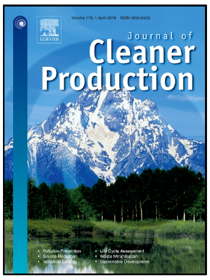
Accepted Manuscript



How do supply chain choices affect the life cycle impacts of medical products?

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PII: S0959-6526(18)30420-7

DOI: 10.1016/j.jclepro.2018.02.107

Reference: JCLP 12054

To appear in: *Journal of Cleaner Production*

Received Date: 04 October 2017

Revised Date: 09 December 2017

Accepted Date: 10 February 2018

Please cite this article as: Cle-Anne Gabriel, Nana Bortsie-Aryee, Natalie Apparicio-Farrell, Enaame Farrell, How do supply chain choices affect the life cycle impacts of medical products?, *Journal of Cleaner Production* (2018), doi: 10.1016/j.jclepro.2018.02.107

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ABSTRACT

The natural resource based view (NRBV) of organisations suggests that there are two main models used by businesses to achieve short-term sustainability outcomes. They are the product stewardship and pollution prevention models. Here is the case of a New York-based wholesaler of medical supplies. The business aims to develop a more environmentally sustainable supply chain for one of its products - an emesis basin. The emesis basin is currently only offered in high-density polyethylene (HDPE) plastic, which has negative effects on the natural environment. This study aimed to assess how the focus of the business' new business model might affect the overall life cycle impacts of this product. To achieve this, we compared the environmental impacts of the conventional product (Scenario 1– an HDPE basin) with equivalent products supplied via pollution prevention (Scenario 2 – a bioplastic basin) and product stewardship (Scenario 3 – green supply chain management and improvements) scenarios, as well as a combination scenario (Scenario 4). The results show that, in line with expectations, the pollution prevention option – switching to a bioplastic product – has the lowest environmental impacts. Unexpectedly though, the product stewardship option had a greater impact on the natural environment than the conventional HDPE, business-as-usual option. We suggest there may greater environmental gains to be obtained by focusing on one's core business, than by extending influence to the entire supply chain.

KEYWORDS

Natural resource-based view (NRBV); Life Cycle Assessment (LCA); sustainable supply chains; medical supply sector

HIGHLIGHTS

- Four scenarios comparing conventional and bio-plastics considered
- Bioplastic product has lowest environmental impact (pollution prevention scenario)
- Supply chain changes (product stewardship) have higher impact due to transport fuels
- There are benefits to focusing on core business over supply chain integration
- We support deeper inclusion of medical supply industry in sustainability discussion

Word Count: 8,082

1. INTRODUCTION

Businesses play a key role in ecological sustainability. Increasingly, embracing ecological sustainability is recognised as an important source of competitive advantage for firms. However, business managers must make an infinite number of decisions to achieve their organisational sustainability goals. Considerable portions of those decisions are about products:type, manufacturers and suppliers; end-user and market engagement; pricing, sales and end-of-life considerations; and choosing business models that will realise the business case for ecologically sustainable products (Iles & Martin, 2013; Lettner et al., 2017). However the question remains, which combination of choices results in the most effective strategy for achieving the lowest overall ecological impact?

The natural-resource based view (NRBV) of the firm suggests that there are three key strategies adopted by sustainability-oriented businesses: pollution prevention, product stewardship and sustainable development (Hart, 1995, 1997; Hart and Dowell, 2011). Research to date has demonstrated that these strategies do lead to improvements in overall ecological impact (see Graham et al (2016) and Bhupendra and Sangle (2017) for example). However, there are innumerable choices and strategic tweaks that each influence the ecological outcome in different ways. It is therefore important to understand how these individual choices may contribute to not only overall ecological sustainability, but also to changes in individual indicators of this sustainability.

In this paper, we present the case of Healthcare Hub LLC, a wholesaler of medical equipment based in Buffalo, New York. Healthcare Hub represents emerging practice in sustainability in the medical supplies field[1]. The business is currently undertaking a change to

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[1] There is a growing market of hospitals and other healthcare providers willing to take the first steps towards ecologically sustainable operations, procurement and service provision. More and more US hospitals are enrolling to Practice Green Health (https://practicegreenhealth.org/about/history) in recognition of the impact of their operations on environmental health. As at 2014, Practice Green Health's Healthier Hospitals Initiative (HHI) has had considerable success (https://practicegreenhealth.org/sites/default/files/upload-files/fnl_hhi_milestone_report_061015_lores.pdf): 457 hospitals

a more environmentally sustainable business model, starting with one of its products, an emesis basin made of high-density polyethylene (HDPE) plastic. We interviewed the managers over the course of one year about the details of its current emesis basin supply chain, and about its plans for improved environmental impact. We conducted a Life Cycle Analysis (LCA) based on its conventional supply chain (Scenario 1). We then compared these results to the LCA results for two greener supply chain alternatives: switching to an emesis basin made of bioplastic (a pollution prevention strategy – Scenario 2), or making greener choices along various stages of the product supply chain (a product stewardship strategy – Scenario 3). We also modelled the life cycle impacts if both alternatives were adopted (Scenario 4). In this paper, we compare and discuss the individual supply chain choices made in each scenario and relate them to the ecological impacts of each strategy.

1.1 The Natural-Resource Based View (NRBV)

Anecdotally and in the literature, growing awareness and consideration of environmental impact among businesses is a move towards sustainable development (Etzion, 2007; Hoffman & Georg, 2013). The consensus is that consideration of the natural environment in management literature is relatively new (Etzion, 2007; Haden, Oyler, & Humphreys, 2009; Sarkis, Zhu, & Lai, 2011). However, there is already some evidence that this concern for natural resources is an increasingly important factor related to business success and survival (Bansal & Roth, 2000; Hart & Dowell, 2011; Hoffman & Georg, 2013). This evidence is underscored by considerable effort to develop and advance the natural

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achieved an aggregate recycling rate of 24%, and reduced their energy use by 2.5%. It is this hospital market, and their associated Group Purchasing Organizations (GPOs), that Healthcare Hub intends to target. Following this emerging best practice trend in the provision of medical services, the medical supplies sector is also taking initiative. More environmentally friendly alternatives are either now available or being developed, such as for intravenous (IV) equipment, rigid endoscopes sterilised with steam instead of chemicals (https://www.greenbiz.com/blog/2012/01/19/how-greener-medical-products-can-address-health-concerns), digital medical imaging equipment and medical waste disposal equipment (https://www.medicaldevice-network.com/features/feature128184/).

resource based view (NRBV) of the firm (see Hart (1995), Hart & Dowell (2011) and Wernerfelt (1984) for example).

