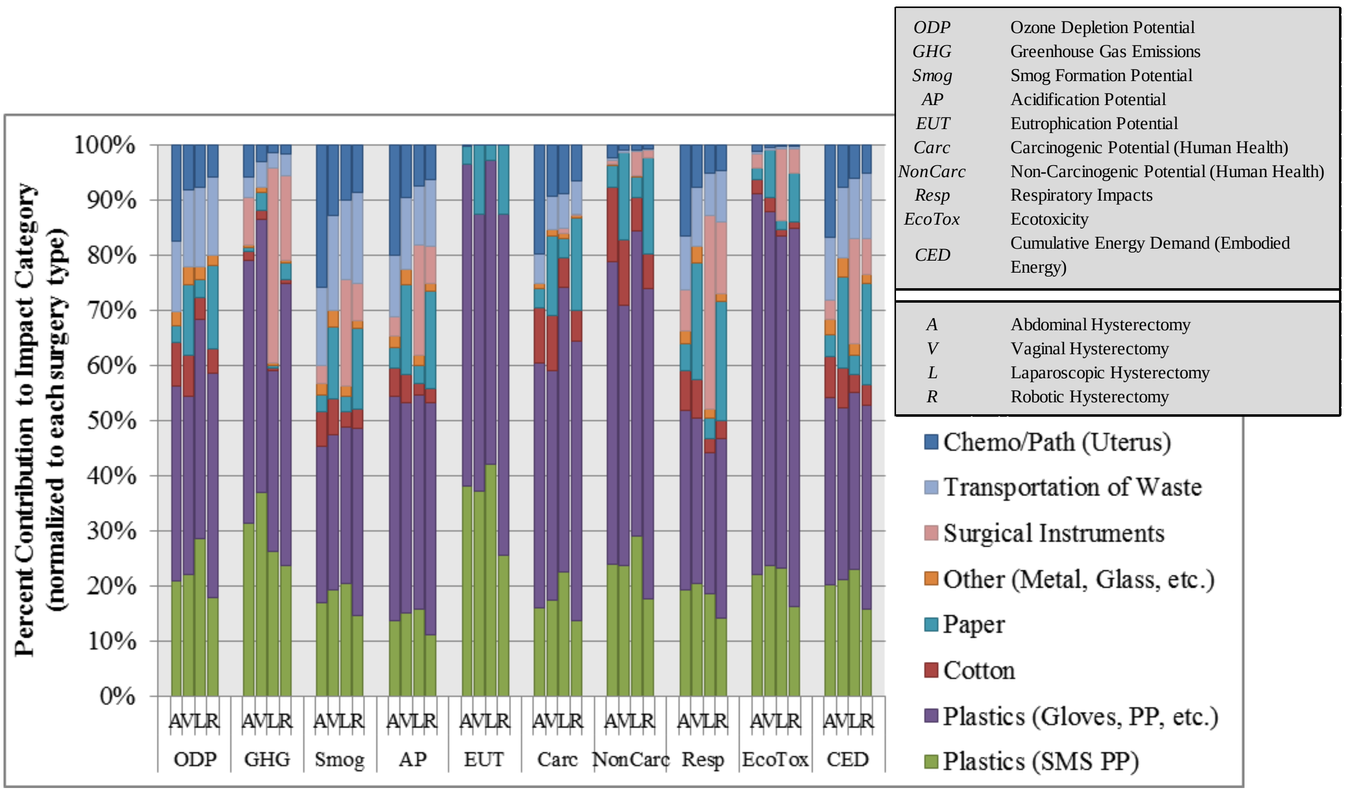


Figure 30: Average Environmental Impacts from the Municipal Solid Waste and Chemo/Pathogenic Waste Disposal from a Single Hysterectomy by Surgery Type (Normalized to 100%)

The chemo and pathogenic waste stream is used to dispose of uteri. In this study, the transportation and incineration impacts of this waste stream were calculated based off of uterine weight from patient charts recorded during the waste audits. It is interesting to note that impacts due to chemo or pathogenic waste for abdominal hysterectomies are nearly double that of the other procedures. This is especially visible in the categories of ODP, acidification potential, respiratory impacts, human health carcinogenics, smog, and CED. Uteri from the abdominal hysterectomies in this study were, on average, nearly twice the size of uteri from the three other hysterectomy procedures, thus reinforcing the validity of the LCA model.

5.3.3.3 Impacts due to Energy and Electricity Use within the OR

Another major contributor to the overall greenhouse gas emissions, smog, acidification potential, respiratory impacts, and cumulative energy demand of hysterectomies is the energy required to run machines, light the OR, and maintain standard air cycles and humidity levels. These categories are generally affected by pollutants produced from electricity generation plants and the burning of fossil fuels. This section discusses energy use in the OR based off of study findings.

A majority of these impacts –over 70% - are caused by the heating, ventilation, and air conditioning (HVAC) in the OR, which was allocated to each surgery type based on average surgery duration in the cases studied. As seen in Figure 31, electricity required to run the machines in the OR makes up 10-30% of every impact category analyzed depending on the hysterectomy type. Lighting in abdominal and vaginal hysterectomies accounts for about 8% more of their environmental impacts in all categories, but only 1% in laparoscopic and robotic procedures. This is due to minimal use of OR lighting during laparoscopic and robotic hysterectomies.

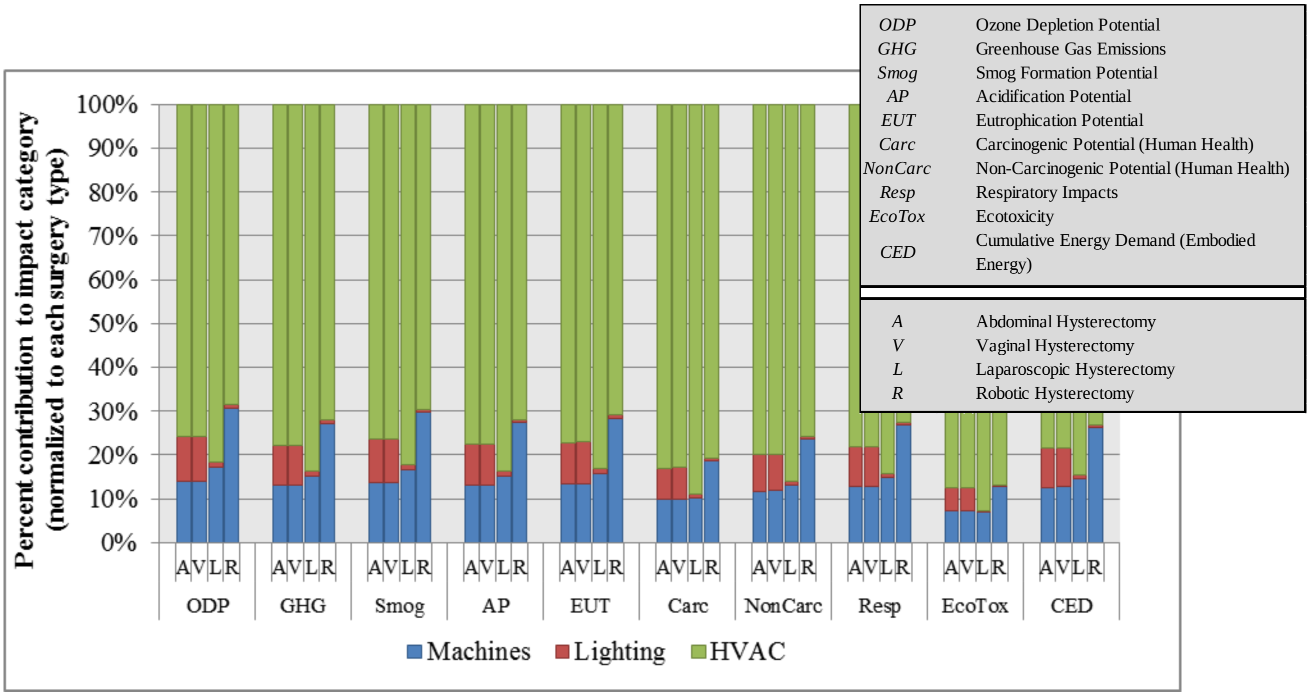


Figure 31: Average Environmental Impacts from Energy (Electricity and Gas) Consumed During a Single Hysterectomy by Surgery Type

5.3.4 Variation in Environmental Impacts

The Monte Carlo Assessment showed the range in potential impacts due to variability in each hysterectomy case and uncertainty in LCI and LCIA data. Certain impact categories were found to have a smaller range of potential impacts as seen in Figure 32. The mean value in Figure 32 is the value used in the results discussion Section 5.3.3: Environmental Impacts of Hysterectomies. In general, the impact categories of carcinogenic and non-carcinogenic human health impacts have greater ranges (or 90% confidence interval) compared to other impact categories. The methodologies and calculations behind these human health impact categories inherently contain greater uncertainties than other categories, so this is expected.

In impact categories where single-use surgical instruments (or the EIO-LCA data) dominates the results, the range of potential impacts is smallest for robotic hysterectomies and usually largest for laparoscopic. Those categories are ODP, GHG, acidification potential, respiratory impacts, and CED. The EIO-LCA database does not contain uncertainty data, and the ranges depicted here are based on variations in the price of robotic and laparoscopic surgical tools per case. The range estimated through Magee's quantity and cost data was about $800 for robotic hysterectomies and over $1000 for laparoscopic hysterectomies, resulting in relatively narrow impact ranges for robotic hysterectomies.

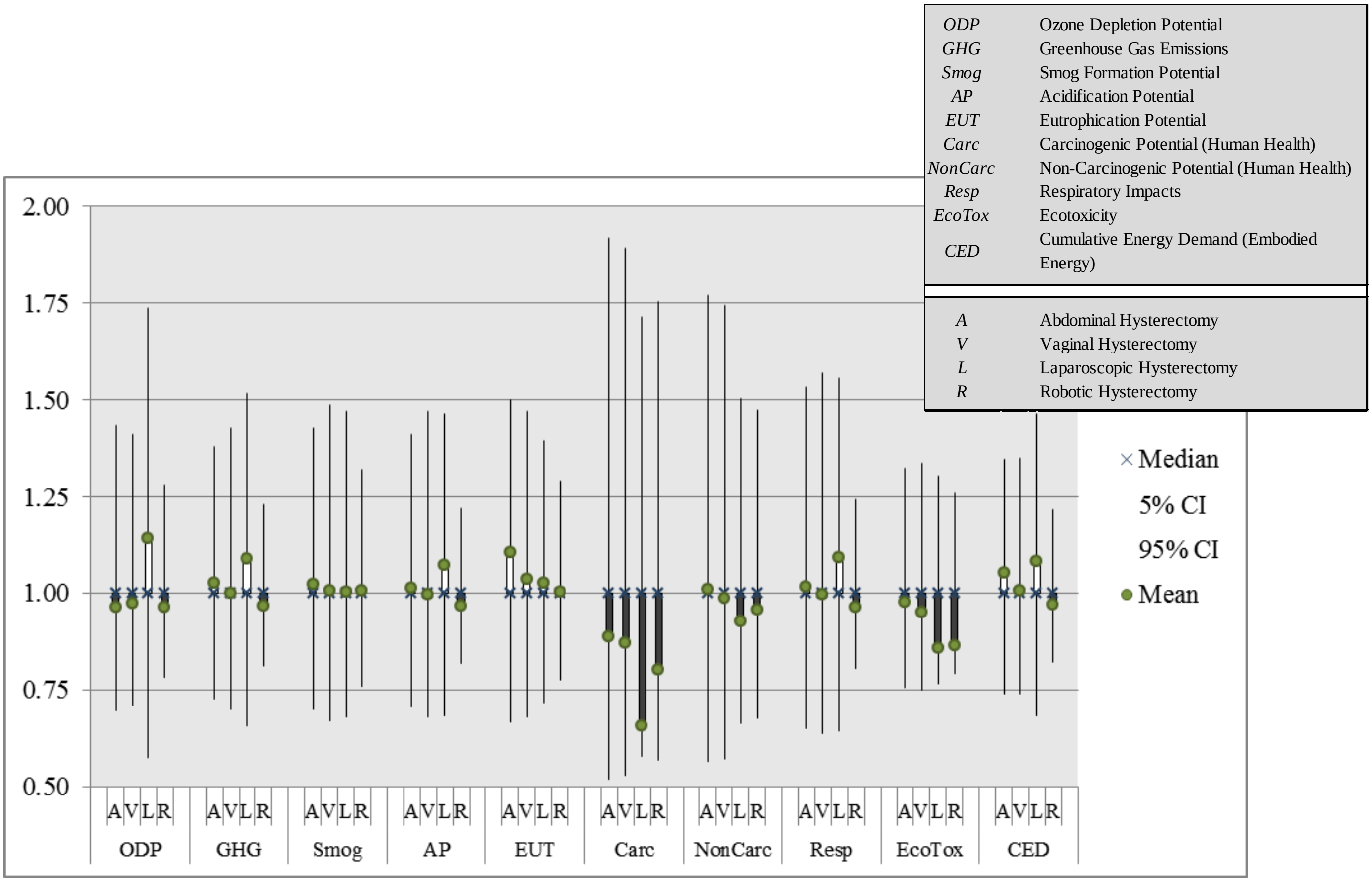


Figure 32: Variations in Total Life Cycle Environmental Impacts of Four Types of Hysterectomies (90% CI) with Median at 1.0; Does not include impacts due to recycling.

Each component of the hysterectomy life cycle has some individual variation which depends upon the impact category. Figure 33 shows that for greenhouse gas emissions (GHG), the 90% confidence interval of reusable materials is smaller than the other life cycle components. It should be noted that the laparoscopic and robotic CO_2 equivalents for production of disposable materials has been cut off at the top of this figure to show greater detail. Their mean values (the top of the colored boxes) were 400 kg CO_2 equivalent and 630 kg of CO_2 equivalents respectively. For greenhouse gas emissions, the effects of single-use material disposal and the chemo/pathogenic waste stream are negligible.

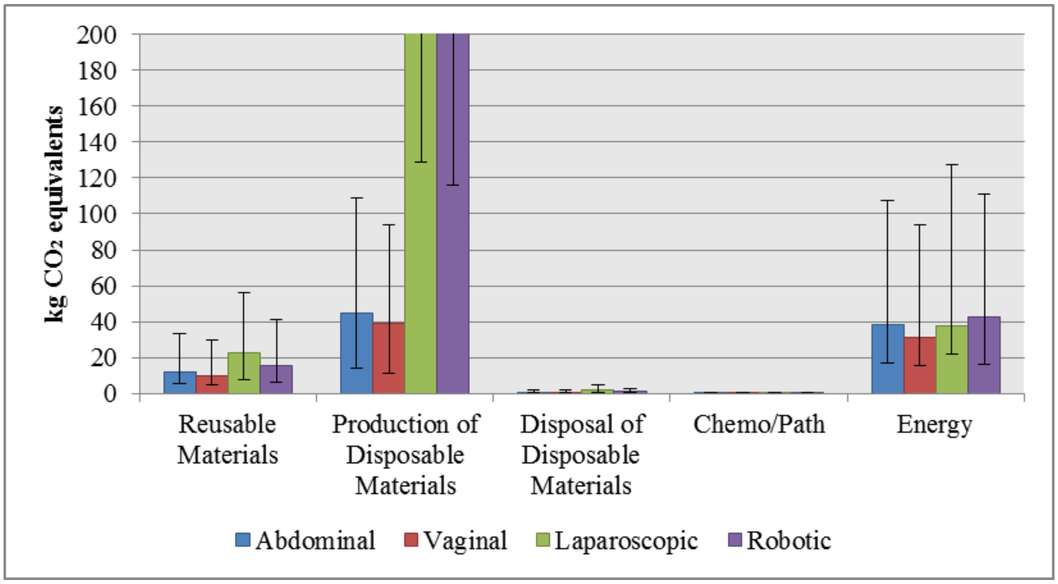


Figure 33: Range in Life Cycle Greenhouse Gas Emissions of Components of Four Types of Hysterectomies; Does not include recycling and laparoscopic and robotic results for 'production of disposable materials' category have been cut off to show detail. Cut-off values are 403 kg CO_2 equivalents for Laparoscopic Hysterectomy and 634 kg for Robotic Hysterectomy.

Looking at a different impact category, such as Eutrophication Potential shown in Figure 34, energy is shown with a narrower confidence interval, ranging only about 15% from the mean value. Impacts associated with the disposal of single-use materials and tools, as well as the production, sterilization, and disposal of reusable materials, have a much larger range of eutrophication potential. Whereas, the eutrophication potential of the chemo/pathogenic waste stream and energy use are negligible.

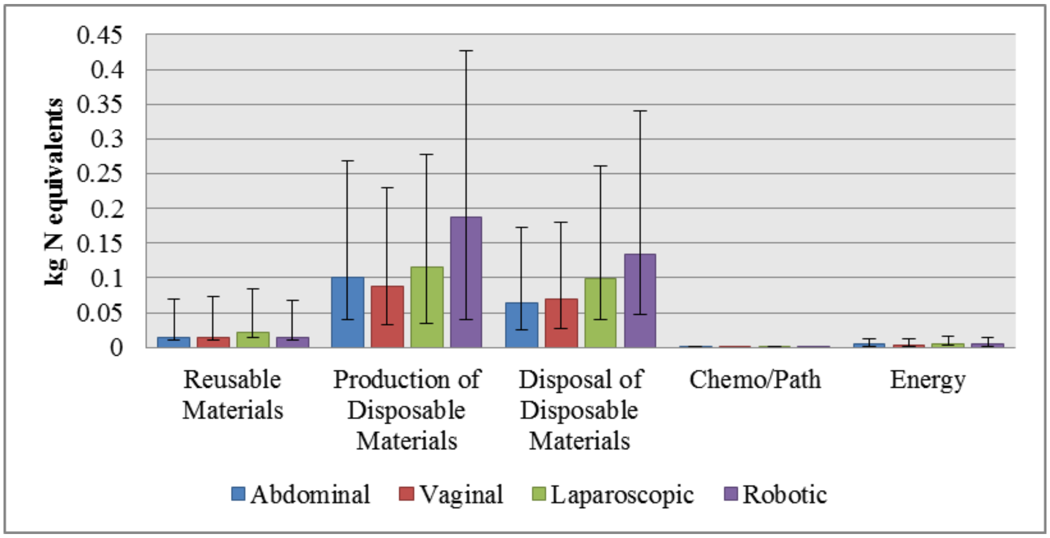


Figure 34: Range in Life Cycle Eutrophication Potential of Components of Four Types of Hysterectomies; Does not include recycling.

