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Assessing the environmental, human health, and economic impacts of reprocessed medical devices in a Phoenix hospital's supply chain

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ABSTRACT

Given increasing healthcare costs and decreasing insurance reimbursements, healthcare administrators are now assessing innovative opportunities for optimizing their medical device supply chains. Reprocessed medical devices are receiving increased attention because of their twofold reduction to costs associated with reductions to purchase cost of devices and reductions to regulated medical waste (RMW) costs. From an environmental standpoint, an increasing number of studies are assessing the environmental impacts of medical devices and the processes by which they are utilized. These studies report significant environmental impacts with respect to how medical devices are manufactured, used, and disposed. In turn, these studies also discuss the potential human health impacts with respect to medical devices and their associated lifecycles. Despite a wide variety of devices suitable for reprocessing, to date there have been no studies that evaluate the potential economic and environmental benefits of a reprocessed device. Additionally, there have been no hospital-wide environmental and/or economic assessments of reprocessed devices. The aim of this study was to fill these knowledge gaps by using life cycle assessment (LCA) and life cycle cost assessment (LCCA) to model the environmental and economic impacts of medical device supply chains when varying levels of reprocessed devices are used at Phoenix Baptist Hospital (PBH) in Phoenix, Arizona. The LCA included all cradle-to-grave processes for the seven medical devices. Results of the study showed that if inputs (i.e., ethylene oxide, water, electricity) were optimized, the use of reprocessed devices offers global warming, human health, and economic benefits over the same devices used as disposables. On the other hand, the excessive use of inputs correlated with reprocessed devices having greater overall environmental and human health impacts than disposable medical devices. Additionally, whether used as a SUD (single-use devices) or a reprocessed device, the use of DVT (deep vein thrombosis) compression sleeves corresponded with the highest environmental impacts when devices were compared one-toone. The DVT compression sleeves were comprised of mostly woven cotton; which is a material associated with significant environmental and human health impacts, resulting from its large quantities of lifecycle inputs. This study recommends that the significant proportion of woven cotton in DVT compression sleeves be reduced for a material with less of an overall environmental footprint.

1. Introduction

The structure of hospital supply chains and the processes by which they utilize and dispose of medical devices is increasingly considered to be materially and economically wasteful. Practice Greenhealth estimates that hospitals generate more than 5.9 million tons of waste on annual basis, where a significant proportion of United States (US) hospital waste is either landfilled or incinerated (Practice Greenhealth, 2014). Additionally, hospitals spend anywhere from $44 to $68 per ton on waste disposal, which equates to $259 to $401 million spent by US hospitals on waste on annual basis (Practice Greenhealth, 2014). The significant volume of waste generated by hospitals has incentivized waste reduction strategies in order to decrease the considerable environmental and economic costs associated with hospital waste. Decreasing utilization of single-use devices (SUDs) in favor of suitable reprocessed medical devices is one waste mitigation strategy that can decrease waste created by hospitals, thus decreasing the environmental and economic costs incurred by hospitals.

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SUDs became more widely utilized in the 1960s with the advent of polymers and the integration of high-density polyethylene (HDPE) and low-density polyethylene (LDPE) into medical products (Greene, 1986). The integration of LDPE and HDPE allowed for medical devices to be manufactured at a cost low enough for the devices to be used once and then disposed without being cost prohibitive. Additionally, the use of SUDs in favor or reprocessed alternatives was attributed to concerns about pathogenic cross-contamination through use of reprocessed devices (Greene, 1986).

However, FDA studies have shown that the use of reprocessed devices does not correlate with an increased infection risk (Favero, 2001; GAO, 2008). The Government Accountability Office (GAO) concluded in 2008 that "[the] FDA's analysis of reported device-related adverse events does not show that reprocessed SUDs present an elevated health risk" (GAO, 2008). The GAO found that the events reported to be associated with the use of reprocessed items were the same types and rates of adverse health events reported for new, non-reprocessed devices (GAO, 2008).

Because there are no cross-contamination risks associated with reprocessed devices, they can be considered as a potential strategy for reducing hospital waste. There are hundreds of devices that either have been reprocessed in the US or have been considered for reprocessing in the US. Reprocessed devices are used in a variety of medical specialties, which includes: cardio, dental, otolaryngology, gastro/urology, neurology, obstetrics/gynecology, ophthalmic, orthopedic, physical medicine, respiratory, and general surgery. While most products are suitable for reprocessing, several characteristics can influence the efficacy of reprocessing for certain devices. These characteristics include either high quantities of polymers or complex design features (Hailey et al., 2008). While polymers allow for limited economic costs, they may not be durable and may deteriorate after undergoing reprocessing. Additionally, complex design features can hinder the ability of reprocessing technicians to fully disassemble a device; where, full disassembly is required to ensure effective reprocessing for a device. Therefore, devices that have stronger materials in favor of polymers and relatively basic assembly/disassembly requirements are typically considered more favorable for reprocessing (Hailey et al., 2008).

Due to the reduced waste and materials used in a hospital's medical device supply chain, reprocessing presents an opportunity for reducing environmental impacts associated with medical devices used in hospital supply chains. Life cycle assessment (LCA) is a widely accepted methodology for determining and validating environmental impacts associated with a particular product or process. LCAs seek to address a number of environmentally related concerns, including the: compilation of energy and material input and outputs; evaluation of potential environmental impacts attributed to the inputs and outputs; and, interpretation of the results to help make a more sustainable decision (ISO, 2006a).