The NRBV is a theory of how firms might gain strategic and operational advantages and disadvantages based on their use and leveraging of the resources offered by the natural environment. It is an extension of the resource-based view (RBV), which traditionally focuses on internal firm resources. RBV researchers extended the theory to take into account the challenges and opportunities offered by the natural environment and natural resources (Hart, 1995; Wernerfelt, 1984). The NRBV fills a void traditionally left in management theory advocating for a study of the performance and competitive advantages of businesses based on their relationship to the natural environment and the impact on resources they use (Brown, Kane, & Roodman, 1994; Hart & Dowell, 2011; Meadows, Meadows, Randers, Green, & Company, 2008). There are three key strategic capabilities under the NRBV: sustainable development, pollution prevention and product stewardship (Hart, 1995). These three strategies take into account the environmental, social and economic dimensions of the challenge presented. The scopes of the pollution prevention and product stewardship strategies are different, but may ultimately add up to a more long-term sustainable development strategy. In the following paragraphs, we briefly explain each strategy in turn.

The pollution prevention strategy considers the emissions, effluents and wastes generated by the production of a product. Such approaches seek to prevent waste and emissions rather than cleaning them up at “end of pipe” (Fowler & Hope, 2007; Maas, Schuster, & Hartmann, 2014). The pollution prevention strategic capability draws on continuous improvement as a key resource. This allows firms to tap into lower costs as a source of competitive advantage (Hart, 1995, 1997; Hart and Dowell, 2011). As it is concerned with cleaner production alternatives, firms adopting this strategy tend to focus on the development of new products or materials, or reducing pollutants from the production process, which can increase efficiency by reducing the inputs required, simplifying the process and reducing compliance and liability costs. Current uses of the NRBV in research have focused largely on pollution prevention strategies (Hart & Dowell, 2011). There has been considerably less empirical research on product stewardship. The prominence of product stewardship in the scenarios considered is an important contribution of this research.

Product stewardship expands the scope of the pollution prevention capability to include the entire value chain and life cycle of the firm’s product system (Hart & Dowell, 2011; Menguc & Ozanne, 2005; Michalisin & Stinchfield, 2010). While it does involve some of the same pollution prevention activities, other key activities involved include stakeholder engagement and supply chain integration (Bhupendra and Sangle, 2017). It also involves developing and exerting influence over the entire supply chain, thereby allowing the business to pre-empt its competitors.

The sustainable development strategy includes principles and approaches embraced under the pollution prevention and product stewardship strategies. It refers to firm strategies that seek to not only cause less environmental damage, but also to produce in a manner that can be sustained indefinitely into the future (Hart, 1997; Hart & Dowell, 2011). The sustainable development strategic capability draws on firm stakeholders’ shared vision and relies on its future orientation as a source of competitive advantage (Hart, 1997; Hart & Dowell, 2011). In such cases, the firm adopts a more holistic view and focuses on minimising the effects of the future growth of the firm on the natural environment. This particular strategic capability is not discussed further in this paper, as the case firm has not communicated a vision that is consistent with a longer-term overall corporate-level strategy towards sustainable development. Their green strategy is instead purely at the business and operational level – it is a product- and supply chain-focused strategy.

The two alternatives considered by Healthcare Hub are pollution prevention and product stewardship strategies. This study intends to move beyond the extant discussion of the importance and usefulness of each strategy. Instead, the study contributes empirically obtained insight into the improved ecological impact caused by adopting these strategies.

1.2 The Case and Scenarios Considered

Healthcare Hub LLC is a wholesaler of healthcare equipment and supplies. The firm has identified an opportunity in its market to procure and supply more ecologically friendly products to its customers. Initiatives such as the United States' Healthier Hospitals Initiative (HHI)[2] have had notable success. In addition, extant research suggests there is a growing need for hospitals and others involved in the medical supplies value chain to take the first steps towards environmental sustainability. In particular, there are calls for more ecologically sustainable operations (Brown, Buettner, Canyon, Crawford, & Judd, 2012; S. Unger & Landis, 2016; S. R. Unger, Campion, Bilec, & Landis, 2016), service provision, design and procurement (Campion et al., 2015; Moultrie, Sutcliffe, & Maier, 2015; Stripple, Westman, & Holm, 2008; Xin, 2015). It is this niche hospital market, and their associated Group Purchasing Organizations (GPOs), that Healthcare Hub intends to target.

Scenario 1: Healthcare Hub's current product offering includes a range of high-density polyethylene (HDPE) medical products. However, for simplicity, one specific product was used – a plastic emesis basin. Scenario 1 analyses the life cycle impacts of one conventional HDPE plastic basin. The use of plastics has grown considerably in the last decades (Kreiger, Mulder, Glover, & Pearce, 2014), and is expected to continue rising (Álvarez-Chávez, Edwards, Moure-Eraso, & Geiser, 2012). However, there are demonstrated critical environmental impact challenges associated with the use of plastics. These include,

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[2] The Healthier Hospitals Initiative was founded "to create a guide for hospitals to reduce energy and waste, choose safer and less-toxic products, and purchase and serve healthier foods". For further information: http://healthierhospitals.org/about-hh

for instance, high electricity consumption during the injection moulding process (Elduque, Elduque, Javierre, Fernández, & Santolaria, 2015) and waste management, reuse and recycling challenges (Kreiger et al., 2014; Martínez Urreaga et al., 2015; Sharma & Bansal, 2016). In Scenario 1, because the analysis focused on the conventional business-as-usual case, we also considered the already employed sustainability practices from the conventional supply chain. For instance, industry figures state that 85% of corrugated packaging is recycled with 12.3% landfilled and 2.7% burned with energy recovery (National Council for Air and Stream Improvement (NCASI), 2014). We accounted for these waste treatments in our calculations. They are also reflected in the impact assessment.

The company also intends to change its business model to include, firstly, the supply of products made of greener plastics with an overall lower ecological impact. They also aim to provide a range of green services around these new products. One of the company's first steps was to consider the ecological impacts of its conventional plastic products, and then compare these impacts with those of the two alternatives they considered: (1) switch to bioplastic products or (2) continue to supply conventional plastic products, but ensure they are manufactured under cleaner production conditions. As these were the two options identified by Healthcare Hub, we limited our analysis to the real-life options and alternatives considered by the firm's managers.