In the case of reusable materials, this confidence interval ranges from a quarter to three times the mean value. Variability in the reusable materials component of a hysterectomy life cycle is largely due to assumptions on life span. Life span of stainless steel surgical instrument trays was assumed to be normally distributed with a mean of 300 and a standard deviation of 150. A lower limit of 50 uses (representing the upper end of the impacts' confidence intervals) was established for the Monte Carlo Assessment. This is a very conservative estimate relative to past studies (Campion, Thiel et al. 2012; Ibbotson, Dettmer et al. 2013), but it follows the work of McGain, et al. (McGain, McAlister et al. 2012). For the purposes of the Monte Carlo, reusable linens were assumed to be reused 40 times with a standard deviation of 20 uses and a lower limit of 5 uses. This was based off of Magee's internal laundering estimates for linen lifespans.

Variation in the life cycle components for the remaining eight impact categories can be seen in Appendix B.3Monte Carlo Scripts for .

5.3.5 Recommended Improvements to Surgical Procedures

Assuming a mix of 40.1% abdominal, 19.8% vaginal, 30.5% laparoscopic and 9.5% robotic for all 600,000 annual hysterectomies performed in the US (Wright, Ananth et al. 2013), this study estimates **greenhouse gas emissions of hysterectomies alone at nearly 150,000 metric tons per year**. That is enough to fill about 97 US Steel Buildings in downtown Pittsburgh or approximately 383 Cathedrals of Learning on University of Pittsburgh campus. If not familiar with Pittsburgh, this is equivalent to nearly 75 Empire State Buildings. This is actually only 0.002% of the US's total GHG emissions in 2011 (US EPA 2013), yet hysterectomies are only one type of surgery. There are over 51.4 million inpatient procedures performed annually in the US (US CDC 2010). Some surgeries, such as orthopedic procedures or Coronary Artery Bypass Grafting, generate larger quantities of surgical waste than hysterectomies, which likely results in greater environmental impacts. Detailed life cycle assessments of hysterectomies can inform general changes within ORs and hospitals which can significantly improve environmental impacts at a larger scale.

The following two subsections highlight potential strategies to reduce impacts of hysterectomies and other surgical procedures in the OR. The first subsection addresses lighting, electricity use, and heating, ventilation and air conditioning systems, which have a larger impact on the hospital as a whole, rather than an individual surgery. The second subsection highlights the many ways of reducing impact related to material use. It is organized into the following categories: reducing excess, recycling and proper waste stream management, reprocessing and reuse, and purchasing and the production of the supply chain. A summary of the major energy and material concerns and potential improvement strategies are listed in Table 15.

Table 15: Components of a Hysterectomy which Contribute the Most to Environmental Impacts and Potential Impact Reduction Strategies, A = Abdominal, V = Vaginal, L = Laparoscopic, R = Robotic, all = All Hysterectomy Types

Issue	***Environmental Impact Categories***	***% of Total Impacts in Categories***	***Potential Reduction Strategies***
Production of Disposable Cotton	• Carcinogens, • Non-Carcinogens, • Ecotoxicity	25-60% (all)	• Reuse cotton, • Recycle cotton, • Use organic cotton, • Use other fibers
	All other categories analyzed	15-40% (A&V)	
Production of Disposable Surgical Instruments	• Ozone Depletion Potential, • Greenhouse Gas Emissions, • Acidification Potential, • Eutrophication, • Respiratory Impacts, • Cumulative Energy Demand	20-99% (L&R)	
Energy used to run HVAC (heating, ventilation, and air conditioning)	• Greenhouse Gas Emissions, • Smog Formation, • Acidification Potential, • Respiratory Impacts, • Cumulative Energy Demand	10-35% (A&V) 5-30% (L&R)	• Use more renewable energy sources • Regular maintenance of mechanical equipment, • Upgrade mechanical equipment and filters, • Reduce energy leaks in ducts and joints, • Reduced ventilation rates when OR not-in-use
Production of Disposable Gowns, Drapes, and BlueWrap (SMS-PP)	• Non-Carcinogens, • Ecotoxicity, • Cumulative Energy Demand	10-30% (all)	• Recycle the material, • Use reusable materials
Disposal of PP (polypropylene)	• Eutrophication	10-20% (all)	• Recycle the material, • use reusable materials

5.3.5.1 Energy Systems

Lighting and HVAC systems, which are based on the duration of a hysterectomy, make up nearly a third of the impacts in the categories of greenhouse gas emissions, smog formation and respiratory impacts. Improvements and upgrades to these energy and electricity systems would have larger impact on the hospital as a whole as opposed to an individual surgery, as these systems typically run 24 hours a day. A majority of the emissions associated with these categories are caused by the burning of fossil fuels. Therefore, reduction in emissions and environmental impacts can be best realized through changing those energy sources. While hospitals may not be capable of installing renewable energy sources on site, they can sometimes choose a “green” electricity supplier depending on the state, or they can work with their utility companies to purchase electricity from commercially produced renewable energy sources (USDOE 2013). Other methods to improve the environmental impacts related to HVAC include regular maintenance and monitoring of the air handling system, sealing and insulating ducts, and upgrading mechanical equipment and filters. ORs have tight air change and temperature conditions during use which result in higher proportional energy use in the OR than other hospital areas. Savings may be realized by relaxing HVAC performance requirements in the OR during off-hours for non-critical ORs (Taddonio 2011). This particular recommendation would not reduce the environmental impacts of a hysterectomy due to the LCA boundary conditions, but it would reduce impacts for the hospital as a whole.

5.3.5.2 Material Production, Use, and Disposal

The single use or disposable materials represent a majority of the impacts in every category analyzed in this study. The following outlines potential changes regarding single use materials which may significantly reduce environmental impacts of surgeries based on our study’s results.

It is organized into subcategories of reducing excess, recycling and proper waste stream management, reprocessing and reuse, purchasing and the production of the material supply chain.

Reduce Excess

More than simply making the current practice more efficient, one of the first steps to reducing the environmental impact of surgeries is to reduce the overall number of surgical interventions required. Previous studies estimate that many diagnostic tests and surgical procedures are unnecessary, which cost the US healthcare system $210 billion in 2009 and increases the resource burden of the healthcare industry (Young and Olsen 2010; Epstein and Hood 2011). Though not related directly to our research, it may be important to address the institutional systems in place which financially reward or litigiously protect medical professionals who conduct excessive, unnecessary, or “defensive” procedures (Mandell and Howell 2007; Yong, Olsen et al. 2010).

Additional focus on public health, preventive care, and personal behaviors can have a profound influence on the need for emergency interventions (Levi, Segal et al. 2013). Studies indicate that increased preventive care could save about $55 billion annually and that healthy lifestyle behaviors can decrease the need for surgical interventions, which reduces overall spending on healthcare (Fries, Koop et al. 1993; Akazawa, Stearns et al. 2008; Morey, Snyder et al. 2009; Maciosek, Coffield et al. 2010; Thorp, Owen et al. 2011). This will likely result in additional improvements to the environmental impacts associated with surgical care and modern living, as the suggested healthy lifestyle changes include increased physical activity (such as reduced use of vehicles, elevators, and other electrically-powered devices) and increased consumption of fresh, whole produce (such as local, organic, and unprocessed foods) (Goodpaster, DeLany et al. 2010; von Gruenigen, Frasure et al. 2012; Levi, Segal et al. 2013).

Surgeries will still be required, even if their overall numbers are reduced. Reducing unnecessary or unused materials can have significant savings related to the economic, environmental, and social sustainability of healthcare facilities. During waste audits, researchers found unused items- most commonly gloves- in the MSW. Many of these items are part of a “pack” or “kit” and when the pack is opened, even if for a single item, everything in the pack is considered unsterile and must be disposed. OR packs should be carefully formulated to help eliminate this type of resource and monetary waste (Kaplan, Sadler et al. 2012). The waste audits also revealed unused, unopened materials and instruments, such as the urinary drainage bag and laparoscopic lens defogging system (D-HELP) pictured in Figure 35, laparotomy pads, and table drapes. Preventing wastage of these materials may also relate to pack formulation or increased training for OR staff.

Figure 35: Examples of Unused, Unopened Items in Municipal Solid Waste of a Hysterectomy, Left: Urinary Drainage Bag, Right: *Defogging Heated Endoscopic Lens Protector* (D-HELP) System

Wastage is also an issue for drugs and other pharmaceuticals (Esaki, Macario et al. 2009; Chaudhary, Garg et al. 2012). Though not directly measured in this study, a number of bottles and IV bags found in MSW still contained fluids. Packaging such disposable items in smaller quantities or developing a different system of drug delivery could reduce unnecessary wastage, but there are concerns with drug safety and security and the availability of supplies in emergency situations.

Recycling and Proper Waste Stream Management

This study estimated the potential recyclability of various materials found in MSW for all hysterectomy procedures. If recycling in the OR were expanded to include a larger quantity of plastics, steel and aluminum pieces, paper, and glass vials, this research estimates recycling rates could be increased by 45 to 60%, reducing the total amount of MSW to one third of the current average quantity by weight. Such a reduction would decrease the greenhouse gas emissions from the production and disposal of materials used in hysterectomies by up to 25%.

Increased recycling rates are difficult to accomplish in the OR due to the additional time required to sort recyclable materials and the associated costs, but previous studies show that recycling initiative can improve a hospital's carbon footprint and spending (Lee, Ellenbecker et al. 2002; Gaiser, Cheek et al. 2004; McGain, Story et al. 2009; Riedel 2011; Grimmond and Reiner 2012). Recycling can be difficult to accomplish, as the recyclability of materials varies by municipality and contaminates (non-recyclable items) can threaten a recycler's willingness to accept materials from frequent violators. This study found materials which could not be recycled in the recycling waste stream of 13 out of the 61 audited procedures. It is anticipated that increased training and education would be required to help hospital staff quickly and properly identify and sort recyclable materials. In the long term, hospital purchasing staff and material manufacturers might consider utilizing entirely recyclable products or labeling recyclable products very clearly.

On the issue of waste stream management, this study found batteries in 75% of the laparoscopic and robotic cases' MSW. The batteries, usually size AA, were frequently removed from the *StrykeFlow 2* suction and irrigation system shown in Figure 36. However, the D-HELP laparoscopic lens defogger (Figure 35) also contained AA batteries which were discovered only during the controlled disassembly of complex materials. This device was frequently found in MSW during the hysterectomy waste audits, and the batteries would be difficult, if not impossible, to remove from the D-HELP in the OR following a surgery. Companies have removed the mercury from alkaline batteries, making them safe to dispose of in MSW streams, but the batteries still contain other heavy metals which are hazardous to human health (Panero, Romoli et al. 1995; Wagner, Toews et al. 2013). Lithium and lithium ion batteries require special disposal, and all batteries can be recycled (Bernardes, Espinosa et al. 2004). In 3 out of the 61 waste audits, researchers also discovered reusable stainless steel instruments in the MSW. Though accidentally discarded with OR table drapes, these clamps and cups represent a financial and environmental cost to the hospital.

Figure 36: Part of the *StrykeFlow 2* Suction and Irrigator System, Which Contains Eight (8) AA Batteries

Reprocessing and Reuse

Recycling in healthcare is not a closed-loop system. Not only do plastics and most other recycled materials degrade in quality with each cycle, recycled products do not find their way back into an OR in the same form in which they first entered (if they find their way back at all). For example, sharps in the OR may be sent to a recycling facility, but the plastics are used to create new sharps containers or non-medical devices, but never new sharps. Manufacturers of medical equipment have responded to concerns over hospital waste generation by developing an industry around medical device reprocessing. Reprocessing is the sterilization and reuse of single-use medical devices (SUDs). Many hospitals have begun contracting with reprocessing facilities to handle specific medical devices, which results in cost savings of up to 55% over purchasing the SUDs new (Alfa 2000; DiConsiglio 2008; Jacobs, Polisena et al. 2008; Polisena, Hailey et al. 2008). The US Food and Drug Administration permits reprocessing of about 70 devices and the industry has set up rigorous standards to ensure quality and safety (Barnett and Rios 2009; Kwakye, Pronovost et al. 2010; Collier 2011).

Reprocessing enables the reuse of certain medical devices, but SUDs can usually only be reprocessed about 5 times (SterilMed Inc. 2012). Truly reusable items- both surgical instruments and other materials- can drastically reduce cost and environmental impacts of the OR (Tieszen and Gruenberg 1992; Kocakulah, Maier-Lytle et al. 2001; Conrardy, Hillanbrand et al. 2010). Device manufacturers can design sturdier, reusable devices which could reduce the environmental impacts associated with instruments which are currently single use or reprocessed. Plastic gowns and drapes can be replaced by reusable linens, materials which were historically used in healthcare. Linens already used in the OR – such as blue towels and laparotomy pads- can be sterilized and reused in the OR rather than discarded in MSW or used as rags (Kümmerer, Dettenkofer et al. 1996). The allocated production impacts of these cotton products and other reusable instruments are halved with each reuse. Changing to reusable or even reprocessed tools and materials can be difficult. Physical space is required to sort and store materials, and often physicians and other staff must undergo behavioral and perception shifts to accommodate reusable materials.

Purchasing and Production of the Material Supply Chain

Impacts to the environment are more than just greenhouse gases and smog, and the effects of a hospital are more than just garbage out the loading dock and treated patients heading home. This study found that the production phase of a material's life cycle has the most significant negative impact on human health. Though these impacts may be directly tied to a separate industry, the healthcare industry's consumption of that resource drives the negative consequences, but it can also drive positive change through hospital's purchasing power (Kaiser, Eagan et al. 2001).

For example, traditional cotton growing practices release many known carcinogens and toxic chemicals into the soil, air, and water. Though a hospital consumes only a handful of towels and laparotomy pads in a single surgery in their OR (cotton products represent only 5-10% of MSW in hysterectomies), the continued production from virgin, traditionally-farmed cotton results in a quarter to half of the human health toxicity and ecotoxicity impacts in every type of hysterectomy as seen in Figure 37. This represents a great opportunity for hospitals to cut environmental impacts across their ORs by requesting organic cotton or another, more environmentally-preferable fiber such as hemp or bamboo, from their Group Purchasing Organization (GPO) or material suppliers.

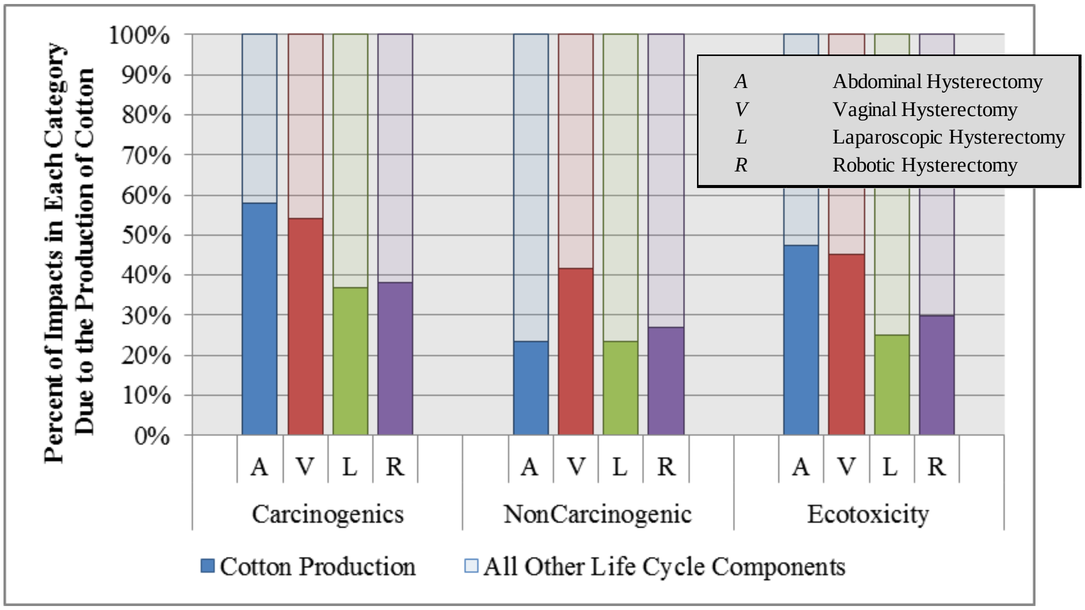


Figure 37: Toxicological Environmental Impacts due to the Production of Cotton Used in an Average Hysterectomy, as a Percent of the Total Life Cycle Impacts of Each Impact Category

It is not just cotton or toxicity concerns that should be addressed when talking about life cycle costs. Other aspects of upstream production can be changed through innovative design decisions such as eliminating the use of synthetic dyes in fabrics and plastics. Upstream production impacts are the major concern for fuel and energy use in hospital's HVAC systems, but that same fossil-based fuel mix is likely used to manufacture and deliver many of the products used within hospitals. There are many considerations and avenues to improve the life cycle impacts of hysterectomies and other surgeries. Life Cycle Assessment enables us to see the impacts of each component of surgery and target areas which have the most impact.

5.4 SUMMARY AND CONCLUSIONS

Primary contributors to the environmental impacts of hysterectomies are the production of disposable materials, their disposal, and the use of fossil-based fuels in providing electricity and energy for heating, ventilation, and air conditioning in the OR. Items accounting for the largest impacts in material production include cotton-based products such as towels and laparotomy pads and spunbound-meltblown-spunbound polypropylene materials such as gowns, drapes, and bluewrap. The disposal of polypropylene, which represents the most material by weight in all hysterectomies analyzed, accounts for the largest amount of impacts in the waste disposal category. In general, the more technologically advanced the surgical procedure, the larger its environmental impact. Environmental impacts of the four procedures overlap in the categories of smog formation, carcinogens, non-carcinogens, and ecotoxicity.