With regards to LCAs focused on medical devices, Stripple et al. (2008) performed an environmental evaluation of plastics used in hydrophilic catheters, which found that polyolefin-based elastomers showed better environmental performance than the thermoplastic polyurethane materials (Stripple et al., 2008). There have also been several other recent LCA studies that have focused their attention on SUDs and other healthcare activities including: ambulance services (Brown et al., 2012), reusable versus single-use bedpans (Sorensen and Wenzel, 2014), incineration vs. non-incineration treatments (Zhao et al., 2009), anesthetic drugs (Sherman et al., 2012), disposable custom packs (Campion et al., 2015), and reusable versus single-use scissors (Adler et al., 2005).

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In addition to LCAs, life cycle cost analyses (LCCAs) account for all recurring and one-time economic costs over the full life cycle of a product. With regards to economic impacts of reprocessed medical products quantified through LCCAs, a 2013 literature review performed by Jacobs et al. was able to show that utilization of reprocessed devices in a hospital's supply chains offers a 49% reduction in direct costs (Jacobs et al., 2008).

Performing a LCA and LCCA on medical devices offers several advantages. First, a LCA characterizes a range of environmental impacts resulting from different medical device supply chains, rather than simply quantifying waste streams. Quantification of waste streams fails to give administrators and healthcare personnel relevant information relating to the procurement, management, use, and disposal of medical devices. Additionally, the use of LCCAs on medical products helps administrators to more effectively understand lifecycle costs of their utilized devices, as opposed to exclusively focusing on procurement costs of devices.

While there are hundreds of items that are suitable for reprocessing, to date there have been no studies that evaluate the potential economic and environmental benefits of a reprocessed device. Additionally a system-wide LCA and life LCCA has not yet been performed on an aggregation of reprocessed devices comprising a hospital supply chain. This study fills this knowledge gap by using LCA and LCCA to model the environmental and economic impacts of medical device supply chains when varying levels of reprocessed devices are utilized.

2. Materials and methods

2.1. Case study description

Phoenix Baptist Hospital (PBH) is a general medical and surgical hospital located in what is considered the metropolitan Phoenix area. At the time of this study, they were called PBH. As of 2015, they were renamed to Abrazo Central Campus. PBH is equipped with 215 certified hospital beds and employs over 900 healthcare professionals. PBH has admitted roughly 9000 patients and performed over 900 births (i.e., approximately one patient/bed/day) since its opening in 1963. Under their classification as a general medical and surgical hospital, PBH performs the following types of procedures: cardiovascular, orthopedics, women's services, radiology, and 24-h emergency services. PBH reprocesses seven devices, including the: deep vein thrombosis (DVT) compression sleeve, pulse oximeter, ligasure, harmonic scalpel, endoscopic trocar, arthroscopic shaver, and scissor tip. Fig. 1 shows these devices, and their associated annual utilization rates.

2.2. Life cycle assessment

Life cycle assessment (LCA) is a method used to assess potential environmental and human health impacts throughout a product's life, including the product's: raw material extraction and processing, manufacture, distribution, use, maintenance and repair, and disposal. LCAs seek to address a number of environmentally related concerns, including: compilation of energy and material input and outputs; evaluation of potential impacts attributed to the inputs and outputs; and, interpretation of the results to help make a more informed decision (EPA, 2010). According to the International Organization for Standardization (ISO) 14040 and 14044 documents, a LCA is defined by four distinct steps, including: goal and scope definition, inventory analysis, impact assessment, and interpretation (Guinée, 2002).

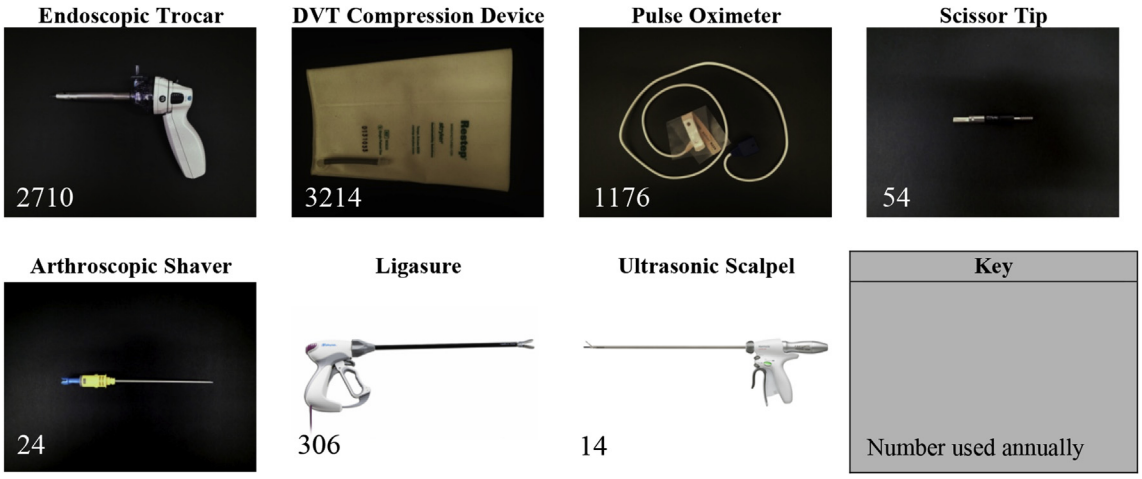

Fig. 1. Devices included in LCA.