Scenario 2: The natural resource-based view suggests that pollution prevention models are strategies adopted by businesses that aim to reduce the ecological impacts of the products themselves by focusing on the source of the emission, effluent or waste (Hart, 1995, 1997; Hart and Dowell, 2011). Interest and demand for biodegradable and bio-based plastics have increased due to concerns about ecological conservation, finding material substitutes for fossil fuel based plastics and the importance of plastics to society (Álvarez-Chávez et al., 2012; Kishna, Niesten, Negro, & Hekkert, 2017; Papong et al., 2014). Optimistically, though they still make up only about 2% share of the polymer market, production capacity is expected to grow by more than 400% by 2018 (Aeschelmann & Carus, 2015) and they have become a real alternative on the market (Kishna et al., 2017). Though still not fully sustainable due to impacts associated with their production (Álvarez-Chávez et al., 2012), they are a more ecologically friendly alternative to fossil-based plastics (Papong et al., 2014; Razza et al., 2015; Tsiropoulos et al., 2015). If Healthcare Hub could either influence or source their products from suppliers involved in cleaner production / greening practices, this would reduce the ecological impacts caused during the production and supply process of fossil-based plastics. Healthcare Hub therefore commissioned a life cycle assessment (LCA) to first compare the environmental impacts of the conventional plastic products to the bioplastic it intends to supply in future. In this Scenario, we combined the documented manufacturing process for the selected bio-ethanol based ethylene[3] alternative (Morschbacker, 2009) with Healthcare Hub's existing supply chain features to generate ecological impact estimates for a basin made from bioplastic.

Scenario 3: Product stewardship models, on the other hand, aim to adopt a holistic perspective of the entire product supply chain. Product stewardship focuses on building capability in managing supply and production relationships (Hart, 1995). Studies of closed loop supply chains[4] , supply chain sustainability[5] and the influence of end-users on consumer preferences for products from cleaner production processes[6] are examples of the application of product stewardship to environmental management research. We therefore investigated whether Healthcare Hub could improve the ecological impacts of the conventional product if the business undertook a product stewardship approach. Therefore, we also conducted an

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[3] Product commercially available from *Braskem*: http://www.braskem.com/site.aspx/Im-greenTM-Polyethylene

[4] See Govindan et al. (2017) and Dangelico and Vocalelli (2017) for instance.

[5] See Kannegiesser, Guenther and Autenrieb (2015), Bechtsis et al. (2017) and Mokhtar et al. (2017) for instance.

[6] See Dangelico and Vocalelli (2017) and Ritter et al. (2015) for instance.

LCA to examine this scenario (Scenario 3). Under this product stewardship scenario, the bunker fuel (diesel) used to power the ship used to transport the naphtha from Brazil to the United States is replaced by a cleaner alternative (liquefied natural gas). So too was the diesel fuel used for land transportation replaced by compressed natural gas. In addition, we used the optimistic assumption of 100% recycling of the corrugated packaging. This may be achievable if Healthcare Hub convinces the hospitals purchasing the basin to return the packaging for recycling.

Scenario 4: The case business initially considered only two alternatives – either the bioplastic basin, or supply chain engagement and improvements. However, we added a fourth scenario to our analysis. A final, fourth LCA was conducted to investigate the potential ecological impacts of adopting a combination of pollution prevention and product stewardship approaches – that is, a bioplastic basin that is also manufactured using cleaner production improvements (Scenario 4). It is important to note here that Scenario 4 does not represent a sustainable development strategy. Indeed, one might consider sustainable development strategies an aggregate of the pollution prevention and product stewardship strategies. However, this is true only insofar as it is a corporate level, longer-term strategy for businesses. The pollution prevention and product stewardship strategies (and, by extension, our Scenarios 2 and 3) are enacted on the business and operational levels of the firm. The combination scenario did not consider broader external environmental and industry-level implications. Instead, it is essentially a short-term combination business-level scenario, and therefore not an example of a sustainable development strategy.

2. METHODS

2.1 Data Collection

As is often the case with research involving businesses, we engaged with Healthcare Hub based on a research consultation exercise. That is, we applied the methodological rigour of life cycle analyses to a series of consultations with the owner and manager of Healthcare Hub. Healthcare Hub had already identified a sustainability challenge and considered a potential solution, so they invited us to analyse the supply chain and make suggestions for improvement. The question we considered was, is the replacement of HDPE plastic with bioplastic the best possible solution for supply chain sustainability for the company? We consulted with Healthcare Hub over the course of one year about the extent of its supply network and influence, and its main partnerships for realising the implementation of its new bioplastics strategy.

We collected the information and data needed in two ways. First, we discussed the business' challenge in a series of phone and email conversations with the Director and Chief Executive Officer (CEO) of Healthcare Hub. In one year, we engaged in six phone conversations with the managers of the business, lasting over seven and a half hours. Additionally, we exchanged 78 emails with the managers. The purpose of these conversations was: to outline the boundaries and parameters to be considered; to clarify the supply chain and its actors; to establish a clear understanding of the existing product's origins, dimensions, customers, main uses and distribution logistics. We also discussed Healthcare Hub's own plans to engage suppliers of the alternative bioplastic basin. Second, we collected secondary data in the form of documents that verify the company's current supply chain as well as the newly proposed supply network for the bioplastic product. We also consulted technical reports and journal articles about the main physical and chemical characteristics of the current and proposed new product, as well as documents detailing the company's current and proposed future business model. We collected a total of 1,994 pages of secondary data relating to the supply chains of conventional and bioplastic products. We consulted 1,349 pages on LCA methodology and parameters[7] and 499 pages related to specific supply chain features related to the product under study, especially the conventional supply chain[8]. Additionally, 73 pages were specific to the bioplastics supply chain[9] and 604 provided information on known ecological impacts and implications of the products[10]. Additional secondary data were collected from various other sources as the basis of the LCA models used for the research, as described and cited in the following sections.

2.2 Goal and Scope Definition

To reiterate, this study aimed to assess and compare the life-cycle impacts of a conventional plastic (HDPE) emesis basin. The research considered the life-cycle impacts of three alternatives: a bioplastic basin; a conventional plastic (HDPE) basin manufactured and supplied under a product and supply chain stewardship strategy; and a bioplastic basin that is also supplied under a product and supply chain stewardship strategy (a combination of previous two alternatives). The scope of the study covered all stages of the emesis basin production and supply chain from raw material production to utilisation and end-of-life. That is, a cradle-to-grave assessment. Figure 1 shows the flow process, from both conventional and green ethylene (plastic) production, to manufacturing of the basin itself and transportation to the customer (hospitals) and end-of-life. These flows are illustrated within the system boundary defined.

[Insert Figure 1 here]

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[7] For example, Guinée, J., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., Koning, A. de, … Udo de Haes, H. A. (2002).

[8] For example, Ammah-Tagoe (2004), Thiriez, A., & Gutowski, T. (2006) and PlasticsEurope (2008).

[9] For example, Alvarenga, R. A. F., & Dewulf, J. (2013), Braskem (2012) and Macedo et al (2008).

[10] For example, CEPI (2015) and Adhikari, D., Mukai, M., Kubota, K., Kai, T., Kaneko, N., Araki, K. S., & Kubo, M. (2016).