The field of healthcare sustainability is ready for more rigorous measurement of baseline environmental performance and scientifically-grounded guidance on improvement methods. This study identified those aspects of surgical procedures and operating rooms which create the largest environmental impacts. Many options exist for addressing and minimizing these impacts, but future studies are needed to inform other aspects of OR and hospital environmental performance and to assess the efficacy of impact reduction strategies. Within the whole healthcare industry, there is a profound opportunity to make healthcare services more efficient environmentally, economically, and socially. Quantification tools such as Life Cycle Assessment provide needed information about the source of environmental impacts and are a great asset in making significant strides towards a sustainable healthcare system.

6.0 CONCLUSIONS

This research focused on analyzing and improving the environmental and human health impacts associated with healthcare through assessment of the physical built environment of a hospital as well as the processes and procedures conducted within the building. This research was set to achieve the following research objectives:

1) Determine the effect of cohesive, green building hospital design on building performance, hospital employees, and patients through a comparative longitudinal assessment of an older, traditional hospital with its new, LEED-certified (Leadership in Energy and Environmental Design) replacement.
2) Develop and test a life cycle assessment (LCA) framework specific to hospitals using case study data collected from vaginal births done in labor and delivery rooms (LDR) and cesarean section births performed in operating rooms (OR).
3) Modify and apply the LCA framework to analyze the environmental impacts of common surgical procedures using four modes of hysterectomies- laparoscopic, robotic, vaginal, and abdominal- as the case study.
4) Identify advantages and limitations of the life cycle human health impact categories when applying LCA to healthcare.

To accomplish these objectives, several study projects were completed involving the application of certain engineering and analytical methods, such as comparative longitudinal assessment, life cycle assessment, and Monte Carlo assessment, to the healthcare industry.

The results of this research advance our understanding of green building performance and enhance existing literature on evidence-based design. Additionally, this work represents the first application of full LCA to surgical operations, beyond carbon footprinting or individual material analysis. This work, therefore, introduces a scientific analytical framework to healthcare professionals as a means of monitoring environmental baseline and the efficacy of policy and programmatic changes. The work has been presented at a variety of engineering and healthcare-related conferences around the United States and abroad. Elements of this research have been incorporated into nurse training at the Community College of Allegheny County, undergraduate and graduate coursework at the University of Pittsburgh and Arizona State University, and public community-lectures and programs at Magee-Womens Hospital of UPMC.

6.1 SUMMARY

These novel applications of engineering and analytical tools allowed new assessments of efficiency in hospitals, specifically related to environmental performance. The results point to the usefulness of these assessment methods in guiding and more-efficiently increasing the environmental, economic, and social sustainability of healthcare – from building design decisions to which materials are purchased for use in a surgery. As the healthcare industry looks toward reducing costs and increasing the overall health of their patients, this data is necessary to inform environmentally-focused design, managerial, and procedural changes. Current results suggest that green building design principles, combined with organizational and cultural changes, have favorable effect on energy intensity, employee satisfaction, and patient outcomes. Hospitals seeking to increase the environmental sustainability of their operating rooms should focus on reducing the upstream impacts from single-use, disposable items and energy consumption due to heating, ventilation, and air conditioning in the OR. Updates and improvements in fields related to life cycle assessment and additional analytical sustainability assessment tools should be incorporated into healthcare assessment to help inform and improve healthcare sustainability.

6.1.1 Evidence-Based Design: Green Hospital Performance

A comparative longitudinal assessment analyzed over seven years of data on hospital building performance, employee satisfaction, and patient outcomes from Children's Hospital's older, traditionally-constructed hospital and its new, LEED-certified replacement. This project sought to answer the following questions in conjunction with research Objective 1:

- How does sustainable hospital design affect hospital performance?
- How can hospital performance metrics help determine the effects of sustainability initiatives within hospitals?

Following the move into the new, green facility, Children's significantly improved their productivity, quality of care, and staff satisfaction. The utility use per square foot dropped over 50% for electricity, heating energy, water, and sewer, while Children's expenses per patient in bed remained stable. This may be due in part to green building design; however, the length of this study limited the ability to separate the impacts of green building design from the effects of managerial and programmatic changes to the hospital. The relative effect of behavioral and organizational changes, cohesive whole-building construction, or green building design decisions is unknown, but there may also be a reinforcing symbiosis between the three elements in regards to improved employee performance and patient outcomes.

6.1.2 Life Cycle Assessment: Healthcare Framework and Effects of Medical Procedures

A life cycle assessment framework was developed, tested, and utilized to analyze the environmental effects of hospital procedures and surgeries. These projects aimed to achieve research Objectives 2 and 3 by answering the following questions:

- How can LCA determine environmental sustainability of the healthcare industry?
- What aspects of hospital operating procedures contribute the most to a procedure's environmental impacts?

A process life cycle assessment framework was developed and tested for use in hospital operations and medical procedures. A case study compared environmental impacts from vaginal births conducted in labor and delivery rooms (LDR) and cesarean section births performed in operating rooms (OR). For all births, the processes contributing the most to environmental impacts were energy consumption due to heating, ventilation, and air conditioning; the end of life impacts of the disposable custom packs; and the production of the disposable custom packs. 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 (Campion, Thiel et al. 2012). 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.

The LCA framework was modified to include of Economic Input-Output LCA data, and the new hybrid LCA model analyzed the environmental impacts of common surgical procedures using four modes of hysterectomies- laparoscopic, robotic, vaginal, and abdominal- as the case study. Primary contributors to the environmental impacts of hysterectomies are the production of disposable materials, their disposal, and the use of fossil-based fuels in providing electricity and energy for HVAC in the OR. Items accounting for the largest impacts in material production include single-use, cotton-based products such as towels and laparotomy pads and single-use, spunbound-meltblown-spunbound polypropylene materials such as gowns, drapes, and bluewrap. The disposal of polypropylene, which represents 22-35% by weight of the municipal solid waste in all hysterectomies analyzed, accounts for the largest amount of impacts in the waste disposal category.

The field of healthcare sustainability is ready for more rigorous measurement of baseline environmental performance and scientifically-grounded guidance on improvement methods. The studies in Chapters 4.0 and 5.0 identified those aspects of surgical procedures and operating rooms which create the largest environmental impacts. For hospitals aiming to become more environmentally efficient or sustainable, these parts of surgery may represent the most cost- or time-effective focal points. Within the entire industry, there is a profound opportunity to make healthcare services more efficient environmentally, economically, and socially. Quantification tools such as life cycle assessment provide needed information about the source of environmental impacts and are a great asset in making significant strides towards a sustainable healthcare system.

6.1.3 Life Cycle Impact Assessment Methodology: Human Health Effects

Research Objective 4 was achieved through an extensive review of life cycle impact assessment methodology, which addressed the following research question:

- What are the advantages and limitations of life cycle impact categories such as human health when applying LCA to healthcare issues?

The accuracy of current LCIA methodology of human health impact categories are still debated today, and their resultant units are not easy to translate into practical application, especially when reporting to medical professionals (Thiel, Campion et al. 2012). Correlation exists between the various emissions at each stage of a product's life cycle and the emissions' effects on human health, morbidity, and mortality. However, actual effects vary based upon exposure pathway, duration, and biological factors, thus limiting the accuracy of causal statements.

Toxicology and risk management, the basis for most LCIA methods, link emissions and human health effects, but use data from animal testing which results in large ranges of uncertainty. Life cycle assessment collapses results across a product's life cycle into a single location and time, and do not usually account for background or existing chemicals or toxins. Some researchers have suggested more meaningful units related the potential reversibility of human health toxicity impacts, but this requires more detailed chemical information from the field of toxicology. Improvements to the fields supporting toxicology and risk assessment, such as epidemiology and clinical studies, will lead to improvements in life cycle assessment, though the static nature of LCA requires incremental updates to LCI databases and LCIA methodology as external data become better.

6.2 RECOMMENDATIONS FOR FUTURE WORK

Healthcare has been working to improve their environmental sustainability for some time, but is just now beginning to embrace and utilize rigorous scientific assessment and hard data in order to identify and alter major sources of environmental impact. Evidence-based design, life cycle assessment, and other sustainability engineering methods and tools will continue to be an important part of increasing sustainability of ORs and hospitals.

6.2.1 Continued Evaluation of Green Hospital Design and Design Decisions

For future studies related to the impact of green design, researchers recommend the additional analysis of data such as employee and patient surveys or focus groups to better understand the perceived and psycho-social impacts of the structure's design, as well as additional modeling which might better predict the relative importance of managerial, policy, and green building design changes. Increased literature related to the impacts of holistic healthcare design might also aid in determining the relative impacts of procedural or staffing changes or green design decisions. Comparative assessments might be conducted on new traditional hospitals versus green hospitals, or, perhaps more feasibly, new green hospital wings compared to older wings performing the same function within the same hospital, in order to normalize the effects of cultural changes on the two study groups. The research team intends to conduct such a study on a traditional and new, green wing at Magee-Womens Hospital.

Related to environmental performance, hospital design may be further studied for its role in establishing the environmental impacts of the hospital's use phase. For example, design features such as operable windows may assist not only in comfort and recovery time of patients but also in building resilience to climate change or severe weather events (Schweitzer, Gilpin et al. 2004; Shin 2004; Lomas and Ji 2009; Lomas and Giridharan 2012). Many hospitals worldwide – most notably in the United Kingdom – effectively and safely utilize natural ventilation, reducing their energy consumption (Lukiantchuki, Matsumoto et al. 2010; Qian, Li et al. 2010; Adamu, Price et al. 2012; Baillie 2012; Gong, Zhou et al. 2012; Taylor and Menassa 2012; Menassa, Taylor et al. 2013). Reductions to energy consumption and associated environmental impacts are often limited to the design and layout of the structure. As such, analyzing the effects of such features before they are built may play a critical role in minimizing environmental impacts of the building's use phase.

6.2.2 Development of Life Cycle Assessment in the Field of Healthcare

To improve future LCAs of surgeries, information should be included on the environmental effects of pharmaceuticals, anesthesia, and cleaning products. Currently, life cycle inventory data on most of these materials is not available, though work is being done specifically on anesthetic gases. This study may also benefit from the inclusion of detailed information on laundering and sterilization processes (rather than estimates), high-tech disposable devices (rather than cost data), and surgical equipment (which was excluded from the studies reported here). These additions require data and the participation of medical device manufacturers and laundering facilities.

The research team established partnerships to analyze and incorporate the global warming potential of anesthetic gases from our cases into the overall results of the hysterectomy LCA. This will allow us to see the relative impacts of anesthetic gases compared to other materials and energy used to conduct various types of hysterectomy. Researchers at the University of Pittsburgh and Magee-Womens Hospital have also begun LCAs of custom birth packs from US hospitals and international hospitals in order to compare the range of materials and environmental impacts associated with a variety of custom birth packs. Additionally, in partnership with Northeastern University and Arizona State University, the University of Pittsburgh sustainability team intends to analyze the impacts of larger medical equipment and continue exploring the life cycle decisions of disposable vs. reusable medical materials.

Life cycle assessment and other sustainability engineering methods and tools will continue to be an important part of increasing sustainability of ORs and hospitals. Orthopedic surgery, with the variety of medical prostheses and the required ultra-sterilization of medical implants, would prove an interesting operation to analyze (Pavlou, Gardiner et al. 2010; Stall, Kagoma et al. 2013). Comparative assessments of other departments within a hospital, as well as other concerns such as employee and patient commuting and food sourcing and consumption, would also help determine critical contributors to the environmental sustainability of hospitals.

Technological advances in the field of medicine represent a large opportunity to analyze, compare, and improve environmental outcomes for the future of healthcare. New medical tools and machines, such as the Stryker *Neptune*, change the dynamic of hospital safety and waste streams. The *Neptune* Waste Management System is a suction devise used to remove fluids and smoke during surgeries in the operating room. The device, despite recent patient safety concerns, allows safe removal of hazardous bodily fluids and smoke by minimizing hospital staff exposure and handling (USFDA 2013). Fluid and gaseous wastes are then flushed directly into the hospital's waste water. In Pittsburgh and other cities in the US with combined sewer systems, this represents a potential health hazard during rain-related sewage overflow events, and it also calls to question waste water treatment plant's ability to safely handle the new influx of biological agents and pharmaceuticals (Kümmerer 2001). As new technologies such as the *Neptune* are developed, life cycle environmental impacts should be calculated and assessed.

Increasing the research and data in supporting fields of study would greatly aid sustainability assessment and help improve environmental efficiencies in healthcare facilities. Life cycle impact assessment would improve with more detailed and more complete data on chemical impacts to human health. This requires increased research in the fields of toxicology, epidemiology, and clinical studies.

6.2.3 Beyond Life Cycle Assessment: Utilizing Other Analytical Tools and Other Aspects of Healthcare Sustainability Research

Moving beyond LCA and analyzing healthcare sustainability holistically, other tools of Industrial Ecology enable integration of hospital material flows and waste streams into the surrounding community network. Materials flow analysis of healthcare facilities would help identify safe waste streams which could serve as inputs to other industrial networks, increasing the sustainability of the entire urban fabric by creating cyclical systems of material use.

Other areas of healthcare, such as hospital sterilization and cleaning, may require further study beyond LCA. Exposure to toxic cleaning chemicals can lead to negative health impacts for hospital staff and patients, yet proper sterilization is necessary to prevent nosocomial infections (Weinhold 2001; Lehman 2003; Bello, Quinn et al. 2009). Some studies suggest that biological alternatives to harsh chemicals and antibacterial agents, such as “probiotics” or “good bacteria,” may reduce the ability of infectious pathogens to colonize hospital surfaces and may even be necessary as more bacterial strains become resistant to antibiotics (Falagas and Makris 2009; Hookman and Barkin 2009; Cristina, Spagnolo et al. 2012). The efficacy, human health effect, and environmental impact of current hospital sterilization and cleaning techniques, and their future alternatives, should be further studied.

Another issue which requires more sound data is the designation and proper treatment of infectious wastes. Hospital waste streams have been regulated since the 1988 Medical Waste Tracking Act, a federal policy written in response to medical waste washed up on New Jersey shorelines (United States Environmental Protection Agency 1988). Yet despite federal, state, and local regulations regarding medical waste, the actual definition of infectious waste or regulated medical waste is liable to wide interpretation. Over the course of this research, medical personnel expressed a wide range of definitions of infectious waste - from “anything with a drop of blood on it,” to “if blood can be wrung out of it.”

In Pennsylvania state code, infectious waste is defined as “items saturated or dripping with human blood,” “items that were saturated or dripping with human blood that are now caked with dried human blood.,” and “items saturated or dripping with body fluids or caked with dried body fluids from persons during surgery.. or other medical procedures” (Commonwealth of Pennsylvania 2001). Interpretation of this definition and the word “saturated” has a profound impact on the quantity of regulated medical waste generated (and thus treatment required) as well as the potential recyclability of general medical wastes. In 1988, the General Assembly of the Commonwealth of Pennsylvania determined “that infectious and chemotherapeutic wastes by their very nature cannot be recycled” (Casey 1988).

Another aspect of infectious waste regulation is the seeming dichotomy between healthcare institutions and other commercial facilities or households. While government regulators and other organizations produce recommendations for proper domestic disposal of needles or “sharps,” there are no recommendations for proper disposal of “items saturated with human blood” produced in a domestic or commercial setting; for example, a female restroom. This may give rise to the question and further research of what actually constitutes infectious waste and whether our current regulatory structure unfairly burdens healthcare facilities due to perceptions of health risk of their waste, or whether we are subjecting waste management employees and others who may encounter domestic waste to increased infectious risk due to improper regulation and handling of household wastes.

APPENDIX A

STATISTICAL ANALYSIS OF HOSPITAL GREEN BUILDING PERFORMANCE METRICS

Appendix A contains supporting data and information related to Chapter 3.0 Effects of Holistic, Green Design on Performance of Hospital Facility.