The first step of a LCA, the goal and scope definition, explicitly sets the context of the study, defines the precise quantities of what product to be analyzed, and characterizes the extent to which a product's life cycle (e.g., manufacturing, use, disposal) is analyzed. After the goal and scope are defined, the second step of the LCA is inventory analysis. Inventory analysis documents exact quantities of emissions, materials and energy to and from the environment. Followed by the inventory analysis is the impact assessment, which aggregates the inventory data into environmental and human health impact categories. The final step of a LCA is interpretation, which is typically performed iteratively throughout each step of the LCA. Interpretation is performed, such that, information from the inventory and impact assessment steps are identified, quantified, and evaluated.

2.2.1. Goal and scope definition

An LCA was performed to model the environmental impacts of varying levels of reprocessing at Phoenix Baptist Hospital (PBH), located in Phoenix, Arizona. The functional unit (FU) was defined as seven medical devices, which is the number of medical devices needed to fulfill the reprocessed device supply chain requirements of PBH. The seven devices included were: a deep vein thrombosis (DVT) compression sleeve, a pulse oximeter, a ligasure, a harmonic scalpel, an endoscopic trocar, an arthroscopic shaver and a scissor tip. The LCA included all cradle-to-grave processes for the seven medical devices, where the processes are further detailed in Fig. 2. Fig. 2 shows that the first five processes in the LCA included the seven devices' fabrication and transport to PBH. Once arriving at PBH, the decision of whether to use any of the seven devices as disposables or as reprocessed devises was established. If used as a reprocessed device, the devices would undergo transport from the hospital to the reprocessing facility, and back from the reprocessing facility to the hospital anywhere from one to five instances. When the devices reached their useful reprocessing lifetime, the devices would then undergo incineration. Disposable devices were incinerated after being used one instance.

Each device was assumed to be interchangeable as either an SUD or a reprocessed device, which assumption is according to the PBH suite of reprocessed devices but it may not be the same for other hospitals. However, this assumption may not be true for other hospitals. This study assumed that the packaging for reprocessing was the same as the packaging for an SUD; the packaging modeled herein was from a new device.

2.2.2. Inventory analysis

In order to determine each device's bill of materials, each device was disassembled and de-manufactured. The materials for each device were weighed using an Ohaus Pioneer analytical scale with ma 0.001-g detection limit. Materials were identified within the corresponding life cycle inventory records from the ELCD (European Reference Life Cycle Database) and ecoinvent v2.2.

Devices that were used more than once underwent reprocessing, where a commercial gas sterilizer was used to reprocess the seven medical devices. The gas sterilization cycle consisted of six phases: pre-sterilization conditioning, sterilization, evacuation, air wash, chamber exhaust, and aeration. The six phases of gas sterilization phases required inputs of electricity and ethylene oxide (ETO). The electricity, ETO, and water were included in the inventory. The inputs related to transporting the medical devices from the hospital to the reprocessing center, and back from reprocessing center to the hospital were also included in the life cycle inventory. At the end of their useful life all devices were treated as regulated medical waste (RMW); where all RMW underwent incineration followed by landfilling. The end-of-life processes were included in the inventory analysis. All LCI inputs and data sources are summarized in Table 1.

Table 3 summarizes the number of devices that PBH would need to purchase on an annual basis to meet their supply chain requirements. Table 2 shows the number of devices needed to fulfill PBH's reprocessed device supply chain for each reprocessing instance (i.e., none, one, two, three, four, and five). For each of the seven devices, these values were calculated using the following equation:

Equation 1 **Number of devices needed to fulfill PBH's reprocessed devices supply chain given each reprocessing instance.**

$$D_x = \frac{D_0}{x+1}$$

$D_x \equiv$ Number of devices purchased with x reprocessing instances
$D_0 \equiv$ Number of devices purchased with 0 reprocessing instances
$x \equiv$ Reprocessing instances
$M_x \equiv$ Reprocessing input multiplier for x reprocessing instances