The functional unit used for all aspects of this study was one basin, or 100 grams (g) of plastic basin per single use. The energy inputs considered included all energy used for sugarcane and naphtha production, the basin manufacturing process, and transportation from each stage. Material inputs accounted for throughout the entire life cycle included crude oil and sugarcane, naphtha, the finished basin itself, and packaging. The outputs considered were emissions of greenhouse gases (GHG) carbon dioxide (CO2), nitrous oxide (N2O) and methane (CH4), as well as materials such as waste packaging and waste char (from the incineration process of handling bioplastic waste).

The impact assessment uses the standard procedure given in ISO 14040 (ISO, 2006) using the guidelines and characterization factors given in the LCA handbook (Guinée et al., 2002) and the ReCiPe life cycle impact assessment method (Goedkoop et al., 2009; Goedkoop & Huijbregts, 2012). The choice of impact assessment method was influenced by the goal of the study, which was to understand the ecological sustainability of the products under study. The impact categories are marine eutrophication (MEP100), climate change (GWP100), terrestrial acidification (TAP100), photochemical oxidant formation (POFP100) and particulate matter formation (PMFP100).

2.3 System Description

Raw material production (Stage 1) involves the series of processes undertaken to convert natural primary resources into raw materials needed to manufacture both types of plastics. For the conventional basin, this is crude oil *(6kWh per basin)*, which is converted to naphtha. For the bioplastic basin, this is the energy *(0.35 MJ per basin)* used to convert sugarcane *(275 g per basin)* to ethanol.

Basin manufacturing (Stage 2) considers the processes involved in manufacturing both types of basins. This stage is where naphtha *(333 g per basin)* is used as the input into the conventional manufacturing process, undergoing polymerisation, extrusion and injection moulding processes, to produce the finished product – the HDPE emesis basin *(finished product weighs 100g, or 1 functional unit)*. For the bioplastic basin, Stage 2 involves the same basic manufacturing processes, but ethanol *(189.4 g per basin)* is used as the input. Again, the output from this stage is the finished 100g bioplastic emesis basin.

Basin transportation (Stage 3) is transportation from manufacturing to Healthcare Hub's inventory and storage facilities in Buffalo, New York. For the conventional basin, one of Healthcare Hub's current products (one particular brand of basin) is used as the example – assumed to be manufactured in the south-eastern United States. Inputs in this stage include energy as well as the packaging *(115g per basin)* in which the finished product is transported. Once the product is purchased by a Healthcare Hub customer, it leaves inventory storage and enters Stage 4 (i.e. the Use stage).

Basin use (Stage 4) involves the various ways that the product is used by healthcare providers around the United States. For this LCA, it was assumed that the basin is transported from inventory to a customer within a 500 mile radius of Buffalo, NY (refer to assumption 3, highlighted in the last paragraph of this section), where it is used for an undefined period of time. At end of life, the basin will enter the final stage (Stage 5).

Basin after use (Stage 5), or end-of-life, involves all the disposal and / or recycling and treatment activities that the product is likely to undergo at the completion of its life cycle. For both basins, this is most likely to be incineration first, then landfilling of the waste ash. Additionally, the intention is that the bioplastic basin will be incinerated and the after use output, waste char, will be produced (Hellweg, Hofstetter, & Hungerbühler, 2001). The material and energy flows considered are illustrated in Figure 2.

[Insert Figure 2 here]

The following assumptions were made when conducting the LCA: First, Healthcare Hub currently stocks emesis basins made by different producers. For simplicity, the manufacturing and transportation parameters used were based on the location of one producer in the United States (longest distance-worst case scenario). Second, it was assumed that the raw materials for both types of plastics – naphtha and ethanol – originated from Port Santos, Brazil. Third, consistent with previous research (See Hendrickson, Lave, & Matthews, 2006; Ingwersen et al., 2016; Matthews & Hendrickson, 2002) , the average distribution channel distance for the United States was assumed to be within a 500-mile radius from the source. Fourth, it was also assumed that the conventional means of handling medical waste – to incinerate, then apply to landfill – applies to these products. Specifically, grate incineration, which produces heterogeneous slag with 45% volume ash, 40% melted material, 5% fractional glass and 2–5% of weight TOC with proper flue gas cleaning, was considered in the analysis (Hellweg, Hofstetter, & Hungerbühler, 2001).

3. RESULTS AND DISCUSSION

3.1 Comparing business-as-usual to the bioplastic alternative

As Healthcare Hub's intended sustainability strategy was to offer bioplastic products instead of HDPE products, we begin our presentation and discussion of the results by focusing on the environmental impacts of this choice.

Over the five life cycle stages considered, CO_2 emissions were, by far, the most significant GHG emissions caused. They are just over 2.7 times higher for the conventional basin than for the bioplastic basin. Although, relative to CO_2, the absolute amounts of N_2O and CH_4 emitted are small, total emissions are higher over the life cycle of the conventional basin than the bioplastic basin. Differences were also observed in the life cycle stages that contributed to GHG emissions. Over the five stages of the life cycle, the conventional basin is responsible for higher emissions in Stage 1, while the bioplastic basin produces the most CO_2

emissions in Stage 3 of its life cycle. For the conventional basin, this is not surprising, as the main raw material used in the production of HDPE is crude oil, which is associated with considerable GHG emissions impacts. The CO_2 emissions show a generally declining trend along the life stages of the conventional basin. For the bioplastic basin, however, Stage 3 is the transportation phase from the site of manufacturing (Texas), to Healthcare Hub's inventory in Buffalo. The CO_2 emissions caused are expected to peak in the middle of the life cycle of the bioplastic basin, due to intense transportation activities in Stages 2 and 3, and the material and energy intensity of the basin manufacturing process. Under the LCA assumptions, the bioplastic basin must be transported over longer distances than the conventional basin as it is less readily available to the market, resulting in more CO_2 emissions from transportation.

N_2O and CH_4 emissions provide further detail that helps clarify the overall life cycle impacts of both basins. Our analysis suggests that during the first two stages of its life cycle the conventional basin contributes more to GHG emissions, particularly CH4, than the bioplastic basin. Interestingly, in terms of N_2O and CH_4 emissions, the bioplastic basin is likely to have almost the same impact on GHG emissions as the conventional basin during the last three stages of its life cycle. That is, during transportation to inventory in Buffalo, during usage, and in its end-of-life / after use stage. This is important for Healthcare Hub's consideration of its future business strategy, as it may be able to control the distances over which its products travel by considering improvements to its logistical efficiency.

Though packaging inputs are the same (expected, as the study assumed that conventional and bioplastic basins are of the same dimensions), the raw material inputs are different, as the conventional plastic is made from crude oil, while bioplastic is made from ethanol produced from sugarcane. The total outputs confirm the higher impacts of the conventional basin. They also confirm the similarity of the impacts, in terms of *mass* of waste produced, of both basins. It is important to note here that although the similar waste impacts are in terms of mass, the *nature* of the materials themselves is different. In the conventional system, the waste product is the ash from incineration of the basin, which would be landfilled or otherwise disposed of. This treatment has significant ecological impacts. However, in the bioplastic scenario, Healthcare Hub has identified potential incinerators of the bioplastic, so the waste product here is waste *char*. The thermal heat generated during the production of incineration wastes can be recovered for use in waste-to-energy systems for renewable generation. Therefore, from a product perspective overall, switching to a bioplastic basin appears to be the cleaner alternative. The question we consider next, it: how do these results stand up compared to other alternatives?