Table 16: Children's Hospital Study Pre-Move and Post-Move Structure and Departmental Equivalent Spaces (Square Feet)

	Pre-Move	Pre-Move	Pre-Move	Post-Move	Post-Move	Post-Move	Post-Move	Post-Move	
Name of Department	**Main**	**DeSoto**	**TOTAL (Study)**	**Hospital**	**AOB**	**Central Plant**	**Faculty Pavilion**	**TOTAL (Study)**	**% Diff. (pre to post)**
EMPLOYEE BENEFITS	-	294	294	-	9,900	-	-	9,900	3267%
NON - PATIENT TELEPHONE	1,090	1,761	2,851	1,045	-	-	-	1,045	-63%
DATA PROCESSING	2,450	-	2,450	10,818	13,525	-	2,200	26,543	983%
ADMITTING	776	-	776	-	-	-	-	-	-100%
CASHIERING & A/R	543	-	543	-	-	-	-	-	-100%
ADMIN. & GENERAL - ALL	3,216	27,042	30,258	130,720	10,070	-	60,289	201,079	565%
ADMIN & GENERAL - NON RSRCH	260	5,600	5,860	4,566	3,800	-	-	8,366	43%
OPERATION OF PLANT	35,041	27,039	62,080	218,722	4,797	46,390	19,060	288,969	365%
HOUSEKEEPING	2,508	6,133	8,641	6,297	724	-	-	7,021	-19%
DIETARY	-	-	-	26,073	-	-	5,598	31,671	-
NURSING ADMIN	-	-	-	6,894	-	-	-	6,894	-
CENTRAL STERILE & SUPPLY	-	3,034	3,034	50,998	-	-	-	50,998	1581%
PHARMACY	3,364	464	3,828	8,514	-	-	-	8,514	122%
MEDICAL RECORDS & LIBRARY	-	6,537	6,537	5,568	-	-	-	5,568	-15%
CHILD LIFE	1,292	-	1,292	3,255	-	-	-	3,255	152%
BIO-MED ELECTRONICS	-	-	-	6,071	-	-	-	6,071	-
SOCIAL SERVICE	606	-	606	-	-	-	-	-	-100%
INTERN & RESIDENT OTHER	392	2,106	2,498	-	-	-	55,743	55,743	2132%
GENERAL ROUTINE CARE	52,618	25,490	78,108	214,725	-	-	-	214,725	175%
INTENSIVE CARE UNIT	12,839	-	12,839	48,691	-	-	-	48,691	279%
CORONARY INTENSIVE CARE	3,082	-	3,082	12,604	-	-	-	12,604	309%
NICU/RCU	5,289		5,289	24,588	-	-	-	24,588	365%
OPERATING ROOM	9,474	15,101	24,575	65,167	-	-	-	65,167	165%
RECOVERY ROOM	-	1,736	1,736	13,109	-	-	-	13,109	655%
ANESTHESIOLOGY	210	3,946	4,156	7,243	-	-	-	7,243	74%
RADIOLOGY - DIAGNOSTIC	8,828	835	9,663	69,801	-	-	-	69,801	622%
LABORATORY	184	11,278	11,462	34,933	-	-	-	34,933	205%
GASTROENTEROLOGY	774	7,052	7,826	-	-	-	-	-	-
BLOOD STORING AND PROC.	316	-	316	3,185	-	-	-	3,185	908%
AUDIOLOGY	-	4,620	4,620	-	-	-	2,025	2,025	-56%

Table 16 (continued)

RESPIRATORY THERAPY	885	1,746	2,631	4,203	-	-	-	4,203	60%
PHYSICAL THERAPY	-	5,015	5,015	5,191	-	-	-	5,191	4%
OCCUPATIONAL THERAPY	-	-	-	5,191	-	-	-	5,191	-
EKG	11,425	561	11,986	36,149	-	-	-	36,149	202%
EEG	-	2,720	2,720	9,868	-	-	-	9,868	263%
UROLOGY	-	1,071	1,071	6,726	-	-	-	6,726	528%
RENAL DIALYSIS	-	730	730	3,103	-	-	-	3,103	325%
ALLERGY/INFECTIOUS DISEASE	-	367	367					-	-100%
DENTAL	-	2,519	2,519	6,440	-	-	3,122	9,562	280%
SHORT STAY	-	7,218	7,218	13,399	-	-	-	13,399	86%
PULMONARY FUNCTION	5,440	122	5,562	4,002	-	-	-	4,002	-28%
TRANSPLANT PROCUREMENT	1,911	503	2,414	-	-	-	-	-	-100%
CHILD DEVELOPMENT	-	300	300	-	-	-	-	-	-100%
BONE MARROW	4,814	-	4,814	2,298	-	-	-	2,298	-52%
NEUROPHYSIOLOGY	957	-	957	-	-	-	-	-	-100%
HEMATOLOGY/ ONCOLOGY	-	9,423	9,423	-	-	-	-	-	-100%
CLINIC	6,676	13,848	20,524	22,309	-	-	-	22,309	9%
EMERGENCY	2,487	14,339	16,826	58,213	10,799	-	-	69,012	310%
AMBULANCE SERVICES	4,099	-	4,099	14,726	-	-	-	14,726	259%
DEVELOPMENT/ MARKETING	-	-	-	-	351	-	-	351	-
RESEARCH-GCRC	1,217	-	1,217	6,353	-	-	-	6,353	422%
OTHER HOSPITAL ACTIVITIES	-	-	-	2,137	-	-	6,209	8,346	-
OTHER			-	29,994	21,038	-	-	51,032	-
GRAND TOTAL	185,063	210,550	395,613	1,203,889	75,004	46,390	154,246	1,479,529	274%

Table 17: Significance and Percent Change in Children's Hospital Quality Indicators and Metrics Between the Old Facility and the New, LEED-certified Facility Based on 2 Sample T-Test or Mann Whitney Test;

ns = not significant, 2SplT = 2 Sample T-Test which compares population means, MW = Mann Whitney which compares population medians, USD = United States Dollar, PIB = patient in bed, RN = registered nurse, PCT = patient care technician, LOS = length of stay, ADE = adverse drug event, FTE = full time employee, SF = square foot, HDD = heating degree day, CDD = cooling degree day

Category of Indicator	Metric Name	Frequency	Pre-Move Count	Post-Move Count	Percent Change	Test Used	P-val
Expense	Salaries and Wages	monthly	22	26	9%	MW	<.001
	Purchased Personnel Expenses – RN	monthly	22	26	-70%	MW	0.008
	Purchased Personnel Expenses - Sitters	monthly	22	26	-56%	MW	<.001
	Total Labor Expenses per PIB	monthly	22	26	ns	2splT	0.100
	Medical / Surgical Supply Expense per PIB	monthly	22	26	ns	2splT	0.323
	Total Operating Expenses by PIB	monthly	22	26	ns	2splT	0.062
	Salaries and Wages (2009USD)	monthly	22	26	7%	MW	<.001
	Purchased Personnel - RN (2009USD)	monthly	22	26	-71%	MW	0.007
	Purchased Personnel - Sitters (2009USD)	monthly	22	26	-57%	MW	<.001
	Total Labor Expenses per PIB (2009USD)	monthly	22	26	ns	2splT	0.970
	Medical / Surgical Supply Expense per PIB (2009USD)	monthly	22	26	ns	2splT	0.802
	Total Operating Expenses by PIB (2009USD)	monthly	22	26	ns	2splT	0.995

Table 17 (continued)

Productivity	Regular Hours (all staff)	monthly	22	26	11%	2splT	<.001
	Overtime Hours (all staff)	monthly	22	26	ns	2splT	0.280
	Staff Regular Direct Care Hours	monthly	22	26	10%	2splT	<.001
	Purchased Personnel Nursing Hours (direct)	monthly	22	26	-100%	MW	0.003
	Purchased Personnel Sitter Hours	monthly	22	26	-61%	MW	0.003
	Overtime Hours (Direct)	monthly	22	26	ns	2splT	0.306
	Total Direct Care Hours per PIB	monthly	22	26	4%	2splT	0.010
	Total Direct Care Productive Hours per PIB	monthly	22	26	6%	2splT	<.001
	Total Direct Care Hours Required	monthly	22	26	ns	MW	0.268
	RN Productivity	monthly	22	26	ns	2splT	0.508
	PCT Productivity	monthly	22	26	-7%	2splT	0.001
	Total Direct Care Productivity	monthly	22	26	ns	2splT	0.081
	Total Paid Hours per PIB	monthly	22	26	6%	2splT	0.007
	Percent of Direct Care Total Nonproductive Hours	monthly	22	26	ns	MW	0.145
	RN Percent of Direct Care Staff	monthly	22	26	ns	2splT	0.310
Quality of Care	Average LOS (inpatient days)	monthly	22	26	4%	2splT	0.004
	Doses Dispensed per Hour	monthly	46	35	ns	MW	0.067
	Medication Events/1000 Doses dispensed Reached Patient	monthly	47	41	ns	MW	0.094
	ADE/1000 Doses dispensed Near Miss	quarterly	7	3	ns	MW	0.820
	ADE/1000 Doses dispensed Reached Pt, no harm	quarterly	7	3	ns	MW	0.255
	ADE/1000 Doses dispensed Harm	quarterly	7	3	ns	MW	0.820
	NonADE/1000 Doses dispensed Near Miss	quarterly	7	3	ns	MW	0.172
	NonADE/1000 Doses dispensed Reached Pt, no harm	quarterly	7	3	ns	MW	0.362
	NonADE/1000 Doses dispensed Harm	quarterly	7	3	ns	MW	0.494

Table 17 (continued)

Quality of Care	# Order/MAR Corrections/1000 Doses Dispensed	quarterly	6	3	-49%	MW	0.028
	# Significant Prescribing Errors/1000 Doses Dispensed	quarterly	6	3	ns	MW	0.197
	Infection Rate: #BSIs/1000line days	monthly	52	40	-70%	MW	<.001
	Case Mix Index (Various versions)	quarterly	27	11	ns	2splT	0.557
	Number of Cases (Mortality)	quarterly	21	11	ns	MW	0.634
	Actual Mortalities	quarterly	21	11	-19%	2splT	0.005
	Expected Mortalities	quarterly	21	11	11%	2splT	0.007
	Mortality Rate	quarterly	21	11	ns	2splT	0.068
	Mortality Index	quarterly	21	11	-28%	2splT	<.001
Staff Satisfaction	Tenure - Total Employees	monthly	16	14	5%	MW	0.004
	Tenure - less 1 Year	monthly	16	14	-8%	MW	0.003
	Tenure - 1 - 1.9 Years	monthly	16	14	ns	MW	0.693
	Tenure - 2 - 4.9 Years	monthly	16	14	19%	2splT	<.001
	Tenure - 5 - 9.9 Years	monthly	16	14	ns	MW	0.198
	Tenure - 10 - 14.9 Years	monthly	16	14	13%	MW	0.001
	Tenure - 15+ Years	monthly	16	14	ns	MW	0.085
	Time to Fill	monthly	18	13	-28%	2splT	0.001
	Turnover - Number of Employees	monthly	17	7	-25%	MW	0.031
	Turnover - Years of Service	monthly	17	7	ns	MW	0.657
	Vacancy - Number of Openings	monthly	19	12	-36%	2splT	<.001
	Vacancy - Ave Position Age (days)	monthly	19	12	-30%	2splT	<.001
	Admissions	monthly	22	26	ns	2splT	0.541
	Total Patients in a Bed	monthly	22	26	5%	2splT	0.027
	Average Daily Census	monthly	22	26	5%	2splT	0.030
	Vacant RN FTEs	monthly	22	26	-61%	MW	<.001
	Vacancy Rate RN	monthly	22	26	-62%	MW	<.001
	Turnover Rate RN	monthly	22	26	ns	MW	0.679
	HR Turnover Rate RN	monthly	22	26	-43%	MW	0.001
	RN Reassigned Hours	monthly	22	26	-100%	MW	<.001

Table 17 (continued)

Utilities	Gas/Steam (kBtu) - raw	monthly	9	31	86%	MW	<.001
	Gas/Steam (kBtu) - per SF	monthly	9	31	-50%	MW	<.001
	Gas/Steam - normalized to HDD	monthly	9	31	ns	MW	0.184
	Gas/Steam - normalized to CDD	monthly	7	22	ns	MW	0.373
	Gas/Steam - normalized to beds (old)	monthly	7	26	25%	MW	0.041
	Electric (kWh) - raw	monthly	12	31	71%	2splT	<.001
	Electric (kWh) - per SF	monthly	12	31	-54%	2splT	<.001
	Electric - normalized to HDD	monthly	12	31	ns	MW	0.228
	Electric - normalized to CDD	monthly	10	22	ns	MW	0.887
	Electric - normalized to beds (old)	monthly	12	26	52%	MW	<.001
	Water (kgal) - per SF	monthly	12	36	-64%	MW	<.001
	Water (kgal) - raw	monthly	12	36	35%	MW	0.003
	Sewage ($) - per SF	monthly	12	36	-77%	MW	<.001
	Sewage ($) - raw	monthly	12	36	ns	MW	0.131

Comparative Longitudinal Assessment Hospital Metric Definitions in alphabetical order

- # Order/MAR Corrections/1000 Doses Dispensed — Number of corrections to the Medical Administration Record per 1000 doses dispensed, averaged over one year
- # Significant Prescribing Errors/1000 Doses Dispensed — Number of errors in prescriptions per 1000 doses dispensed, averaged over one year. Hospitals strive for 0%
- Actual Mortalities — Number of patient deaths in a three month (quarter) period
- Adverse Drug Event (ADE)/1000 Doses dispensed Harm — Ratio of unintended physical injuries due to a preventable drug-related error in medical care that required additional monitoring, treatment or hospitalization relative to 1000 doses dispensed, averaged over one year
- Adverse Drug Event (ADE)/1000 Doses dispensed Near Miss — Ratio of preventable drug-related errors in medical care which did not reach the patient relative to 1000 doses dispensed, averaged over one year

• Adverse Drug Event (ADE)/1000 Doses dispensed Reached Pt, no harm	Ratio of preventable drug-related errors in medical care which reached the patient and required monitoring or intervention to confirm that it resulted in no harm to the patient relative to 1000 doses dispensed, averaged over one year
• Admissions	Number of patients admitted to Children's during one month
• Average Daily Census	Monthly average of the number of patients admitted to and staying at Children's in a 24 hour period
• Average Length of Stay (inpatient days)	Sum of days a person stays at the hospital (date of discharge minus the admission date) divided by the number of admissions in that month
• Case Mix Index (Various versions)	A measure of the types of cases handled in a given hospital for Medicare reporting requirements, calculated by multiplying the number of cases in a specific Diagnosis Related Group by that DRG's relative weight and dividing by the total number of DRGs during one quarter (three months)
• Doses Dispensed per Hour	Average hourly quantity of medicine dispensed from the pharmacy on a monthly basis
• Electric - normalized to beds (old)	Quantity of electricity utilized at Children's in a one month period (normalized per number of patient beds)
• Electric - normalized to CDD	Quantity of electricity utilized at Children's in a one month period (normalized per cooling degree day)
• Electric - normalized to HDD	Quantity of electricity utilized at Children's in a one month period (normalized per heating degree day)
• Electric (kWh) - per SF	Quantity of electricity utilized at Children's in a one month period (normalized per square foot of hospital floor area)
• Electric (kWh) - raw	Quantity of electricity utilized at Children's in a one month period
• Expected Mortalities	Number of expected patient deaths based on patient's condition upon admission to hospital in a three month (quarter) period
• Gas/Steam - normalized to beds (old)	Quantity of energy utilized for heating at Children's in a one month period (normalized per number of patient beds)
• Gas/Steam - normalized to CDD	Quantity of energy utilized for heating at Children's in a one month period (normalized per cooling degree day)
• Gas/Steam - normalized to HDD	Quantity of energy utilized for heating at Children's in a one month period (normalized per heating degree day)

• Gas/Steam (kBtu) - per SF	Quantity of energy utilized for heating at Children's in a one month period (normalized per square foot of hospital floor area)
• Gas/Steam (kBtu) - raw	Quantity of energy utilized for heating at Children's in a one month period
• Human Resources Turnover Rate RN	Number of registered nurses leaving their positions at Children's relative to total number of RN positions in a one month period
• Infection Rate: #BSIs/1000line days	Number of cases of blood stream infections as a fraction of total number of patients with intravenous lines each day averaged over a one month period
• Medical / Surgical Supply Expense per PIB (2009USD)	Average cost of medical and surgical supplies in a month-long period based on the number of patients served during that month (normalized to the 2009 US dollar)
• Medication Events/1000 Doses dispensed Reached Patient	Number of dispensing errors as a percentage of total prescriptions dispensed at the hospital pharmacy in a one month period
• Mortality Index	Actual mortality divided by the expected mortality in a three month period. Hospitals strive for a value less than one.
• Mortality Rate	Number of patient deaths relative to total patients admitted in a three month (quarter) period
• Non-Adverse Drug Event (ADE)/1000 Doses dispensed Harm	Ratio of unintended physical injuries due to a non-preventable drug-related error in medical care that required additional monitoring, treatment or hospitalization relative to 1000 doses dispensed, averaged over one year
• Non-Adverse Drug Event (ADE)/1000 Doses dispensed Near Miss	Ratio of non-preventable drug-related errors in medical care which did not reach the patient relative to 1000 doses dispensed, averaged over one year
• Non-Adverse Drug Event (ADE)/1000 Doses dispensed Reached Pt, no harm	Ratio of non-preventable drug-related errors in medical care which reached the patient and required monitoring or intervention to confirm that it resulted in no harm to the patient relative to 1000 doses dispensed, averaged over one year
• Number of Cases (Mortality)	Number of patient mortalities in a three month (quarter) period
• Overtime Hours (Direct)	Number of hours worked beyond regular hours in a month

• Overtime Hours (all staff)	Number of hours worked beyond regular hours in a month
• Patient Care Technician (PCT) Productivity	Number of PCT hours required to provide care (based on patient acuity and workload data) divided by the number of hours provided in a month long period. Hospitals strive for a value near 100%.
• Patient in Bed (PIB)	See 'Total Patients in a Bed'
• Percent of Direct Care Total Nonproductive Hours	Percent of staff nonproductive hours (paid hours such as sick leave, holidays, and vacations) to direct care hours
• Purchased Personnel Expenses - RN (2009USD)	Total wages and salaries of Children's temporary registered nursing personnel in a month-long period (normalized to the 2009 US dollar)
• Purchased Personnel Expenses - Sitters (2009USD)	Total wages and salaries of Children's temporary baby sitters in a month-long period (normalized to the 2009 US dollar)
• Purchased Personnel Nursing Hours (direct)	Total hours of temporary registered nursing personnel in a month-long period (absolute)
• Purchased Personnel Sitter Hours	Total hours of temporary baby sitters in a month-long period
• Regular Hours (all staff)	Total hours of all Children's regular staff in a month
• RN Percent of Direct Care Staff	Number of hours worked in direct patient care by registered nurses as percent of total direct patient care hours worked by hospital staff in a month
• RN Productivity	Number of RN hours required to provide care (based on patient acuity and workload data) divided by the number of hours provided in a month long period. Hospitals strive for a value near 100%
• RN Reassigned Hours	Number of hours in a month long period an RN works in a unit other than the one to which he/she is normally assigned
• Salaries and Wages (2009USD)	Total wages and salaries of all Children's employees in a month-long period (normalized to the 2009 US dollar)
• Staff Regular Direct Care Hours	Number of total direct care hours (hours spent in direct care of the patient, exclusive of vacation, sick time, and holiday pay) worked by all Children's staff per month
• Sewage ($) - per SF	Cost of sewage treatment at Children's in a one month period (normalized per square foot of hospital floor area)
• Sewage ($) - raw	Cost of sewage treatment at Children's in a one month period

• Tenure - 1 - 1.9 Years	Total number of employees at Children’s with 1-1.9 years of service
• Tenure - 10 - 14.9 Years	Total number of employees at Children’s with 10-14.9 years of service
• Tenure - 15+ Years	Total number of employees at Children’s with more than 15 years of service
• Tenure - 2 - 4.9 Years	Total number of employees at Children’s with 2 to 4.9 years of service (absolute)
• Tenure - 5 - 9.9 Years	Total number of employees at Children’s with 5 to 9.9 years of service (absolute)
• Tenure - less 1 Year	Total number of employees at Children’s with less than one year of service (absolute)
• Tenure - Total Employees	Total number of employees at Children’s (absolute)
• Time to Fill	Average number of days in which a position filled during a month-long period had previously been open
• Total Direct Care Hours per PIB	Number of direct care hours (hours spent in direct care of the patient, exclusive of vacation, sick time, and holiday pay) worked by Children’s employees per month divided by the number of patients in a bed during that month
• Total Direct Care Hours Required	Number of direct care hours (hours spent in direct care of the patient, exclusive of vacation, sick time, and holiday pay) required per month based on patient acuity and workload data
• Total Direct Care Productive Hours per PIB	Number of direct care hours worked by Children’s employees per month divided by the number of patients in a bed during that month. Direct care hours are hours spent in direct care of the patient, exclusive of vacation, sick time, and holiday pay. Productive direct care hours also usually include per diem and traveler agency nurses with direct care responsibilities, and excludes nurses on orientation, nurse managers, and other nurses who do not have direct care assignments such as charge nurses
• Total Direct Care Productivity	Number of direct care hours required (based on patient acuity and workload data) divided by the number of hours provided in a month long period. Direct care hours are hours spent in direct care of the patient, exclusive of vacation, sick time, and holiday pay. Hospitals strive for a value near 100%

• Total Labor Expenses per PIB (2009USD)	Average cost of Children's staff in a month-long period based on the number of patients served during that month (normalized to the 2009 US dollar)
• Total Operating Expenses by PIB (2009USD)	Average cost of Children's hospital in a month-long period based on the number of patients served during that month (normalized to the 2009 US dollar)
• Total Paid Hours per PIB	Hours paid to Children's employees in a month per PIB including vacation, sick, and holiday time
• Total Patients in a Bed	A hospital inpatient, a one day observational patient, a one day observational patient who is admitted, or an outpatient in a bed during a month-long period
• Turnover - Number of Employees	Number of employees leaving their positions at Children's in a one month period (absolute)
• Turnover - Years of Service	Total years of service of all employees leaving their positions at Children's in a one month period
• Turnover Rate RN	Number of registered nurses leaving their positions at Children's in a one month period relative to the total number of positions
• Vacancy - Ave Position Age (days)	Average age of positions opened during a month-long period
• Vacancy - Number of Openings	The total number of open positions during a one month period
• Vacant RN FTEs	The total number of open Registered Nurse Full Time Employee positions in a one month period
• Vacancy Rate RN	Number of unfilled registered nurse positions at Children's relative to the total number of RN positions in a one month period
• Water (kgal) - per SF	Quantity of water utilized at Children's in a one month period (normalized per square foot of hospital floor area)
• Water (kgal) - raw	Quantity of water utilized at Children's in a one month period

APPENDIX B

DATA COLLECTION AND ANALYSIS METHODS FOR LIFE CYCLE ASSESSMENT OF HYSTERECTOMIES

Appendix B contains figures, tables, data, and other supporting information for Chapter 4.0 Evaluating Environmental Impacts of Medical Procedures: Life Cycle Assessment of Birthing an Infant and Chapter 5.0 Environmental Impacts of Advancing Surgical Technologies: Life Cycle Assessment of Hysterectomies. Waste audit procedural information can be found in Section B.1 and information related to the life cycle assessment can be found in Section B.2. For supporting information and data related to Monte Carlo uncertainty assessment, refer to Appendix Section B.3.