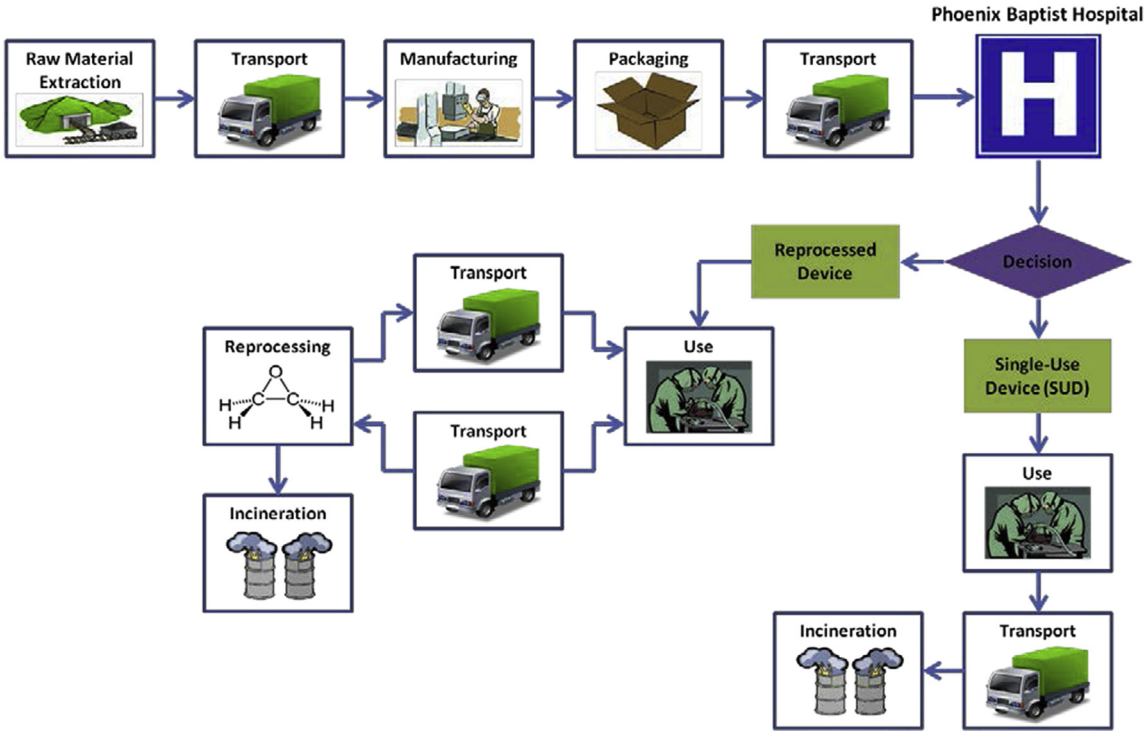

Fig. 2. System boundary showing processes included in the LCA. While not shown, the system boundaries include energy, materials, and emissions associated with each process.

Table 1
Utilized inventory data.

Material/process	LCI database	Process name
Aluminum	Ecoinvent v. 2.2	Aluminum, secondary, shape casted/RNA
Copper	Ecoinvent v. 2.2	Copper, secondary, shape casted/RNA
Cotton	Ecoinvent v. 2.2	Textile, woven cotton, at plant/GLO U
Electricity	Modified Ecoinvent v. 2.2	Electricity, production mix Arizona/Arizona U
Ethylene oxide	USLCI	Ethylene Oxide, at plant/RNA
High-density polyethylene (HDPE)	Ecoinvent v. 2.2	Polyethylene, HDPE, granulate, at plant/RER U
Incineration	Ecoinvent v. 2.2	Incineration/CH U
Kraft paper	Ecoinvent v. 2.2	Kraft paper, bleached, at plant/RER U
Low-density polyethylene (LDPE)	Ecoinvent v. 2.2	Polyethylene, LDPE, granulate, at plant/RER U
Paperboard	Ecoinvent v. 2.2	Solid bleached board, SBB, at plant/RER U
Stainless steel	Ecoinvent v. 2.2	Stainless steel hot rolled coil, annealed & pickled, elec. arc furnace route, prod. mix, grade 304 RER U
Tap water	Ecoinvent v. 2.2	Tap water, at user/RER U
Van transport	Ecoinvent v. 2.2	Transport, van <3.5t/RER U

USLCI: United States Life Cycle Database Inventory.

The reprocessing inputs were also varied given the number of devices that were used for each associated reprocessing instance. For example, a number of devices reprocessed with a certain number of reprocessing instances will have differing associated reprocessing inputs (i.e., ethylene oxide, electricity, water) when compared to the same number of devices that are reprocessed more or less instances. The varied inputs for electricity, water, and ethylene oxide each reprocessing instance were calculated with using the following equation and summarized in Table 2:

Table 2
Number of devices needed to fulfill PBH's reprocessed devices supply chain for each reprocessing instance.

	Reprocessing instances					
	0	1	2	3	4	5
Arthroscopic Shavers/Burs	47	24	16	12	9	8
Compression Device – Pairs	6427	3213	2142	1607	1285	1071
Endoscopic Trocars	5418	2709	1806	1355	1084	903
Ligasures	29	14	10	7	6	5
Pulse Oximeters	2351	1175	784	588	470	392
Scissor Tips	110	55	37	27	22	18
Ultrasonic Scalpels	613	307	204	153	123	102

Equation 2 **Associated reprocessing inputs given each reprocessing instance.**

$$M_x = D_x \cdot x$$

Results showed that ETO and electricity were the significant contributors to most of the environmental impacts, and as such a sensitivity analysis on ETO, electricity, and water was performed. The sensitivity analysis varied quantities of ETO consumed by the commercial gas sterilizer. The utilized quantities for ETO and carbon dioxide were based on the values described in both the *Sterilisation of Polymer Healthcare Products* and the *Ethylene Oxide*

Table 3
Kilograms of ETO used by gas sterilizer based on gas sterilizer volume and ETO concentration for the sensitivity analysis.