3.2 Comparing the emissions and energy consumed from all four scenarios

To reiterate, in this study we not only compared Healthcare Hub's conventional business-as-usual strategy (i.e. Scenario 1) to its pollution prevention strategy (i.e. Scenario 2 – bioplastic). We also explored the potential impacts of adopting a product stewardship strategy (i.e. Scenario 3 – supplier engagement and efficiency improvements) and a combination strategy that combined the parameters of both alternatives (Scenario 4). In this section, we compare the emissions and energy consumed in all four scenarios, and discuss some of the managerial decisions that resulted in these impacts. Figures 3 and 4 illustrate the CO_2, N_2O and CH_4 emitted from all four of the scenarios considered.

[Insert Figures 3 and 4 here]

Scenarios 2 (bioplastic) and 4 (combination) emerged as the lowest emitters of CO_2 and N_2O in our comparison, with the combination scenario resulting in slightly less CO_2 than the bioplastic scenario. This suggests that combining pollution prevention and product stewardship strategies is more effective at reducing overall CO_2 emissions than if either strategy were adopted on their own. We did find, however, that though the CH_4 emitted from the combination scenario would be lower than the product stewardship scenario, it is significantly higher than the pollution prevention scenario. The combining effect of two greener alternatives has not reduced the methane emissions caused. Looking to the individual parameters of Scenario 4 and the individual managerial decisions to be made, we suggest that this CH_4-emitting effect can only be reduced if engine efficiency of heavy duty vehicles in the combustion of compressed natural gas are improved. Secondly, this CH4 emitting effect can also be reduced if leaking methane emissions through the drilling and extraction of natural gas is reduced in the supply chain of the fuel (Camuzeaux et al., 2015; Brandt et al., 2014). Figure 5 illustrates the total energy consumed by the supply chains in all four of the scenarios considered, and Figure 6 shows the total emissions from the life cycle stages of each scenario.

[Insert Figures 5 and 6 here]

In terms of the total energy consumed, again Scenarios 2 and 4 emerge as the lowest consumers of energy in their supply chains, with Scenario 2 producing only slightly more. These results suggest, again, that a combination of strategies is more effective than considering and adopting either pollution prevention or product stewardship in isolation.

3.3 Comparing the ecological life cycle impacts of all four scenarios

Next, it is important to compare the overall life cycle impacts of all four scenarios. The managerial decisions affecting the emissions produced and energy consumed aggregate to these ecosystem-level impacts. There are a number of Life Cycle Impact Assessment (LCIA) methods available. For the purpose of this particular LCA however, it was determined that *ReCiPe 2008 version 1.11* was the best fit because it offered a problem-oriented approach to fulfilling the aims of the study. The emissions were classified under five impact assessment categories: marine eutrophication (MEP100), climate change (GWP100), terrestrial acidification (TAP100), photochemical oxidant formation (POFP100) and particulate matter formation (PMFP100). This best suited the finding that only three emissions (CO2, N2O and

CH4) were significant to the products under study. The findings from the ecological impact assessment are summarised in Figure 7.

[Insert Figure 7 here]

The ecological impact results paint a considerably different picture than the one illustrated by the emissions and energy consumption results. Here, Scenario 2 (the bioplastic basin, pollution prevention scenario) has emerged as having the smallest overall ecological impacts. This can be compared to results from the emissions and energy consumption analyses where, for the most part, both Scenarios 2 and 4 emerged as the least emitting. Scenario 4 has significantly higher potential climate change impacts than Scenario 2. We infer that this is a result of the higher global warming potential (GWP) of CH_4 than CO2, as CH_4 emissions were found to be significantly higher in Scenario 4 than Scenario 2 (refer to previous section 3.2).

Marine eutrophication impacts are linked to N_20 emissions, which peak during the manufacturing stage. For the conventional basin, though, the effects of crude oil processing for naphtha production come a close second in terms of causing these effects. Climate change impacts refer to the effects of emissions of CO_2, N_2O and CH_4 on long-term changes and variability of Earth's natural climate and weather patterns. As mentioned in section 3.2, for the emesis basins CO_2 emissions are the most worrying of these three, as it is emitted in the largest quantity. Eliminating the fossil fuel production and processing (to produce naphtha) aspects of the process alone would reduce the entire life cycle impacts of the conventional emesis basin by about 54%. A bioplastic basin would be responsible for only about 37% of the global warming potential (GWP) of a conventional basin.

Terrestrial acidification and particulate matter formation can both be caused by the emissions of N_2O from various stages of the life cycles of both basins. Acidification is caused by emissions of nitrogen and sulphur, which may eventually be deposited on the soil, leading eventually to a decrease in the relative richness of vascular plants. Particulate matter is the term used to refer to solid and liquid particles that are found in the air. They may be formed in the atmosphere when N_2O is released and reacts to form fine particles. Over the life cycles of both basins, this is most likely to occur during the first three stages (refer to Figure 4). In addition to particulate matter formed from the industrial manufacturing process, the transportation processes involves diesel vehicles, which are also a serious source of these pollutants. Overall, increasing the use of bioplastic basins will reduce the impact on both terrestrial acidification and particulate matter formation by about 43%. On average, across all the impact categories considered, the impact assessment suggests that an emesis basin made of bioplastic is likely to have an overall 42% less impact on the ecological environment.

Focusing on take back recycling initiatives as part of a product stewardship supply chain strategy (Scenario 3) resulted in some improvements in the environmental impacts of the conventional basin (Scenario 1). In comparison to the business as usual where we assumed 85% recycling, advocating 100% recycling results in a 4.6% reduction in particulate matter formation. There was also a 15.9% reduction in photochemical oxidant formation. Smog emissions are lower for the 100%-recycled product than for the industry-average product. This is mainly because NOx emissions are lower at pulp and paper mills that use 100%-recycled fibre than for the industry-average, most likely due to a different fuel mix (Blanco et al., 2004; CEPI, 2015). Recycling also results in a 4.7% decline in eutrophication. The results for the eutrophication indicator are significantly lower for the 100%-recycled product than for the industry-average product. The main explanation is that NO_x emissions to air and phosphorus releases to water are significantly lower at pulp and paper mills that use 100%-recycled fibre. It is important to note, however, that phosphorus releases from pulp and paper mills are uncertain for both the industry-average and 100%-recycled products.