B.1 WASTE AUDIT PROCEDURES

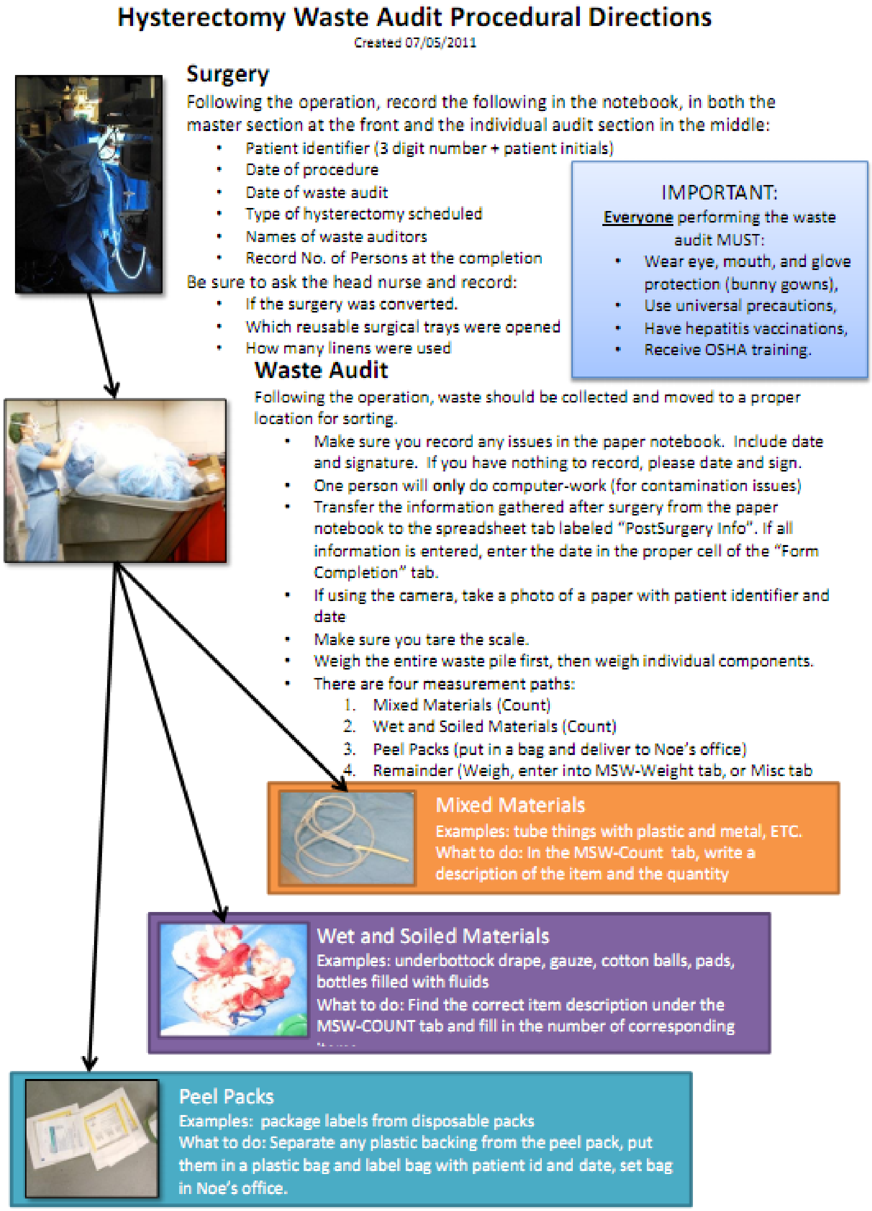


Figure 38: Waste Auditing Procedural Directions Given to Each Auditor

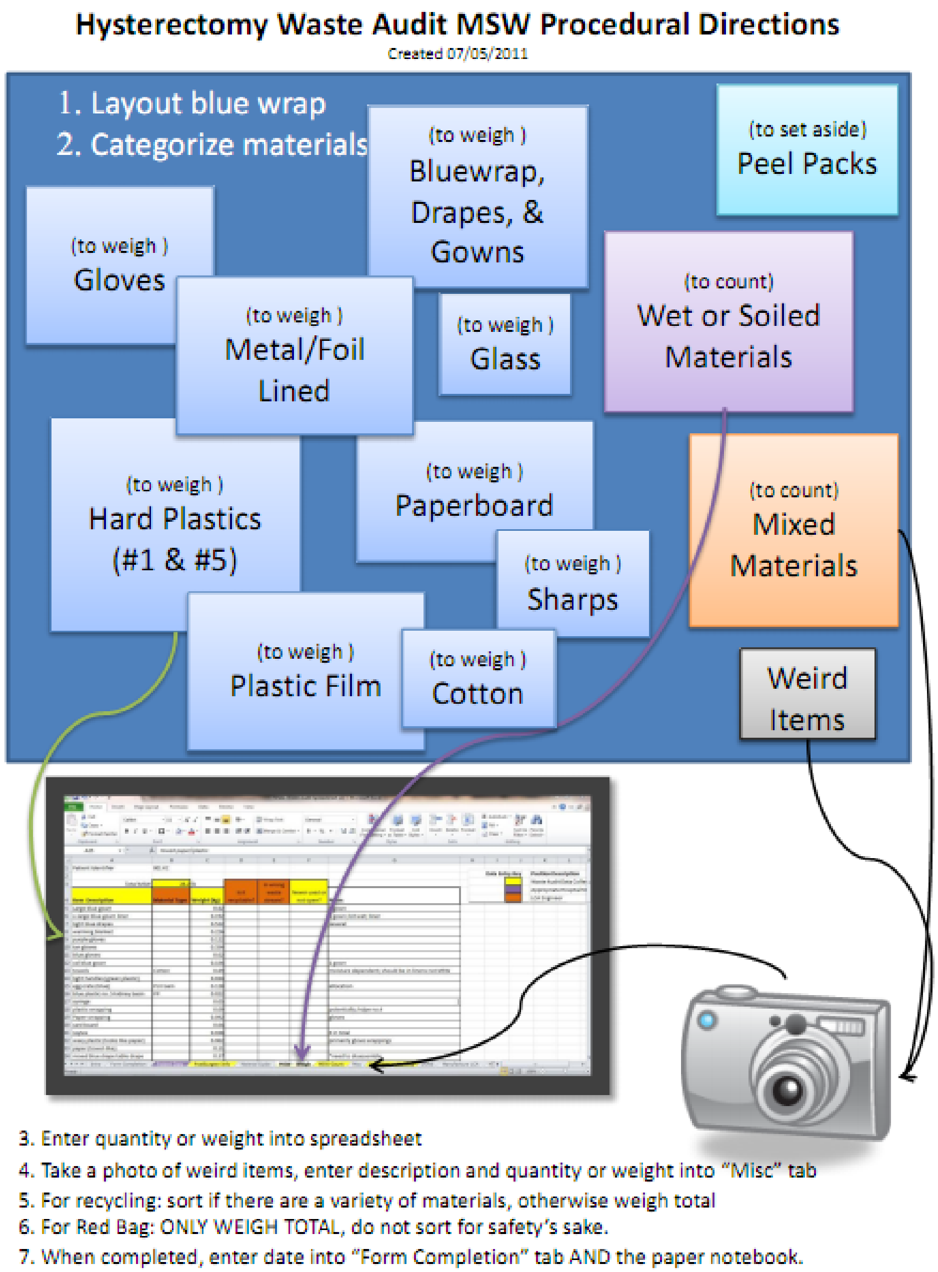


Figure 39: Waste Audit Procedure Graphical Directions for Sorting MSW

Figure 40: Material Identification Guide for Weighed Materials in MSW, p1

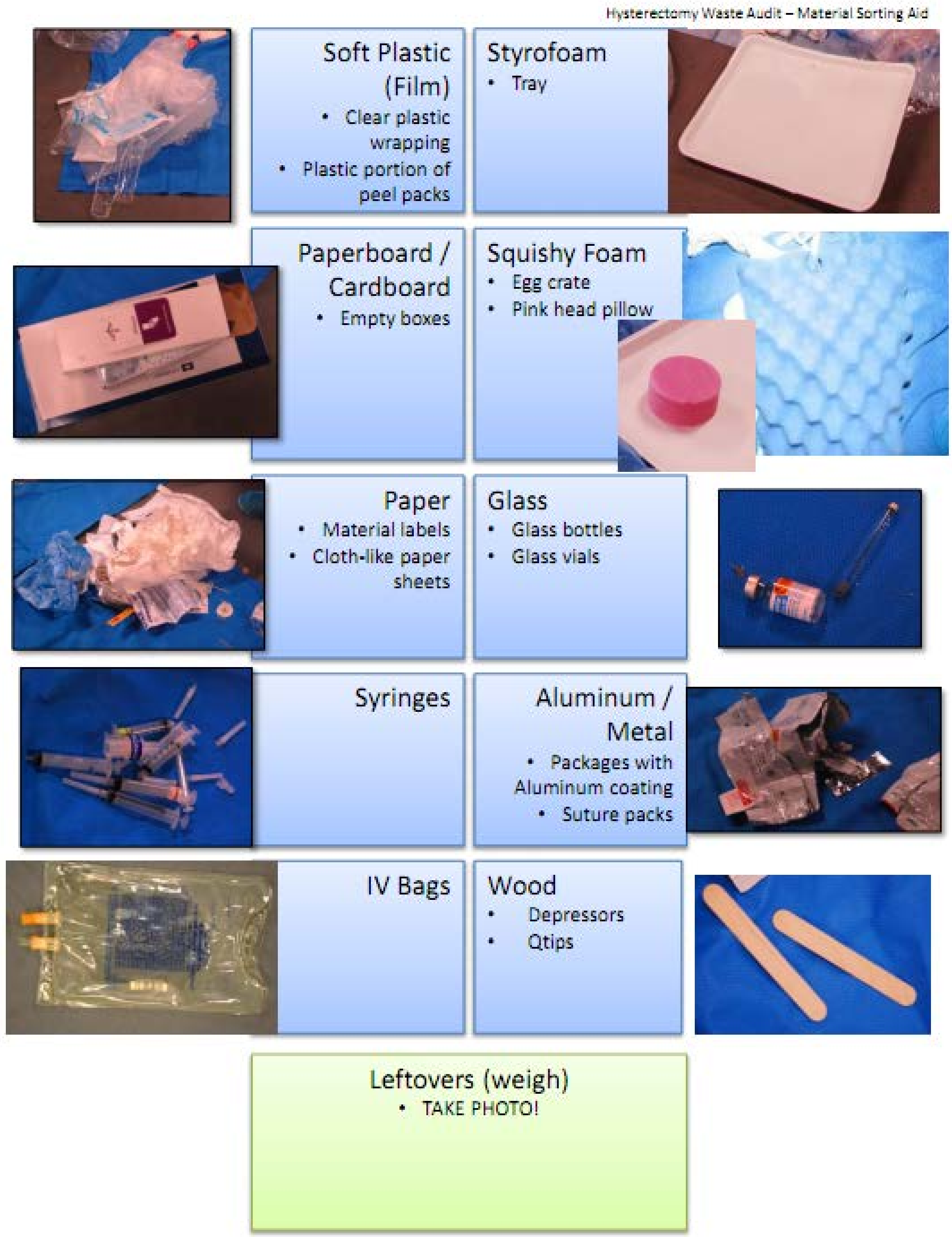


Figure 41: Material Identification Guide for Weighed Materials in MSW, p2

Figure 42: Material Identification Guide for Counted Materials in MSW, p1

Figure 43: Material Identification Guide for Counted Materials in MSW, p2

B.2 DATA COLLECTION AND ANALYSIS TABLES

Table 18: Machines and Surgical Equipment in Operating Rooms for Hysterectomies at Magee-Womens Hospital; Green cells = variable electrical draw equipment; Blue cells = equipment found in robotic operating room

No. in OR	Machine Name	Manufacturer	Purpose	W total
1	Surgical clippers	Allegiance	Electric razor	0
1	Photosmart D5460 Printer	HD	Printer	0
1	Endoscopy 40L High Flow Insuflator	Stryker	Insuflator (CO2 into abdomen)	65
1	L9000 LED Light	Stryker	Viewing surgery	
1	1288 HD High Def Camera	Stryker	Viewing surgery	
1	Exera CLV-160 Scope	Olympus	Viewing surgery	
3	HDTV Surgical Display (WiSe)	Stryker	TV for surgical displays	270
2	Computer tower	HP	For doctors to pull up charts	168
2	Computer monitor	HP	For nurses to pull up charts	62
1	HD Radio	Sony	music	15.8
1	Ranger Blood and Fluid Warming System	Arizant Health	warms IV fluids	1.6
1	MP90 Monitor (anesthesia)	Philips	anesthesia machine	160
1	MP90	Philips	anesthesia machine	
1	G5 Gas Monitor	Philips	anesthesia machine	
1	Aestiva 5	Datex / Ohmeda	anesthesia machine	
1	Computer monitor & tower	HP	anesthesia machine	102
1	Amsco 3085 SP	Steris	Surgical Table	9
1	Solutions Warmer	OR Solutions	tray for warming tools in fluid	164
1	SCD Express	Kendall	vascular refill detection/leg compression	2.9
1	WarmAir	Cincinati Subzero	warm air machine (for drapes)	866.14
1	Neptune 2 Ultra	Stryker	Removes patient fluids	710
1	G400 Workstation (orange)		PK Maryland	45
1	part of above workstation (white)	Ethicon Endo-Surgery	enseal	41
1	Force Triad	Valleylab	ligasure machine	63.4
1	Force FXc	Valleylab	Bovie grounding pad	14.5
1	unidrive GYN - endoscope	STORZ		
1	Morcellator	Ethicon / Gynecare	morcellator	
2	Robot Surgeon Console	Intuitive	DaVinci Robot	1932
1	Robot Patient Cart	Intuitive	DaVinci Robot	966
1	Robot Vision Cart	Intuitive	DaVinci Robot	1380
1	Robot ISI Core	Intuitive	DaVinci Robot	650
1	Robot Illuminator	Intuitive	DaVinci Robot	0
1	Robot DoCo	Intuitive	DaVinci Robot	100

Table 19: Life Cycle Inventory Databases and Processes Chosen for Hysterectomy Materials found in MSW

Material Type	LCI Database	Production Process Name	LCI Database	Disposal Process Name
Cotton	ecoinvent unit process	Textile, woven cotton, at plant/GLO U	ecoinvent unit process	Disposal, inert material, 0% water, to sanitary landfill/CH U
PVC	ecoinvent unit process	Polyvinylchloride, at regional storage/RER U	ecoinvent unit process	Disposal, polyvinylchloride, 0.2% water, to sanitary landfill/CH U
HDPE	ecoinvent unit process	Polyethylene, HDPE, granulate, at plant/RER U	ecoinvent unit process	Disposal, polyethylene, 0.4% water, to sanitary landfill/CH U
LDPE	ecoinvent unit process	Polyethylene, LDPE, granulate, at plant/RER U	ecoinvent unit process	Disposal, polyethylene, 0.4% water, to sanitary landfill/CH U
PU Foam	ecoinvent unit process	Polyurethane, flexible foam, at plant/RER S	ecoinvent unit process	Disposal, polyurethane, 0.2% water, to sanitary landfill/CH U
PP	modified ecoinvent unit process	SMS PP Disposable Gown - with energy and materials from C. Ponder dissertation	ecoinvent unit process	Disposal, polypropylene, 15.9% water, to sanitary landfill/CH U
Styrofoam	ecoinvent unit process	Polystyrene, general purpose, GPPS, at plant/RER U	ecoinvent unit process	Disposal, polystyrene, 0.2% water, to sanitary landfill/CH U
Stainless Steel	ecoinvent unit process	Stainless steel hot rolled coil, annealed & pickled, elec. arc furnace route, prod. mix, grade 304 RER U	ecoinvent unit process	Disposal, steel, 0% water, to inert material landfill/CH U
Aluminum	USLCI	Aluminum, secondary, shape casted/RNA	ecoinvent unit process	Disposal, aluminium, 0% water, to sanitary landfill/CH U
Isoprene	ecoinvent unit process	Synthetic rubber, at plant/RER U	ecoinvent unit process	Disposal, plastics, mixture, 15.3% water, to sanitary landfill/CH U