Gas sterilizer volume (m^3)	Concentration ETO (mg/L)	Concentration ETO (kg/m^3)	Kilograms ETO
2.8	400	0.4	1.12
15.4	400	0.4	6.16
28	400	0.4	11.2
2.8	950	0.95	2.66
15.4	950	0.95	14.63
28	950	0.95	26.6
2.8	1500	1.5	4.2
15.4	1500	1.5	23.1
28	1500	1.5	42

Kilograms of ETO were the product of gas sterilizer volume and the ETO concentration in kg/m^3.

Commercial Sterilization and Fumigation Operations NESHAP Implementation Document (Midwest Research Institute, Environmental Protection Agency, & Office of Air Quality Planning and Standards, 1997; Rogers, 2005). The *Sterilisation of Polymer Healthcare Products* describes the range of ETO concentrations that may be used is healthcare product gas sterilizers. The sensitivity analysis included the range of ETO concentrations described in the *Sterilisation of Polymer Healthcare Products*, which was 400 to 1500 mg/L. Additionally, the *Ethylene Oxide Commercial Sterilization and Fumigation Operations NESHAP Implementation Document* describes the range of loading volumes for healthcare product gas sterilizers. The sensitivity analysis also included the range the loading volumes for gas sterilizers shown in the *Ethylene Oxide Commercial Sterilization and Fumigation Operations NESHAP Implementation Document*, which was 2.8 m^3–28 m^3. Table 4 shows the gas sterilizer volumes and concentrations of ETO used to calculate the kilograms ETO consumed by the commercial gas sterilizer.

2.2.3. Impact assessment

The Life Cycle Impact Assessment (LCIA) was conducted using the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) v2.0 developed by the EPA (2013). TRACI was used to calculate the following environmental and human health impacts: global warming, carcinogenic, non-carcinogenic, and respiratory effects. TRACI utilizes global warming potentials (GWPs) to calculate the potency of greenhouse gases (relative to carbon dioxide) that are emitted during lifecycle phases of a product or process (Bare, 2011). These values are used to determine the overall global warming impact of a product or process. For human health impacts (i.e., carcinogenic, non-carcinogenic, respiratory effects), TRACI employs USEtox, which assess the toxicological effects of a chemical emitted into the environment through the following cause-effect chain: environmental fate, exposure, and resulting effects (Rosenbaum et al., 2008).

The characterization factor, CTU_h (i.e., comparative toxic unit), was used to express human toxicity (i.e., carcinogenic and non-carcinogenic impacts). CTU_h are the estimated increase in morbidity per unit mass of a chemical emitted. CTU_h are determined by calculating the aggregate potential for carcinogenic or non-carcinogenic diseases based on a combination of factors. These factors include a chemical's: fate factor, exposure factor, effect factor, and intake factor.

The reference emission, PM_{10} (i.e., particulate matter less than 10 μm in diameter), was used to determine the human respiratory impacts posed by reprocessed and/or disposable devices. Respiratory effects were calculated by modeling and correlating fate and exposure with intake fractions (i.e., a portion of an emitted substance, which is expected to be inhaled by a human being). The intake fractions were calculated as a function of the amount of PM_{10} emitted into the environment, the resulting increase in PM_{10} atmospheric concentration, and the breathing rate of the exposed population (Bare, 2012). PM_{10} was used as the reference substance because numerous epidemiology studies have shown increased levels of adverse human respiratory impacts with elevated levels of ambient particulate matter (Dominici et al., 2006; Pope III et al., 2002).

2.3. Life cycle cost analysis

A LCCA was also performed to model the economic impacts of varying levels of reprocessing at PBH. The LCCA modeled the economics costs incurred by PBH when using varying levels of reprocessed devices vs. SUDs, which spanned each of the seven devices' procurement to disposal. The system boundary of the LCCA matches that of the LCA, where both include each device's manufacturing, use, and disposal phases. Several inputs constructed the LCCA, which were the: price of each device (in terms of 2013 US dollars), quantity of each device used on an annual basis, waste disposal costs, and the reprocessing markdown for each device; all data was obtained from PBH.

The reprocessing markdown for devices was 50%, which was the markdown set by PBH's third-party reprocessor, Stryker. Additionally, PBH's waste handler, Stericycle, charged $0.14 per kilogram of waste generated by PBH, where this markdown was used to calculate waste disposal costs for all devices that were not reprocessed by PBH. Because Stryker would incur costs for all reprocessed devices, any instance of reprocessing for PBH would correlate with no waste disposal costs incurred by PBH. Or, any device or any number of devices that were not reprocessed would represent increased waste disposal costs incurred by PBH.

3. Results

3.1. LCA

Given median/mean reprocessing lifecycle inventory inputs, Fig. 3 shows that the reprocessing of the seven analyzed devices slightly reduces global warming impacts, but concurrently exacerbates human health impacts (i.e., carcinogenic, non-carcinogenic, respiratory effects). Irrespective of the number of reprocessing instances, the driving factor in both global warming and human health impacts was the reprocessing lifecycle inventory. This lifecycle inventory data included: the amount of ETO, electricity, and water consumed. The sensitivity anaylsis' results discussed later varies these inputs based on accepted regulatory reprocessing standards.