However, more recycling results in some increases in ecological impact – acidification sees a 6% increase, and global warming potential sees a 295% increase. We suggest there may be three explanations for this. Firstly, there are significantly more removals of CO_2 from the atmosphere associated with the industry-average (due to its consumption of virgin fibre) that are not offset by emissions at the end-of-life because 85% of the product is recovered for recycling. Secondly, the 100%-recycled product consumes more purchased energy that is almost fully generated using fossil fuels. Finally, there are more fossil fuels burned at mills using 100%-recycled fibre. From a management and supply chain perspective, one must therefore weigh the consequences of recycling initiatives, and carefully consider the impact metrics to be used (e.g. global warming versus particulate matter formation).

3.4 Sensitivity Analysis across all four scenarios and life cycle stages

Photochemical oxidant formation is a form of air pollution likely caused during the first three stages of the life cycle of both products. Additionally, the final stage ('after use') also contributes to emissions of methane, most likely due to the incineration and landfilling activities occurring at this stage. According to the impact assessment results, however, an emesis basin made of bioplastic is likely to make about a 42% smaller contribution to the formation of photochemical oxidants in the atmosphere. Figure 8 summarises the sensitivity analysis results. It shows percentage contribution to ecological impacts with the change in supply chain strategy for each scenario.

[Insert Figure 8 here]

Perhaps one of our more interesting findings however is that the ecological impacts of all four scenarios are almost the same in the last three stages of the product life cycle: Transport, Use and After Use. Indeed, regardless of the strategic and supply chain changes to produce each scenario, the impacts in these three stages are almost the same. We argue that there are three main reasons for this. Firstly, it is difficult to influence a change in transport fuels used by other businesses. Though fossil fuel alternatives exist, they are much less mainstream than deeply embedded diesel and natural gas. Therefore, given the current status quo and technological and operational best practice, we expect that the transport vehicles used to transport basins to consumers will continue to run on fossil energy. It is also important to note our expectation that Scenario 2 (the bioplastic basin) will produce relatively higher emissions than the other alternatives - it is a rarer form of plastic, and therefore not easily sourced from nearby suppliers. Secondly, despite the adoption of a bioplastic basin and the use of supply chain engagement and greening strategies, the packaging of the product remains the same. In our scenarios, we assumed that the bioplastic basin would have the same dimensions as the HDPE basin, and therefore would require the same dimensions of packaging material to be recycled in a similar manner and to the same extent. Thirdly, although the materials and the way they are handled changes, it is important to remember that, after use, the waste produced is still medical waste. There are numerous regulations around the handling of medical waste (Makajic-Nikolic et al., 2016; Campion et al, 2015). All the waste produced in each scenario must be incinerated. The hazardous and sensitive nature of the material reduces the chances that the waste ash from the bioplastic basin will be applied to agricultural fields (Makajic-Nikolic et al., 2016; Campion et al, 2015).

3.5 Lessons learned: How can ecological impacts inform supply chain decisions in the medical supplies sector?

So far, we have investigated and discussed how different supply chain strategies and decisions may affect the environmental impacts of medical products. Now, we consider a different perspective: that is, that results such as these might (and, perhaps, should) influence the supply chain strategies and decisions of business managers. In writing this section, we aim to highlight the importance of reflection in management decision-making, especially for achieving sustainability goals.

The first lesson for businesses in the medical supplies sector is that metrics matter. Certainly, the impact categories and measures used by businesses have a considerable effect on the ecological impact outcomes achieved and, therefore, on the managerial decisions to be made. In industries new to ecological sustainability considerations, there appears to be an overwhelming focus on impacts in terms of GHG emissions. Focusing on emissions only, managers might be inclined to choose the combination scenario. However, our research suggests that GHG emissions are only part of the picture. In this research we found that the combining effect of two greener alternatives has not reduced the methane emissions caused because of technological deficiencies in the use phase of the fuel (engine efficiency) and production phase (methane leakages). To make this strategic choice more effective, managers would need to exercise influence over the transportation industry to encourage the use of more sustainable transportation fuels and the design and availability of alternative modes of transportation. Alternatively, if managers in the medical supply chain focus instead on physical ecological impacts, they would need to consider a different set of decisions. From our findings, one might be inclined to switch to a bioplastic alternative of the product. From the perspective of ecological impacts, switching from conventional plastic to bioplastic products is indeed preferable because the raw material used to produce the product is itself a cleaner alternative compared to the crude oil used to manufacture HDPE products.

Businesses with little or no influence over the medical supply industry's upstream activities might prefer to use physical ecological impact metrics. Using these metrics could assure eco-conscious customers that choosing bioplastic instead of HDPE products reflects the business' responsible sourcing priorities. Indeed, it is important for managers to consider the aspects of their operational activities that are directly and indirectly within their control, to inform strategic decision-making about ecological sustainability. However, in an industry as large as medical supplies, vertical supply chain integration is difficult to achieve. Therefore, for businesses who have achieved integration and therefore have some control over individual supply chain players, a combined strategy of alternative products and supply chain engagement is achievable. In best practice cases, such businesses should rely on both physical ecological impact and GHG emission metrics to highlight their ecological sustainability achievements on both pollution prevention and product stewardship fronts.

The second lesson for medical supply businesses is the importance of the decision to focus on upstream versus downstream activities. The estimated ecological impacts of the firm are likely to have a significant impact on this decision. Due to safety, infection-control and hygiene concerns, there are difficulties along the road to lowering the ecological impact of the downstream activities of the medical supplies sector (Campion et al., 2015; Makajic-Nikolic et al., 2016). However, reducing ecological impacts in this sector need not be a zero-sum game. This, we argue, is the third lesson for other sustainability-seeking businesses in this industry. For example, medical suppliers considering implementing product take back and closed-loop initiatives face the challenge of recycling or repurposing contaminated hospital waste (Makajic-Nikolic et al., 2016). There is also the challenge of negotiating with raw material producers and product manufacturers who are not otherwise affiliated with the medical supply industry and therefore lack an understanding of the peculiar sustainability challenges faced. Rather than espousing an all-or-nothing approach to ecological sustainability, our findings suggest that it is indeed possible to achieve some reduction in impact by adopting what we loosely describe as an *all-or-something* perspective instead. There is strong evidence from our research to suggest that the combination scenario, which represents an 'all' approach, produces the least overall ecological impacts compared to simply doing 'something' in scenarios 2 and 3. Indeed, the impacts were considerably better than doing 'nothing', illustrated in the business-as-usual scenario. Given the innumerable decisions to be made along the supply chain, sustainability-seeking medical supply companies might consider and be motivated by the implication that, even if vertical integration is difficult to achieve, engaging with one or a few key stakeholders makes a difference to the overall GHG emissions from their activities.