Table 19 (continued)

Nitrile	USLCI	Polybutadiene, at plant/RNA	ecoinvent unit process	Disposal, plastics, mixture, 15.3% water, to sanitary landfill/CH U
Neoprene	ecoinvent unit process	Synthetic rubber, at plant/RER U	ecoinvent unit process	Disposal, plastics, mixture, 15.3% water, to sanitary landfill/CH U
Rubber	ecoinvent unit process	Synthetic rubber, at plant/RER U	ecoinvent unit process	Disposal, plastics, mixture, 15.3% water, to sanitary landfill/CH U
Paper	ecoinvent unit process	Kraft paper, bleached, at plant/RER U	ecoinvent unit process	Disposal, paper, 11.2% water, to sanitary landfill/CH U
Paperboard	ecoinvent unit process	Solid bleached board, SBB, at plant/RER U	ecoinvent unit process	Process-specific burdens, sanitary landfill/CH U
Glass	ecoinvent unit process	Packaging glass, white, at plant/RER U	ecoinvent unit process	Disposal, glass, 0% water, to inert material landfill/CH U
Wood	USLCI	Plywood, at plywood plant, US SE/kg/US	ecoinvent unit process	Process-specific burdens, sanitary landfill/CH U
Complex Instruments (Sharps)	EIO-LCA	Sector # 339112: Surgical and Medical Instrument Manufacturing	EIO-LCA	Sector #562000: Waste management and remediation services

Table 20: Additional LCI Databases and Processes

Material Type	LCI Database	Process Name
Chemo/Path Waste (Uterus)	ecoinvent unit process	Disposal, biowaste, 60% H2O, to municipal incineration, allocation price/CH U
Waste Transport	ecoinvent unit process	1 tkm Transport, lorry 16-32t, EURO3/RER S (of project Ecoinvent system processes)
Recycling	ecoinvent unit process	Recycling PP/RER U
Recycling	ecoinvent unit process	Recycling PET/RER U
Recycling	ecoinvent unit process	Recycling PS/RER U
Reusable Linens	ecoinvent unit process	Textile, woven cotton, at plant/GLO U
Stainless Steel Surgical Instruments	ecoinvent unit process	Stainless steel hot rolled coil, annealed & pickled, elec. arc furnace route, prod. mix, grade 304 RER U
Laundry Detergent	ecoinvent unit process	Sodium perborate, tetrahydrate, powder, at plant/RER S
Electricity	modified USLCI	Electricity PA mix
Natural Gas	USLCI	Natural gas, combusted in industrial equipment/RNA

Table 21: Variable Electrical Draw OR Machines

Surgery Type	Wattage (W)		Vaginal		Abdominal		Laparoscopic		Robotic	
Patient ID	**Idle**	**Use - Average**	**Ave. Time in Use**	**% of Total Surgery**	**Ave. Time in Use**	**% of Total Surgery**	**Ave. Time in Use**	**% of Total Surgery**	**Ave. Time in Use**	**% of Total Surgery**
Warmer Temp (°C)			43		43		43		43	
Warmer Time (hr:min)	-	866	1.83	100%	2.57	100%	2.69	100%	2.70	100%
PK Time (min:sec)	45	86	0.00	0%	0.00	0%	4.43	3%	10.19	6%
Monopolar Bovie (min:sec)	14.5	95	1.63	1%	6.49	4%	3.09	2%	4.55	3%
Ligasure 37cm (min:sec)	63.4	123	2.57	2%	0.37	0%	0.00	0%	0.00	0%
Endoshear (min:sec)	41	116	0.00	0%	0.00	0%	0.82	1%	3.60	2%
Surgical Table	9	-	0.50	0%	0.50	0%	0.50	0%	0.50	0%

Table 22: Distributions of MSW Materials Weighed during Waste Auditing; LN =Lognormal MEV = Most Extreme Value; No Dist = No distribution (assumed an average); Para. = Parameter

	Abdominal Hysterectomy			Vaginal Hysterectomy			Laparoscopic Hysterectomy			Robotic Hysterectomy		
Material	**Dist. Type**	**Para. 1**	**Para. 2**	**Dist. Type**	**Para. 1**	**Para. 2**	**Dist. Type**	**Para. 1**	**Para. 2**	**Dist. Type**	**Para. 1**	**Para. 2**
Gowns	Normal	1.096	0.563	Normal	1.38	0.445	Normal	1.46	0.324	Normal	1.2871	0.354
Blue Drape	No Dist.	0.42	0	Normal	0.39	0.196	Normal	0.51	0.43	No Dist.	0.32	0
Blue Towels, Clean Gauze	No Dist.	1.009	0	No Dist.	0.807	0	No Dist.	0.54	0	No Dist.	0.709	0
CSR Blue Wrap	No Dist.	0.346	0	No Dist.	0.189	0	Normal	1.34	0.562	Normal	0.98	0.442
Purple Gloves	Normal	0.117	0.068	Normal	0.082	0.055	LN	-2.259	0.3731	Normal	0.12	0.044
Tan Gloves	Normal	0.162	0.038	Normal	0.153	0.063	Normal	0.21	0.071	No Dist.	0.2695	0
Blue Gloves	Normal	0.083	0.062	LN	-2.406	0.6773	LN	-2.508	0.5962	Normal	0.055	0.032
Green Gloves	No Dist.	0.004	0	No Dist.	0.01	0	No Dist.	0.005	0	No Dist.	0.009	0
Rubber	No Dist.	0.042	0	No Dist.	0.035	0	No Dist.	0.029	0	Normal	0.08	0.027
Hard Plastic (#5)	LN	-1.73	0.6504	No Dist.	0.2734	0	LN	-1.988	0.6052	No Dist.	0.615	0
Soft Plastic	No Dist.	0.508	0	No Dist.	0.5107	0	No Dist.	0.693	0	No Dist.	1.432	0
Styrofoam	No Dist.	0.023	0	No Dist.	0.032	0	No Dist.	0.018	0	No Dist.	0.047	0
PU Foam	No Dist.	0.004	0	No Dist.	0.005	0	No Dist.	0.11	0	Normal	0.43	0.235
Cardboard/ Paperboard	LN	-3.23	1.2096	No Dist.	0.0571	0	MEV	0.149	0.118	Normal	0.1156	0.053
Glass	Normal	0.14	0.139	Normal	0.23	0.18	Normal	0.16	0.138	Normal	0.2451	0.198
Paper	Normal	0.35	0.131	No Dist.	1.237	0	Normal	0.362	0.111	No Dist.	2.337	0
Syringes	Normal	0.088	0.034	LN	-2.268	0.9233	Normal	0.16	0.079	Normal	0.12	0.048
Aluminum/ Metal	LN	-2.77	0.5402	No Dist.	0.06	0.045	LN	-3.324	0.6075	Normal	0.05	0.018
IV Bags	MEV	0.038	0.057	MEV	0.068	0.069	Normal	0.07	0.065	No Dist.	0.0453	0
Wood	No Dist.	0.002	0	No Dist.	0.002	0	No Dist.	0.002	0	Normal	0	0.002
Metal (Non-Aluminum)	No Dist.	0	0	No Dist.	0.004	0	No Dist.	0.001	0	No Dist.	0.001	0

Distribution Identification for Gowns

Descriptive Statistics

N	N*	Mean	StDev	Median	Minimum	Maximum	Skewness	Kurtosis
15	0	1.28713	0.354040	1.228	0.84	1.994	0.653801	-0.280769

Box-Cox transformation: Lambda = -0.5

Goodness of Fit Test

Distribution	AD	P	LRT P
Normal	0.287	0.570	
Box-Cox Transformation	0.157	0.939	
Lognormal	0.156	0.942	
3-Parameter Lognormal	0.194	*	0.542
Exponential	3.814	<0.003	
2-Parameter Exponential	0.430	>0.250	0.000
Weibull	0.330	>0.250	
3-Parameter Weibull	0.160	>0.500	0.066
Smallest Extreme Value	0.624	0.092	
Largest Extreme Value	0.179	>0.250	
Gamma	0.199	>0.250	
3-Parameter Gamma	0.169	*	0.425
Logistic	0.252	>0.250	
Loglogistic	0.169	>0.250	
3-Parameter Loglogistic	0.199	*	0.544

ML Estimates of Distribution Parameters

Distribution	Location	Shape	Scale	Threshold
Normal*	1.28713		0.35404	
Box-Cox Transformation*	0.90422		0.12054	
Lognormal*	0.21819		0.26960	
3-Parameter Lognormal	-0.37897		0.46743	0.52678
Exponential			1.28713	
2-Parameter Exponential			0.47907	0.80806
Weibull		3.99103	1.41925	
3-Parameter Weibull		1.69183	0.62901	0.72673
Smallest Extreme Value	1.46692		0.35972	
Largest Extreme Value	1.12695		0.27320	
Gamma		14.77171	0.08714	
3-Parameter Gamma		5.72850	0.14227	0.47211
Logistic	1.25987		0.19791	
Loglogistic	0.21295		0.15425	
3-Parameter Loglogistic	-0.45828		0.30520	0.58372

* Scale: Adjusted ML estimate

Figure 44: Individual Distribution Identification Test Results for Gowns in Robotic Hysterectomies; Distributions were selected where the Anderson Darling (AD) value was greater than 0.05 and preference was given to Normal, Lognormal, and Most Extreme Value (in that order)

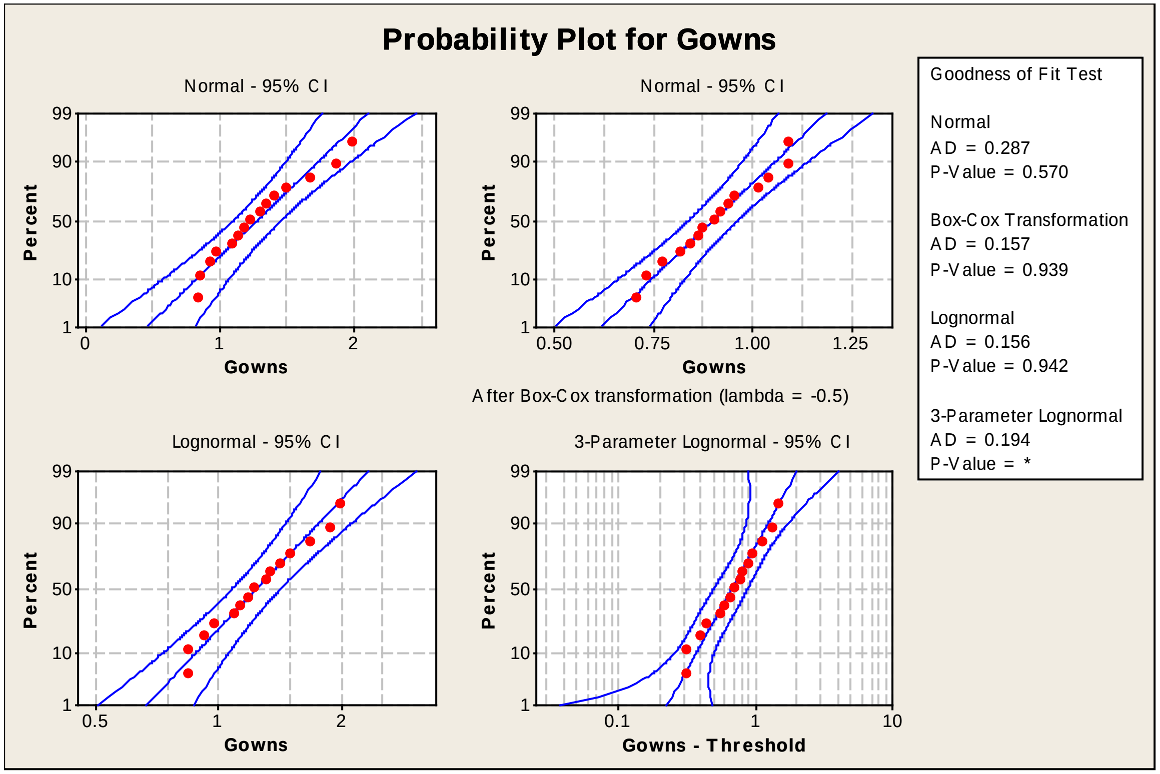


Figure 45: Graphical Results of Individual Distribution Identification Test Results for Gowns in Robotic Hysterectomies; Distributions were selected where the Anderson Darling (AD) value was greater than 0.05 and preference was given to Normal, Lognormal, and Most Extreme Value (in that order)

Table 23: Partial Selection of Cost Data of Surgical Instruments for Laparoscopic Hysterectomy Cases Based off of Peel Packs Removed from MSW and Magee Purchasing Information in 2012 US dollars

Peel Packs	***Average***		*Case 1*	*Case 2*	*Case 3*	*Case 4*	*Case 5*
5.5 mm Pediport	$ 53		$ -	$ -	$ 74	$ 74	$ 74
Endoshears	$ 39		$ -	$ 56	$ -	$ 56	$ 56
Enseal trio (5 mm)	$ 306		$ 445	$ 445	$ 445	$ 445	$ -
Auto suture Bluntport plus 5-12mm	$ 28		$ -	$ -	$ 50	$ 50	$ 50
Carter-thomason closesure system	$ 55		$ -	$ -	$ 110	$ 110	$ -
New wave surgical adv L/S care kit	$ 18		$ -	$ 40	$ 40	$ -	$ 40
Versa-port plus v2 5-12mm	$ 18		$ -	$ -	$ -	$ 41	$ -
5.5 mm pediport	$ 21		$ -	$ 111	$ -	$ -	$ -
Gyrus Pk Lyons dissecting forceps	$ 41		$ -	$ -	$ -	$ -	$ -
Ligature blunt tip L/S sealer/divider 5mm - 37cm	$ 54		$ -	$ -	$ -	$ -	$ 435
10 mm endo clip	$ -		$ -	$ -	$ -	$ -	$ -
15mm Storz morcellator handle	$ 42		$ -	$ -	$ -	$ -	$ -
5 mm covidien SIL5 hook	$ -		$ -	$ -	$ -	$ -	$ -
Auto suture 5.5mm trocar with gas port	$ 1		$ -	$ -	$ -	$ -	$ -
Auto suture step 14 G insufflation needle	$ 1		$ -	$ -	$ -	$ -	$ -
Autosure skin stapler single use	$ -		$ -	$ -	$ -	$ -	$ -
Endocatch gold - 10mm	$ 4		$ -	$ -	$ -	$ -	$ -
Gyrus plamsa spatula	$ 22		$ -	$ -	$ -	$ -	$ -
L-Hook Con Med	$ -		$ -	$ -	$ -	$ -	$ -
Lapra T4: L/S suture clip applier (ethicon)	$ -		$ -	$ -	$ -	$ -	$ -
Ligature V - vessel sealing - 5 mm	$ 25		$ -	$ -	$ -	$ -	$ -
Ligature	$ 49		$ -	$ -	$ -	$ -	$ -
Versa step 12 plus	$ 3		$ -	$ -	$ -	$ -	$ -
total	**$ 780**		$ 445	$ 652	$ 719	$ 776	$ 655
High	**$ 1,561**						
Low	**$ 437**						

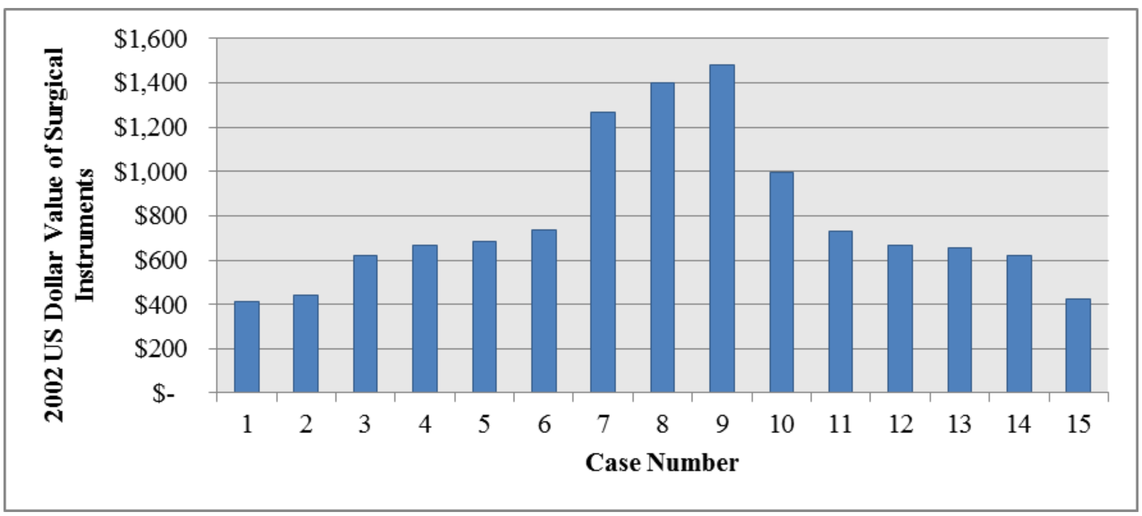


Figure 46: Cost Distribution of Surgical Instruments for Each Laparoscopic Hysterectomy Case Based off of Peel Packs Removed from MSW and Magee Purchasing Information in 2002 US Dollars

Table 24: Average Cost Data of Surgical Instruments for Robotic Hysterectomy Cases Based off of Peel Packs Removed from MSW and Magee Purchasing Information in 2012 US dollars