Whether used as a SUD or a reprocessed device, the use of DVT compression sleeves had the highest contribution of all the devices (excluding disposal and reprocessing impacts) to environmental impacts, while the trocar was second highest. The significant environmental impacts associated with DVT compression sleeves and trocar were driven by the high utilization rates; PBH uses 6427 of DVT compression sleeves and 5418 trocars on annual basis. The other devices were used less frequently (summarized Fig. 1). In addition, the compression sleeve was made up of 93% cotton on a weight basis, while all other devices were primarily made of plastic and metal. Cotton production has significant energy, chemical, and water inputs, which result in the environmental impacts in Fig. 3. These environmental impacts are due to the significant direct and indirect agricultural lifecycle inputs involved with manufacturing woven cotton.

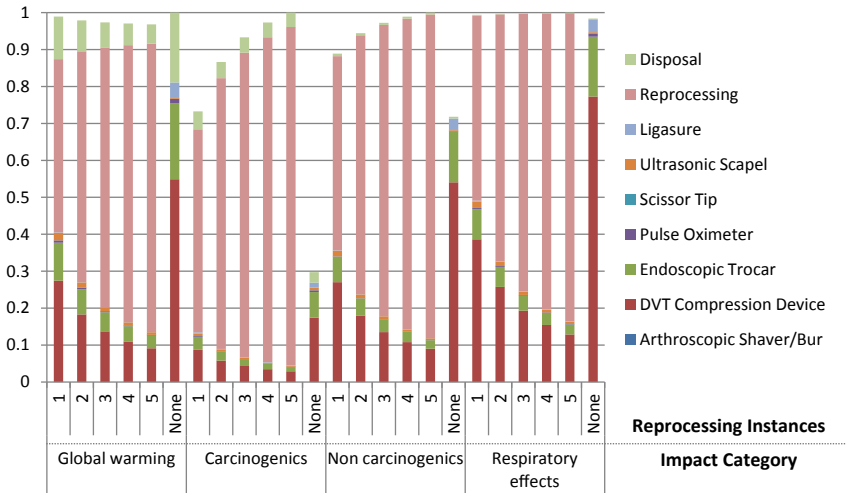

Fig. 3. Normalized global warming, carcinogenic, non-carcinogenic, and respiratory effects for PBH's reprocessed device supply chain using median/mean reprocessing lifecycle inventory inputs. Disposal corresponds with incineration and waste-handling processes. The seven devices (i.e., ligasure, ultrasonic scalpel, scissor tip, pulse oximeter, endoscopic trocar, DVT compression device, arthroscopic shaver/bur) include all processes related to raw material extraction, device manufacturing, and device packaging.

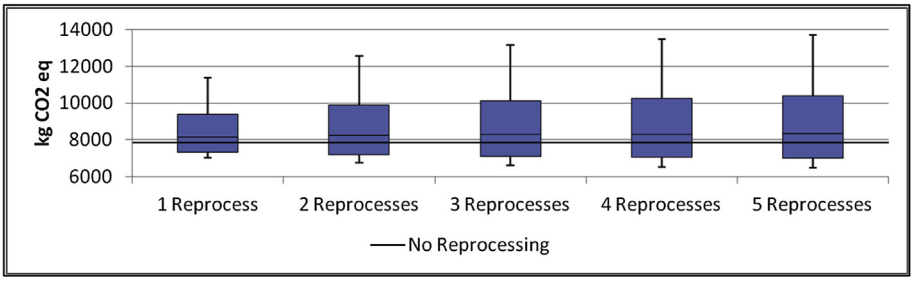

Fig. 4. Greenhouse gas emissions in kg CO_2 eq with varied reprocessing inputs for devices reprocessed one, two, three, four, five, and no instances for PBH on an annual basis.

The kg CO_2 eq emitted by PBH reprocessed devices on annual basis given varied reprocessing inputs is shown in Fig. 4. The reprocessing inputs were based on the values used in the sensitivity analysis, which varied the water and ethylene oxide used during reprocessing. Fig. 4 shows that decreased reprocessing inputs were correlated with decreased levels of kg CO_2 eq. Increased instances of reprocessing were also correlated with decreased levels of kg CO_2 eq when the reprocessing lifecycle inputs were approximately less than half of the median reprocessing lifecycle inputs. In terms of a breakeven point when compared to no reprocessing, the most statistically similar data points were that of median reprocessing inputs. Additionally, as reprocessing inputs decreased, the kg CO_2 eq would be further reduced with each additional reprocessing instance.

The carcinogenic, non-carcinogenic, and respiratory effects produced from PBH on an annual basis given varied reprocessing inputs are shown in Figs. 5–7, respectively. Similar to Figs. 4–7 show that decreased reprocessing inputs were correlated with decreased magnitudes of human health impacts. When limiting reprocessing lifecycle inputs, increased instances of reprocessing were also correlated with decreased magnitudes of human health impacts.