4. CONCLUSIONS

This study was of course subject to certain limitations and assumptions. For instance, the functional unit of 100 grams plastic per single use was based on the weight of one conventional basin, in order to ensure comparative consistency between the two types. Additionally, the LCA used Tennessee as the manufacturing base of the conventional product, based on information provided by the case company about the current brands sold to customers. However, bioplastic manufacturing is also known to occur in Texas. If the distance from manufacturing to inventory was assumed to be the same for both basins, this too would lead to yet another alteration of the result – resulting in a further increase in the ecological impacts of the conventional basin. However, this would not have affected the overall finding that the conventional basin was the least sustainable alternative of the four scenarios considered. Additionally, we assumed that the distance to the end users of the product is 500 miles, which is consistent with the estimated national average of the United States (Ammah-Tagoe, 2004). Therefore, the ecological impacts of all scenarios considered will increase for customers that are located outside a 500-mile radius from Buffalo, New York. These assumptions are important considerations for decision-making about the future of Healthcare Hub’s business model.

However, despite these limitations and assumptions, the operationalisation of LCA as scenarios proved to be a powerful tool for research-motivated comparison and practical management decision-making. The advantages are twofold. Firstly, as Healthcare Hub operates within the medical supplies sector, supply chain sustainability and engagement is important. LCA’s use of life cycle stages as the units of analysis, and the ability to compare between stages and scenarios provides managers with multiple discrete decision points for improving the ecological impacts of their activities. The LCA scenarios considered provide the manager with a stage-wise map of ecological impacts and options for improvement. Secondly, the use of LCA scenarios could be a powerful tool for supply chain communication. For instance, although Healthcare Hub is willing to provide more ecologically sustainable products, the results on transport fuels indicate that it is difficult to influence other supply chain partners to do the same. However, presenting scenarios, which could indicate the sensitivity of ecological impacts to the actions of a single actor, could seed discussion about more sustainable alternatives. Indeed, the scenarios highlight how a single actor or process in the supply chain might influence the outcome for an entire sector. In sum, the use of LCA methodology in scenarios provides managers with more parameters and therefore greater conceptual advantage for future decision-making.

The bioplastic basin itself is indeed a more ecologically friendly product than the conventional HDPE basin. However, Healthcare Hub has some opportunities to further neutralise any remaining ecological impacts, and therefore improve the overall sustainability of the company’s supply chain and distribution activities. Firstly, simply incinerating the products at end of life is not enough. As the LCA shows that the end-of-life effects of both products are almost the same, it would be important to take additional steps to improve the after use ecological impacts of the bioplastics basin. Secondly, the land use impacts of both basins was not included in the system boundary of the LCA. However, given existing knowledge about the amount of sugarcane needed to produce one basin (275g), the research extrapolated that the production of a single bioplastic basin requires about 0.033 square meters of land. With critical land use changes occurring around the world, the dependence of the bioplastic basin manufacturing process on land is a considerable disadvantage (Tomei and

Helliwell, 2016; Spangenberg, 2008; Searchinger et al., 2008). It is possible that land use changes and challenges could cause the price of the basin to increase with time. Future business planning should consider these possibilities.

The findings strongly support the adoption of a pollution prevention supply strategy going forward. Additionally, with some changes and careful decision-making about more sustainable transport options, a combination of both pollution prevention and product stewardship strategies may yield optimal results and lower ecological impacts. Furthermore, we did not consider the potential for Healthcare Hub to influence the bioplastic production process, where improvements such as pesticide and burning reduction or elimination would yield even better ecological impact outcomes (Tsiropoulos et al., 2015). This would improve the overall ecological sustainability of this and other medical supply chains.

These findings are also a call for deeper inclusion of the medical supply industry in sustainable innovation initiatives and research globally. There is still much to be learned, and given the importance of the industry to healthcare providers and systems worldwide, there is a need for further research into the motivations and justifications used by providers to seek greener alternatives that do not compromise (and may, perhaps, even improve) the quality of care provided.

Our results are significant for a number of reasons. Firstly, we highlight the challenges involved in improving the sustainability of medical products, which come with their own restrictions on disposal and handling at the end of life. These restrictions suggest that medical suppliers might consider prioritising upstream supply chain changes (e.g. raw material extraction and manufacturing) rather than downstream interventions (i.e. the customer interface and end of life). Secondly, as discussed in section 3.5, the results demonstrate the complex interlinkages between sustainability and managerial decision-making. Managers should carefully consider the metrics used and prioritising sustainability interventions in the parts of the supply chain that are core to their business and which they can control. Finally, our findings suggest that combining pollution prevention and product stewardship strategies is more effective for reducing overall CO_2 emissions than if a business adopts either strategy on its own. The natural-resource based view of firms and their interactions with the natural environment outlines a three-pronged perspective of the strategies businesses use to achieve lower ecological impacts (Hart, 1995, 1997; Hart and Dowell, 2011). Our findings are a timely reminder that there is indeed overlap between these strategies and that they are perhaps more effective when used in tandem.