Peel Packs	***Average***		Case 1	Case 2	Case 3	Case 4	Case 5
8 mm bladeless obturator (da Vinci)	$ 17		$ 25	$ -	$ 25	$ 25	$ -
8 mm cannula seal (intuitive)	$ 10		$ 15	$ 15	$ 15	$ 15	$ 15
Auto suture Bluntport plus 5-12mm	$ 33		$ 50	$ -	$ 50	$ -	$ 50
Auto suture step 14 G insufflation needle	$ 8		$ 15	$ 15	$ -	$ 15	$ 15
Versa step 12 plus	$ 17		$ -	$ -	$ -	$ 41	$ 41
Carter-thomason closesure system	$ 28		$ -	$ -	$ -	$ 110	$ -
XCEL bladeless trocar 12mm	$ 10		$ -	$ -	$ -	$ 41	$ -
8 mm LONG bladeless obturator (da Vinci)	$ 2		$ -	$ -	$ -	$ -	$ -
Auto suture 120mm surgineedle	$ 3		$ -	$ -	$ -	$ 41	$ -
Auto Suture Pediport	$ 3		$ -	$ -	$ -	$ -	$ -
Auto Suture Versa Step	$ 3		$ -	$ -	$ -	$ -	$ -
Auto Suture Versa Step (LONG)	$ 3		$ -	$ -	$ -	$ -	$ -
daVinci cautery spatula tip, 5mm	$ 17		$ -	$ -	$ -	$ -	$ -
daVinci lrg 8mm needle driver (stainless ste	$ -		$ -	$ -	$ -	$ -	$ -
Disposable nevessory kit 4-arm (intuitive su	$ 22		$ 260	$ -	$ -	$ -	$ -
Gynecare morcellex tissue morcellator	$ 56		$ -	$ -	$ -	$ 670	$ -
Versa-port plus v2 5-12mm	$ 3		$ 41	$ -	$ -	$ -	$ -
Versastep plus 12 mm	$ 3		$ -	$ 41	$ -	$ -	$ -
ROBOTIC TOOLS - PK dissecting forceps	$ 48		$ 48	$ 48	$ 48	$ 48	$ 48
ROBOTIC TOOLS - monopolar scissors	$ 320		$ 320	$ 320	$ 320	$ 320	$ 320
ROBOTIC TOOLS - caudiere graspers	$ 200		$ 200	$ 200	$ 200	$ 200	$ 200
ROBOTIC TOOLS - needle drivers	$ 440		$ 440	$ 440	$ 440	$ 440	$ 440
total	**$ 1,247**		$ 1,414	$ 1,079	$ 1,098	$ 1,966	$ 1,129
High	**$ 1,966**						
Low	**$ 1,079**						

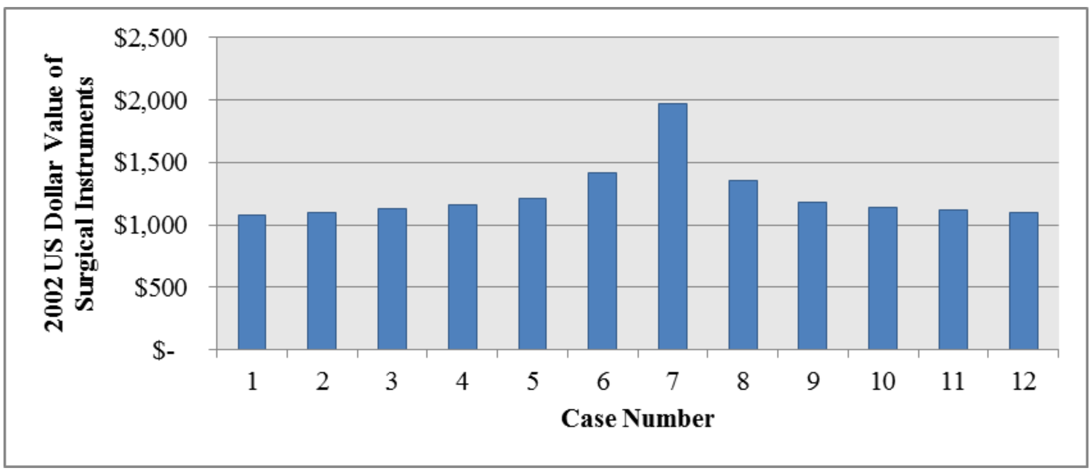
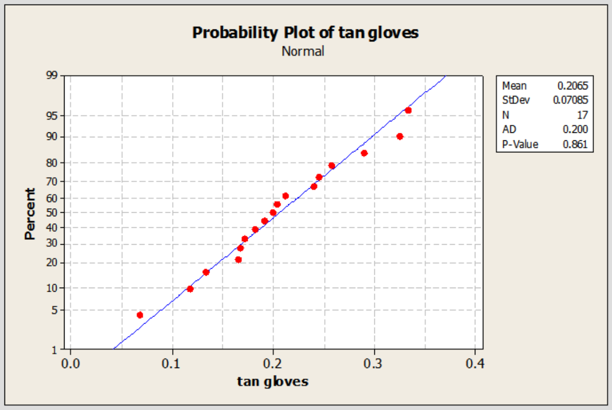


Figure 47: Cost Distribution of Surgical Instruments for Each Robotic Hysterectomy Case Based off of Peel Packs Removed from MSW and Magee Purchasing Information in 2002 US dollars

MCA Step 1: Identify Distributions of Each Material by Hysterectomy Type

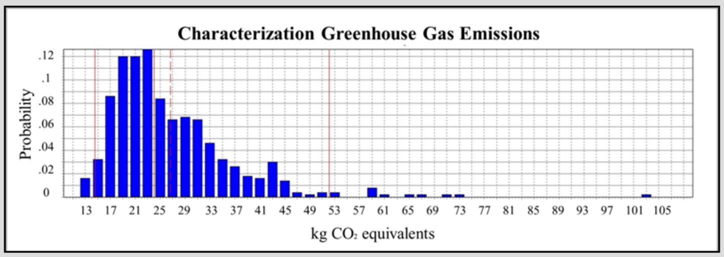
Laparoscopic Hysterectomies

Patient ID	Tan Gloves (kg)
004DN	0.068
008LZ	0.326
009MM	0.166
011KH	0.246
012JW	0.134
013ST	0.258
014JD	0.2
016LH	0.29
019MS	0.192
020CL	0.118
021CI	0.168
023MB	0.204
028BR	0.334
030RS	0.212
031 TZ	0.172
034BF	0.182
036MP	0.24



Tan glove materials for Laparoscopic Hysterectomies are normally distributed with mean of 0.21kg and standard deviation of 0.071kg

MCA Step 2: Conduct Individual MCAs to Determine Uncertainty in Each Material's Impact



The range of GHG impact per unit of glove material (synthetic rubber) is lognormally distributed with a mean of 2.64kg CO_2 eq / kg rubber and a standard deviation of .229kg

MCA Step 3: Prepare Data for Analysis

Uncertainty analysis of 1 kg 'Synthetic rubber, at plant/RER U',
Method: TRACI 2 V4.00, confidence interval: 95 %

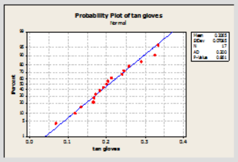
Impact category	lnMean	lnSD	Scaled Mean	Scaled SD	Scalar	Mean	Median	SD
Ozone depletion	13.54611	0.477318	856000	433000	1E+12	8.56E-07	7.53E-07	4.33E-07
Global warming	7.874786	0.08658	2640	229	1000	2.64	2.63	0.229
Smog	11.65823	0.152947	117000	18000	1000000	0.117	0.114	0.018
Acidification	6.296477	0.110831	546	60.7	1000	0.546	0.539	0.0607
Eutrophication	8.798275	0.519602	7580	4220	1000000	0.00758	0.0065	0.00422
Carcinogenics	8.836564	1.107062	12700	19700	1E+11	1.27E-07	9.41E-08	1.97E-07
Non carcinogenics	7.721118	0.759707	3010	2660	1E+10	3.01E-07	2.32E-07	2.66E-07
Respiratory effects	5.643271	0.180064	287	52.1	100000	0.00287	0.00279	0.000521
Ecotoxicity	7.789878	0.652918	2990	2180	1000	2.99	2.56	2.18
Single score	9.111707	0.080288	9090	731	100	90.9	90.6	7.31

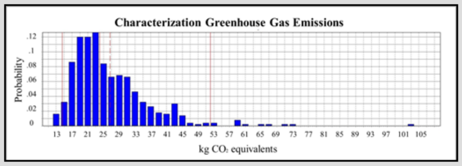
Confidence interval:

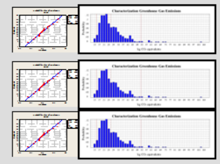
Results of individual MCA of impacts are scaled to prevent analysis errors with values less than one, and converted into lognormal distribution parameters

Figure 48: Monte Carlo Assessment Calculations and Flowchart

MCA Step 4: Data is Imported into MATLAB and Random Numbers are Generated from the Various Distributions to Create A Single Distribution for Total Environmental Impacts of a Type of Hysterectomy







Trial 1: 0.250 x 8.01 = 2.0025 + ……

.

.

.

Trial 100,000

Random number from material distribution

Random number from impact distribution

Potential impact of rubber material

Potential impact of other materials

MCA Step 5: Convert Resultant Data into Original Units

Impact Category	Process LCA Units (TRACI)	Production of Disposable Materials (from MATLAB)			Scalar	Production of Disposable Materials (Scaled)		
		50%	5%	95%		50%	5%	95%
ODP	kg CFC-11 eq	1107300	788070	1555800	1E+12	1.11E-06	7.88E-07	1.56E-06
GWP	kg CO2 eq	44399	30674	64267	1000	44.399	30.674	64.267
Smog	kg O3 eq	2515200	1558100	4060100	1000000	2.5152	1.5581	4.0601
AP	mol H+ eq	18147	11753	28019	1000	18.147	11.753	28.019
EUT	kg N eq	100060	59564	168090	1000000	0.10006	0.059564	0.16809
Carc	CTUh	207580	107990	399030	1E+11	2.08E-06	1.08E-06	3.99E-06
NonCarc	CTUh	67998	35400	130610	1E+12	6.8E-08	3.54E-08	1.31E-07
Resp	kg PM10 eq	6611.9	3662.2	11937	100000	0.066119	0.036622	0.11937
EcoTox	CTUe	143460	112920	182250	1000000	0.14346	0.11292	0.18225
CED	MJ	111750	80545	155030	100	1117.5	805.45	1550.3

The impacts per glove material are incorporated into the overall impacts of both the production and disposal of disposable materials, as well as the total impacts to a laparoscopic hysterectomy. The 50% of the newly formed distributions represents the averages reported in the graphs, while the 5% and 95% values represent the error bars.

Figure 48 (continued)

B.3 MONTE CARLO SCRIPTS FOR MATLAB

```
%Function takes matrix X and returns a column vector of values based on the
%distribution flags and parameters in each row. Mode flag is 0=median,
%1=random

function P = calcdist(X,mode)

P = zeros(size(X,1),1);

if mode==1 %Random
    for i=1:size(X,1)
        if X(i,1) >= 0 %static
            P(i) = X(i,2);
        elseif X(i,1) == -1 %lognormal
            P(i) = random('logn',X(i,2),X(i,3));
        elseif X(i,1) == -2 %binomial
            int = rand;
            if int<=X(i,2)
                P(i) = 1;
            elseif int<=X(i,3)+X(i,2)
                P(i) = 2;
            else
                P(i) = 3;
            end
        elseif X(i,1) == -3 %uniform
            P(i) = random('unif',X(i,2),X(i,3));
        elseif X(i,1) == -4 %triangular, mid, low, high
            P(i) = trirnd(X(i,2),X(i,3),X(i,4),1);
        elseif X(i,1) == -5 %normal
            P(i) = random('norm',X(i,2),X(i,3));
        elseif X(i,1) == -6 %Weibull
            P(i) = random('wbl',X(i,2),X(i,3));
        elseif X(i,1) == -7 %Extreme value
            P(i) = random('ev',X(i,2),X(i,3));
        elseif X(i,1) == -8 %logistic
            P(i) = random('logistic',X(i,2),X(i,3));
        end
    end
elseif mode==0 %median
    for i=1:size(X,1)
        if X(i,1) >= 0 %static
            if numel(X) >1
                P(i) = X(i,2);
            else
                P(i) = X(i,1);
```

```
            end
        elseif X(i,1) == -1 %lognormal
            P(i) = icdf('logn',.5,X(i,2),X(i,3));
        elseif X(i,1) == -2 %binomial
            [~,P(i)] = max(X(i,:));
            P(i) = P(i)-1;
        elseif X(i,1) == -3 %uniform
            P(i) = (X(i,3)+X(i,2))/2;
        elseif X(i,1) == -4 %triangular, mid, low, high
            P(i) = X(i,2);
        elseif X(i,1) == -5 %normal
            P(i) = X(i,2);
        elseif X(i,1) == -6 %Weibull
            P(i) = icdf('wbl',.5,X(i,2),X(i,3));
        elseif X(i,1) == -7 %Extreme value
            P(i) = icdf('ev',.5,X(i,2),X(i,3));
        end
    end
end
```

Figure 49: MATLAB Script to Defining Random Number Generating Function for Monte Carlo Assessment of Hysterectomy Data

```
%import data beforehand (outside)
%matsDist (25x4);
%impsDist (10x26x4);

trials= 100000;
%trials should be set at 100000 for actual test

mats = zeros(37,1);
imps = zeros(10,26);
uslci = zeros(10,9);
lcia = ones(10,6);
%change back to zeros.. maybe..
results = zeros(10,6,trials);

for i=1:trials
    %Generate random values
    mats = calcdist(matsDist,1);

    %To remove negative values from results to prevent errors
    for j=1:length(mats)
        if mats(j) < 0 && j~=30&&j~=2&&j~=4;
            mats(j) = 0.000000000000001;
        end
        if j==30 && mats(j)<50;%puts a floor on operation time
            mats(j)=50;
        end
        if j==2 && mats(j)<50;%puts a floor on number of reuses
            mats(j)=50;
        end
        if j==4 && mats(j)<5;%puts a floor on number of reuses
            mats(j)=5;
        end
    end

    %Generate random values for impacts
    for j=1:size(uslciDist,3)
        uslci(:,j) = calcdist(uslciDist(:,:,j),1);
    end

    for j=1:size(impsDist,3)
        imps(:,j) = calcdist(impsDist(:,:,j),1);
    end


    %Map impacts to materials
    lcia(:,1) = mats(1)/mats(2)*(imps(:,10)+(19.3/1000*(imps(:,25))))...
        +mats(3)/mats(4)*(imps(:,1)+imps(:,13)+(19.3/1000*(imps(:,25))))...
        +(mats(3)*.0274)*uslci(:,7)...
        +mats(3)*(uslci(:,8)*.2)+mats(31)*counts(20)*uslci(:,8);
    %lcia(:,1) calculates impacts due to REUSABLE materials - production, sterilization,↙
and landfilling of
```

Figure 50: MATLAB Script to Run Monte Carlo Assessment of Hysterectomy Data

```
    %cotton and transportation of cotton and steel to landfill (though steel is↙
recycled)- steel
    %recycling is included OUTSIDE of MCA model.

    lcia(:,2) = (mats(5)+mats(6)+mats(8)+counts(7))*uslci(:,6)+(mats(7)+counts(11))*imps↙
(:,1)...
        +mats(9)*uslci(:,2)+(mats(10)+mats(11)+mats(12)+mats(13)+counts(12))*imps(:,7)↙
+...
        (mats(14)+counts(3)+counts(4))*imps(:,3)+(mats(15)+counts(2)+counts(5))*imps(:,↙
4)+...
        (mats(16)+counts(8))*imps(:,6)+(mats(17)+counts(6))*imps(:,5)+mats(18)*imps(:,9)↙
+...
        mats(19)*imps(:,11)+(mats(20)+counts(13))*imps(:,8)+(mats(21)+mats(23)+counts↙
(1))*imps(:,2)+...
        (mats(22)+counts(10))*uslci(:,1)+mats(24)*uslci(:,3)+(mats(25)+counts(9))*imps↙
(:,10)+...
        mats(36)*uslci(:,4)+mats(32)*uslci(:,6)+mats(33)*imps(:,3)+mats(34)*imps(:,6);
    %lcia(:,2) calculates impacts due to production of disposable
    %materials (includes EIO and recycling production)

    lcia(:,3) = (mats(5)+mats(6)+mats(8)+counts(7))*imps(:,17)+(mats(7)+counts(11))*imps↙
(:,13)+....
        (mats(9)+mats(10)+mats(11)+mats(12)+mats(13)+counts(12))*imps(:,23)+(mats(14)↙
+mats(15)+...
        counts(2)+counts(3)+counts(4)+counts(5))*imps(:,15)+(mats(16)+counts(8))*imps(:,↙
18)+(mats(17)+...
        counts(6))*imps(:,16)+(mats(18)+mats(24))*imps(:,24)+mats(19)*imps(:,22)+(mats↙
(20)+counts(13))*imps(:,21)+...
        (mats(21)+mats(23)+counts(1))*imps(:,14)+(mats(22)+counts(10))*imps(:,19)+(mats↙
(25)+counts(9))*imps(:,20)+...
        mats(37)*uslci(:,5)+mats(35)*imps(:,24)+(((sum(mats(5:25))+(sum(counts(1:16))))↙
/1000))*mats(27)*imps(:,25)+...
        (sum(mats(32:35))/1000)*mats(28)*imps(:,25);
    %lcia(:,3) calculates impacts due to EOL of disposable materials
    %(includes EIO, MSW from recycling, and transportation of all waste streams *does↙
NOT include recycling itself)

    lcia(:,4) = mats(29)/1000*imps(:,26)+mats(29)/1000000*mats(26)*imps(:,25);
    %lcia(:,4) calculates impacts due to chemo/path (uterus)

    lcia(:,5) = (counts(17)+counts(18))*(mats(30)/60)*uslci(:,8)+counts(19)*(mats(30)↙
/60)*uslci(:,9);
    %lcia(:,5) calculates impacts due to Energy (machines, lighting, hvac)
    %consumption with a distribution on DURATION (but not electricity or
    %gas)

    lcia(:,6) = sum(lcia(:,1:5),2);


    %Sum and store
    results(:,:,i) = lcia;
```

Figure 50 (continued)

```
    if mod(i,round(trials/10))==0
        fprintf('%d%% Complete\n',i/trials*100);
    end
end


%Generate final distributions
finalDist = cell(10,size(lcia,2));
lciaMeans = zeros(10,size(lcia,2),3);
parmhat = zeros(10,2,size(lcia,2));

for i=1:10
    hist(squeeze(results(i,6,:)),100);
    figure;
end

for i=1:10
    for j=1:size(lcia,2)
        finalDist{i,j} = fitdist(squeeze(results(i,j,:)),'logn');
        parmhat(i,:,j)=lognfit(squeeze(results(i,j,:)));
    end
end

disp('Distributions fit');

for i=1:10
    for j=1:6
        lciaMeans(i,j,:) = icdf(finalDist{i,j},[.5,.05,.95]);
    end
end

%summation of ave, low, and high for boxplot
ODP = squeeze(lciaMeans(1,6,:));
GWP = squeeze(lciaMeans(2,6,:));
Smog = squeeze(lciaMeans(3,6,:));
AP = squeeze(lciaMeans(4,6,:));
EUT = squeeze(lciaMeans(5,6,:));
Carc = squeeze(lciaMeans(6,6,:));
NonCarc = squeeze(lciaMeans(7,6,:));
Resp = squeeze(lciaMeans(8,6,:));
EcoTox = squeeze(lciaMeans(9,6,:));
CED = squeeze(lciaMeans(10,6,:));


boxplot([GWP AP Carc NonCarc Resp EUT ODP EcoTox Smog CED],'boxstyle',...
   'filled','labels',{'ODP','GWP','Smog','AP','EUT','Carc','NonCarc',...
   'Resp','EcoTox','CED'});
xlswrite('MCA - Results.xlsm',[ODP,GWP,Smog,AP,EUT,Carc,NonCarc,Resp,EcoTox,CED]);
csvwrite('MCA - Results for m and s.csv',parmhat(:,:,:));
csvwrite('MCA - Results all divisions.csv',squeeze(lciaMeans(:,:,:)));
```

Figure 50 (continued)

APPENDIX C

ENVIRONMENTAL IMPACTS OF HYSTERECTOMIES AND VARIATION IN RESULTS BY IMPACT CATEGORY

This Appendix presents graphical results of Monte Carlo Assessments of 4 types of hysterectomies. Each graph represents the contribution of components of the hysterectomy to a specific environmental impact.