Carcinogenic impacts required the lowest quantity of reprocessing inputs to reach breakeven with respect to reprocessed and disposable devices. Respiratory effects required the highest amounts of reprocessing inputs to reach breakeven with respect to reprocessed and disposable devices. Therefore, carcinogenic impacts are especially vulnerable to being exacerbated given

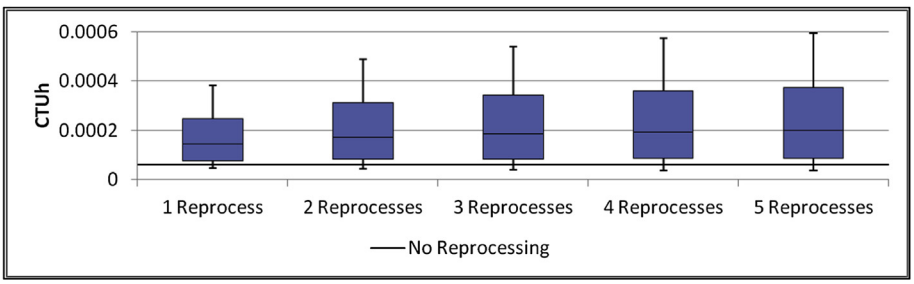

Fig. 5. Carcinogenic in Comparative Toxic Units (CTUh) with varied reprocessing inputs for devices reprocessed one, two, three, four, five, and no instances for PBH on an annual basis.

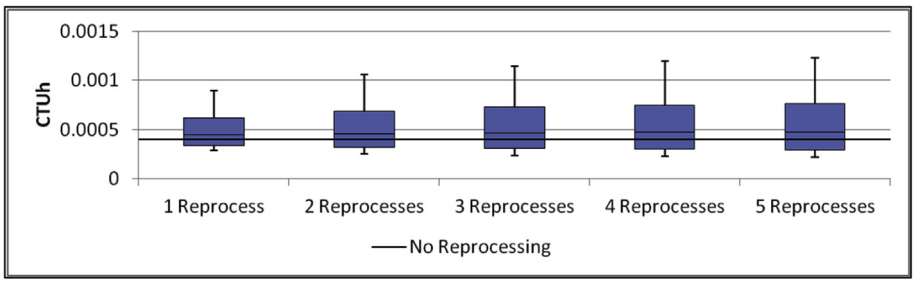

Fig. 6. Non-carcinogenic impacts in Comparative Toxic Units (CTUh) with varied reprocessing inputs for devices reprocessed one, two, three, four, five, and no instances for PBH on an annual basis.

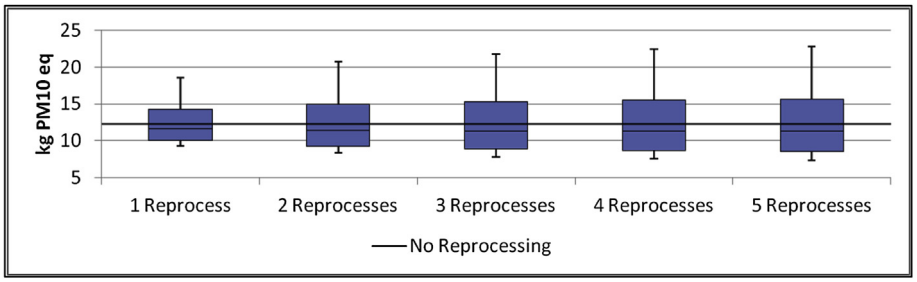

Fig. 7. Respiratory effects kg PM_{10} eq with varied reprocessing inputs for devices reprocessed one, two, three, four, five, and no instances for PBH on an annual basis.

increased reprocessing inputs; and, vice versa for that of respiratory effects.

Fig. 8 shows the relative global warming and human health impacts for the seven analyzed devices where annual usage is not taken into account (i.e., one-to-one device comparison). The compression device and ligasure are the devices with the highest environmental impacts; while the ultrasonic scalpel is consistently third and the endoscopic trocar is consistently fourth. The woven