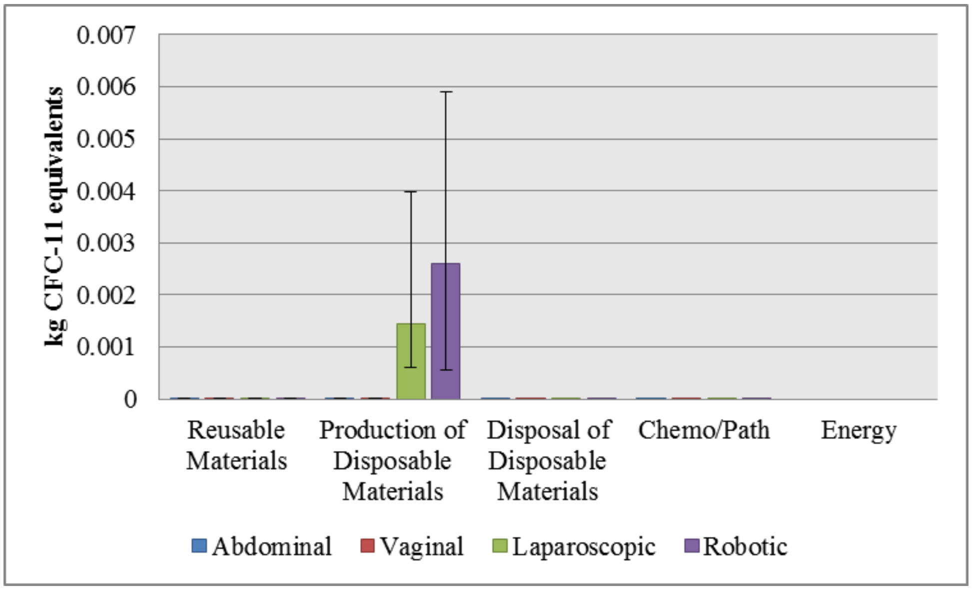


Figure 51: Range in Life Cycle Ozone Depletion Potential of Components of Four Types of Hysterectomies; Does not include recycling.

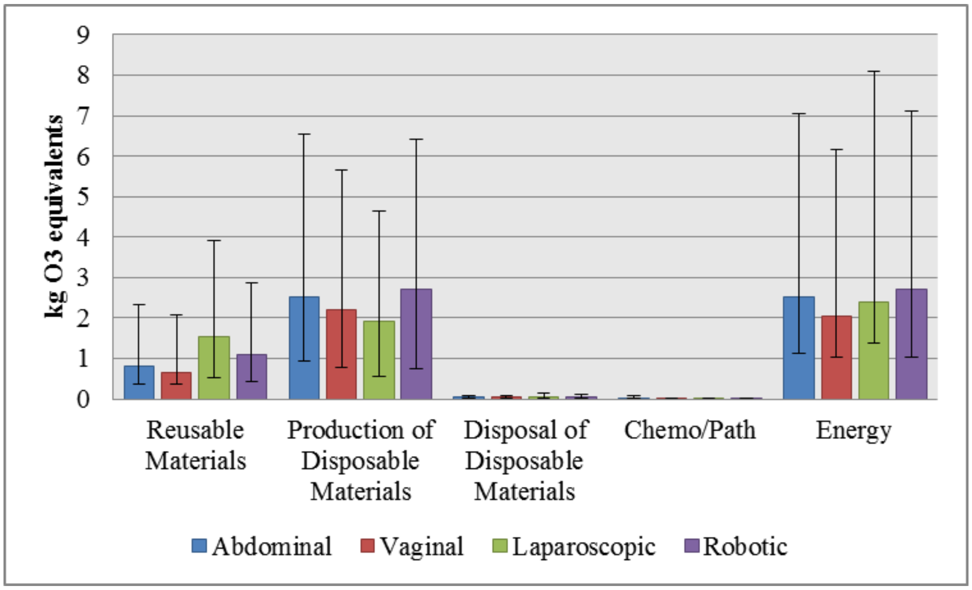


Figure 52: Range in Life Cycle Smog Formation Potential of Components of Four Types of Hysterectomies; Does not include recycling.

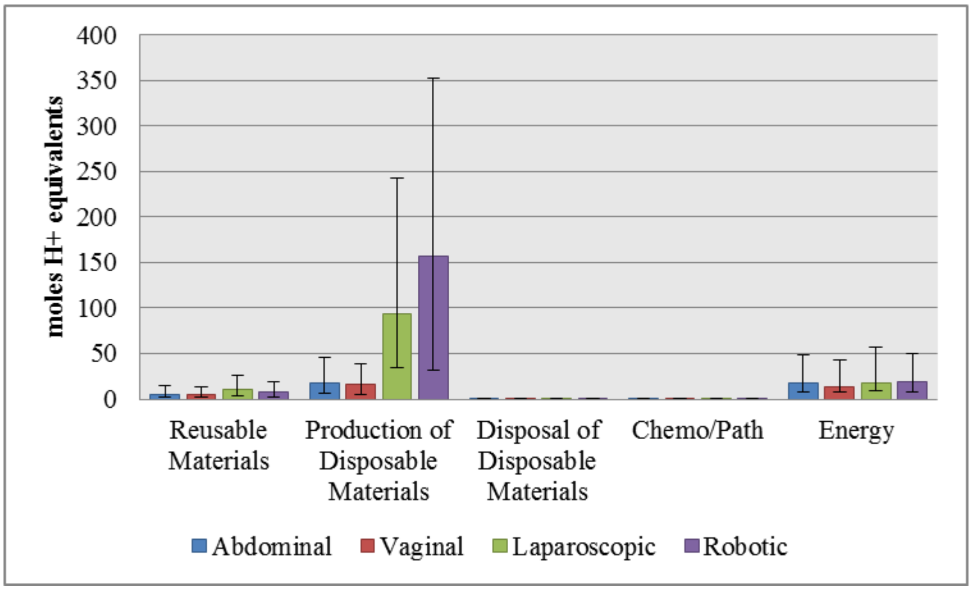


Figure 53: Range in Life Cycle Acidification Potential of Components of Four Types of Hysterectomies; Does not include recycling.

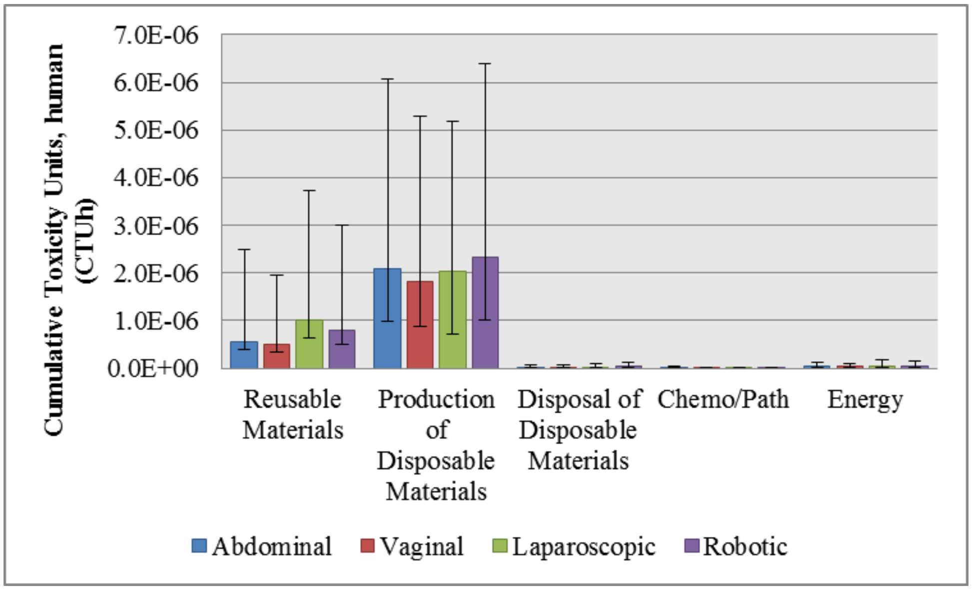


Figure 54: Range in Life Cycle Human Health Carcinogenic Impacts of Components of Four Types of Hysterectomies; Does not include recycling.

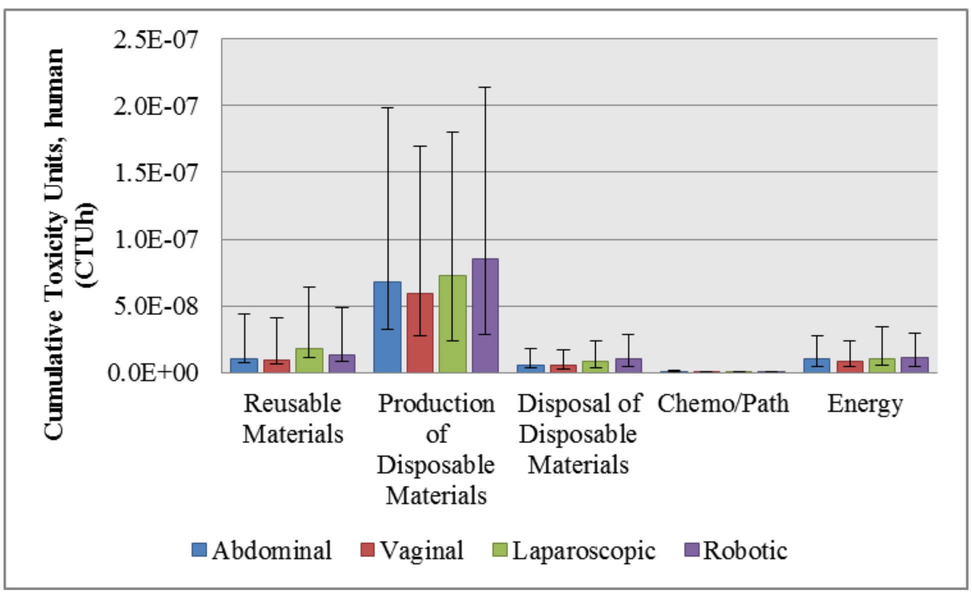


Figure 55: Range in Life Cycle Human Health Non-Carcinogenic Impacts of Components of Four Types of Hysterectomies; Does not include recycling.

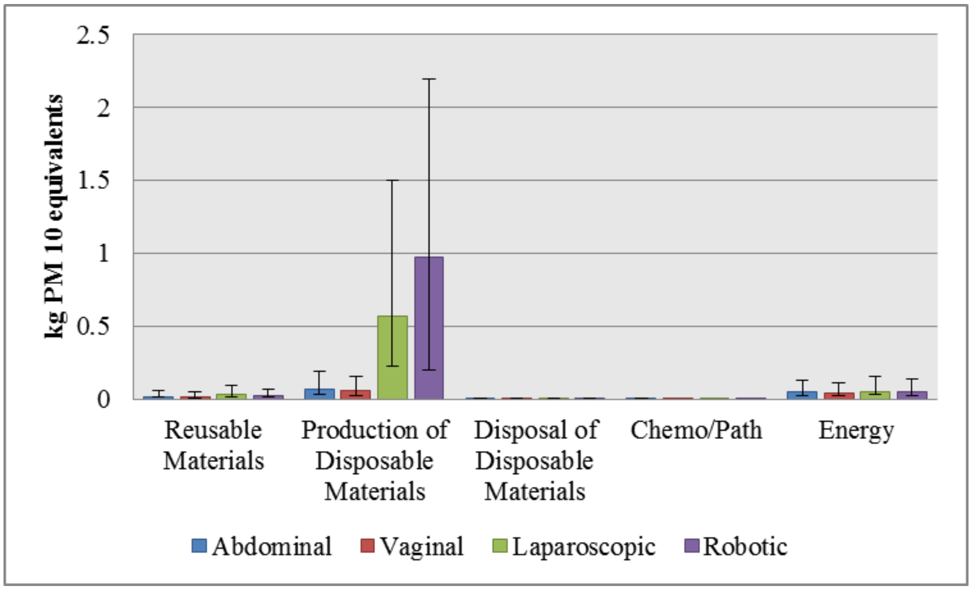


Figure 56: Range in Life Cycle Respiratory Impacts of Components of Four Types of Hysterectomies; Does not include recycling.

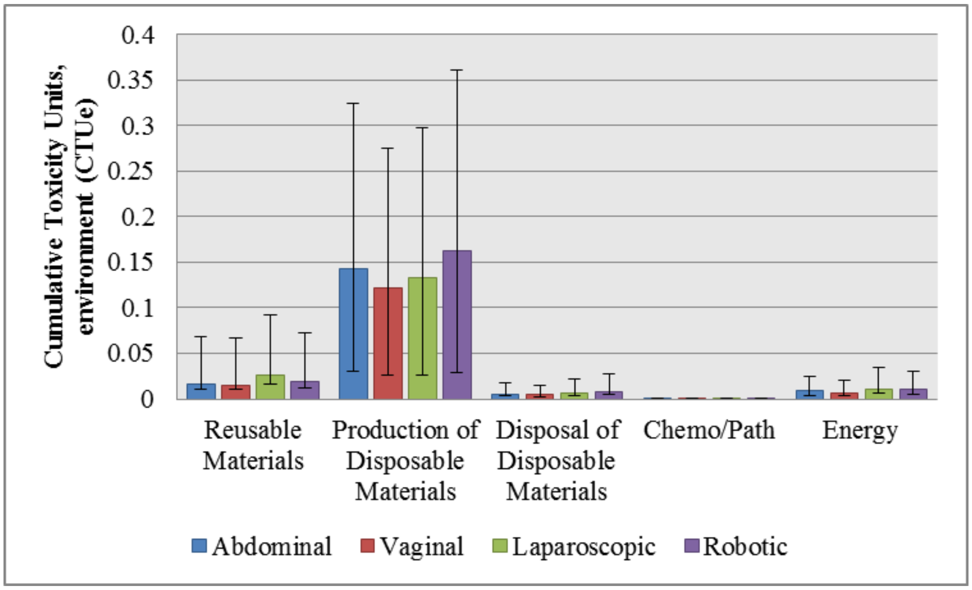


Figure 57: Range in Life Cycle Ecotoxicity Impacts of Components of Four Types of Hysterectomies; Does not include recycling.

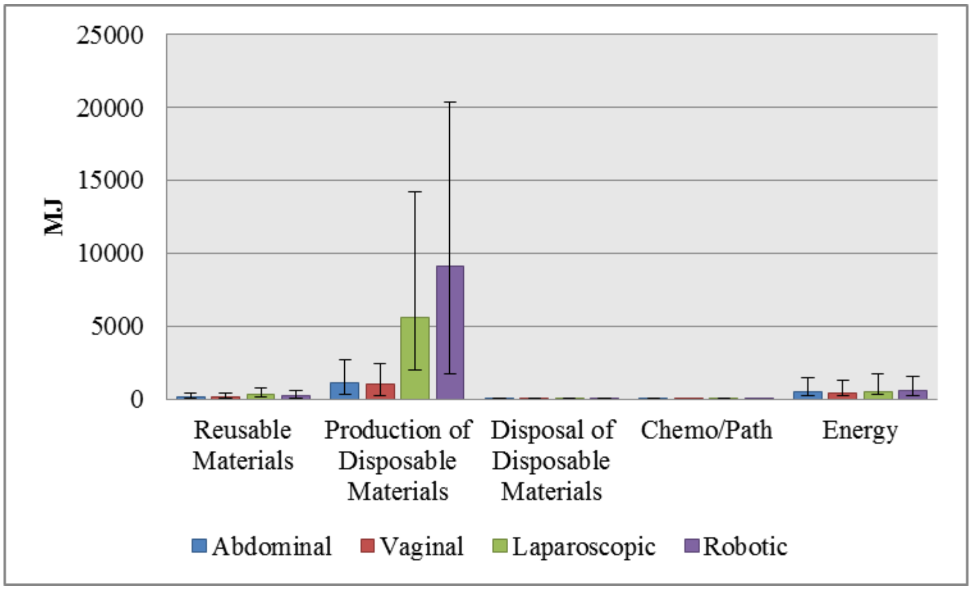


Figure 58: Range in Life Cycle Cumulative Energy Demand of Components of Four Types of Hysterectomies; Does not include recycling.

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