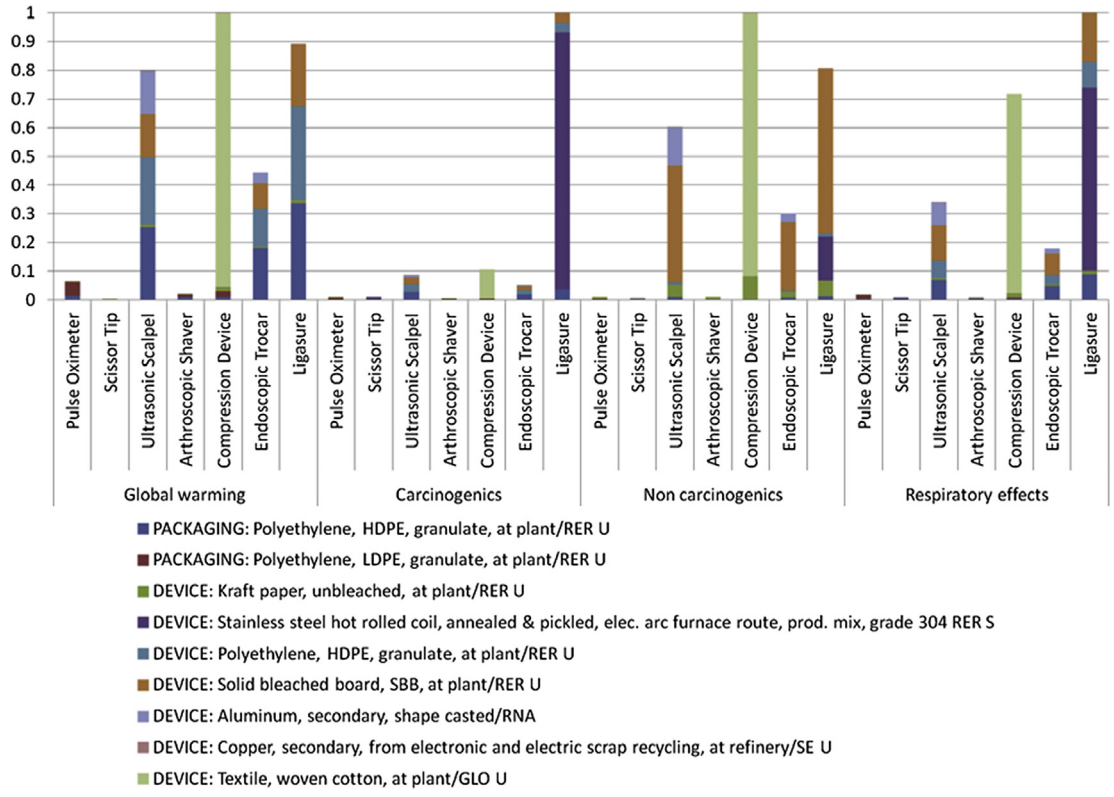

Fig. 8. Global warming and human health impacts for the seven analyzed devices normalized to the device with the highest impact.

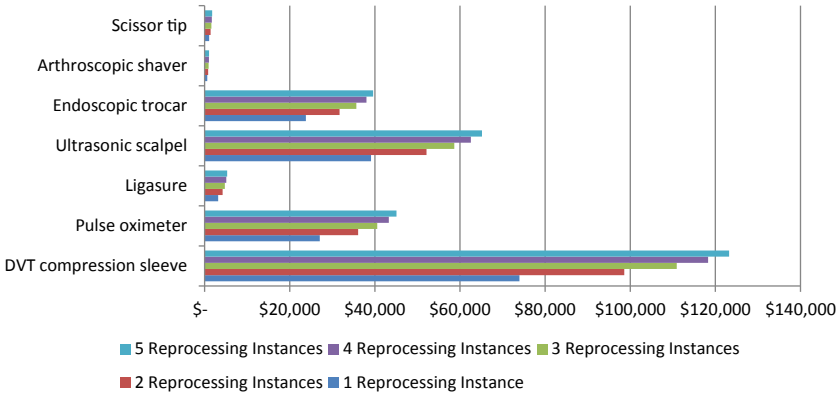

Fig. 9. Reductions in supply chain cost for each device versus instances reprocessed.

cotton textiles drive the environmental impacts of the compression device; textiles contribute over 91% to all four compression device impact categories. Additionally, the high levels of polyethylenes in the ligasure and its packaging are statistically significant in contributing to environmental impacts. The pulse oximeter, scissor tip, and arthroscopic shaver were not statistically significant; where, these devices had normalized global warming and human health impact values that were all less than 7%.

3.2. LCCA

Increased reprocessing of the seven medical devices utilized by PBH correlated with a decrease in overall economic costs associated with the manufacturing, use, and disposal of those devices. When all seven devices were reprocessed one through five instances, the total savings on an annual basis (versus when no devices were reprocessed) were $182 k, $351 k, and $520 k (in terms of 2013 US dollars), respectively. These results are further detailed in Fig. 9.

Additionally, the reprocessing of DVT compression sleeves had the highest potential for cost savings, where the cost savings for DVT compression sleeves represented nearly half of the potential savings realizable to the hypothetical hospital. And because of the high original equipment manufacturer (OEM) costs associated with harmonic scalpels, the reprocessing of ultrasonic scalpels also represented significant reductions to the economic costs of PBH's supply chain.

4. Conclusions

When employing 'average' reprocessing inputs, the results showed that the global warming impacts were marginally lower in reprocessing scenarios when compared to scenarios that employed no reprocessing. On the other hand, the human health impact results marginally favored that of no reprocessing when compared to reprocessing scenarios when using median values. While these results are pertinent, the overarching result is that if reprocessing inputs are minimized, then employing reprocessing is favorable from both a global warming and human health perspective.

Whether used as a SUD or a reprocessed device, the use of DVT compression sleeves have the highest environmental impacts when devices are compared one-to-one. The significant environmental impacts associated with DVT compression sleeves were driven by the high utilization of DVT compression sleeves on annual basis at PBH, as well as the considerable environmental impacts associated with manufacturing woven cotton. Therefore, substituting woven cotton for a less environmentally intensive material could reduce environmental impacts associated with DVT compression sleeves. It should also be noted that the high quantities of plastics (i.e., HDPE, LDPE) in ligasures correlated with significant environmental and human health impacts when used as either reprocessed or disposable devices.

When taking into consideration the economic benefits of reprocessing, the favorability of reprocessing medical devices becomes more apparent. Even in scenarios of high reprocessing inputs, the global warming and human health tradeoffs between reprocessed and disposable supply chains is not sufficiently significant to outweigh the financial benefits of reprocessing.

Hospitals that are comparable in size, services provided, and overall reprocessing profile to PBH can expect similar results. Hospitals that also have increased levels of reprocessing, in terms of instanced reprocessed and devices in reprocessing profile, can expects greater economic benefits; and, reduced global warming and human health impacts, under the assumption that reprocessing inputs are minimized. For all hospitals, if reprocessing inputs are optimized, reprocessing offers global warming, human health, and economic benefits over the same devices used as disposables.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2015.07.144.

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