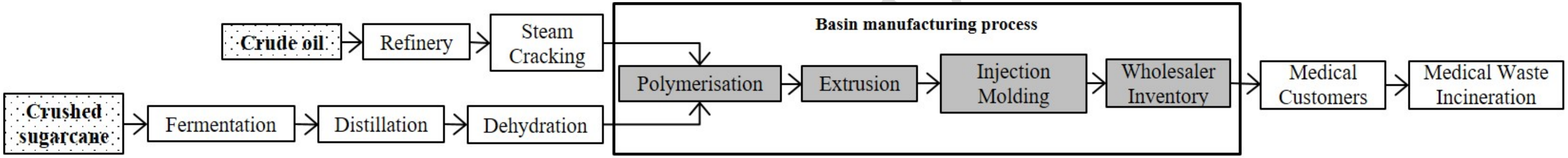

Figure 1. The basin supply chain considered for the study

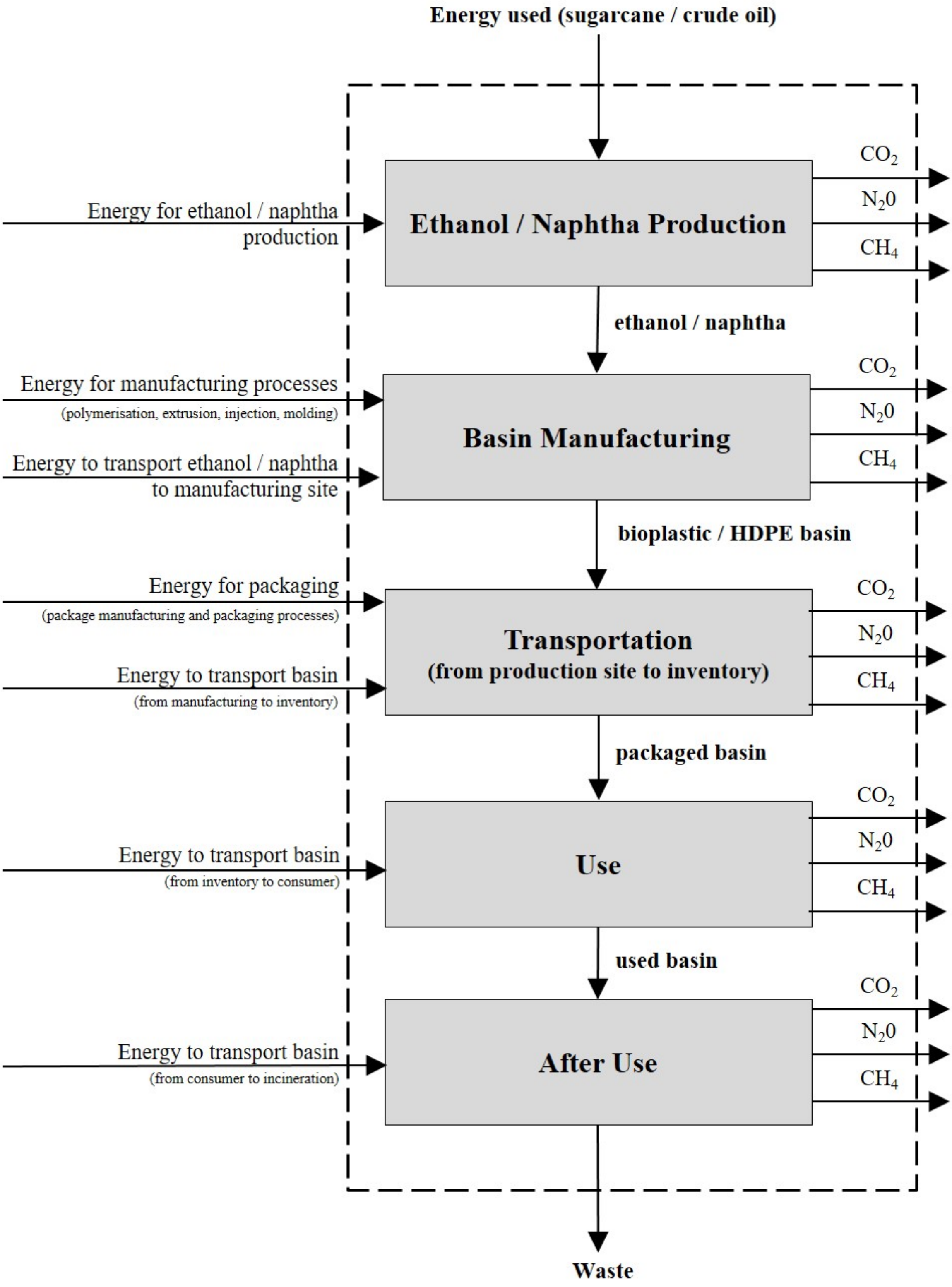

Figure 2 The material and energy flows considered

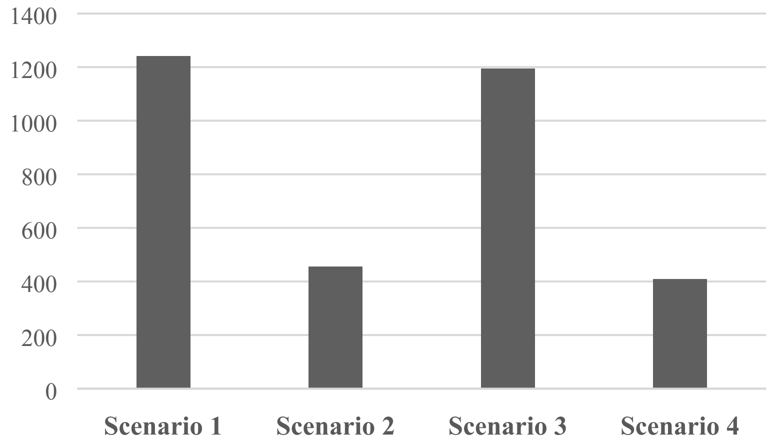

Figure 3 Total CO_2 emissions from each scenario (gCO_2 per basin)

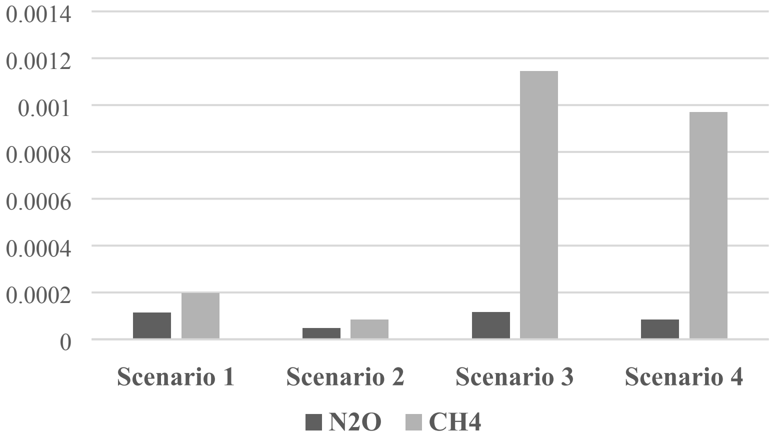

Figure 4 Total N_2O and CH_4 emissions from each scenario (grams per basin)

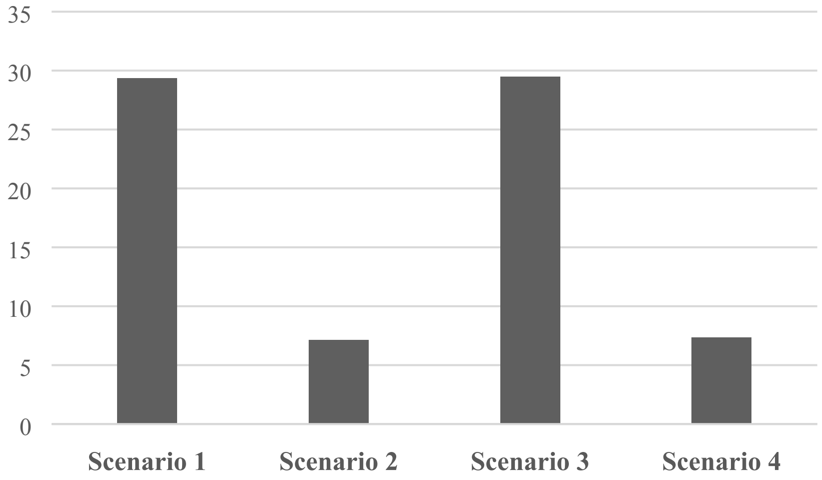

Figure 5 Total energy consumed in each scenario (MJ per basin)

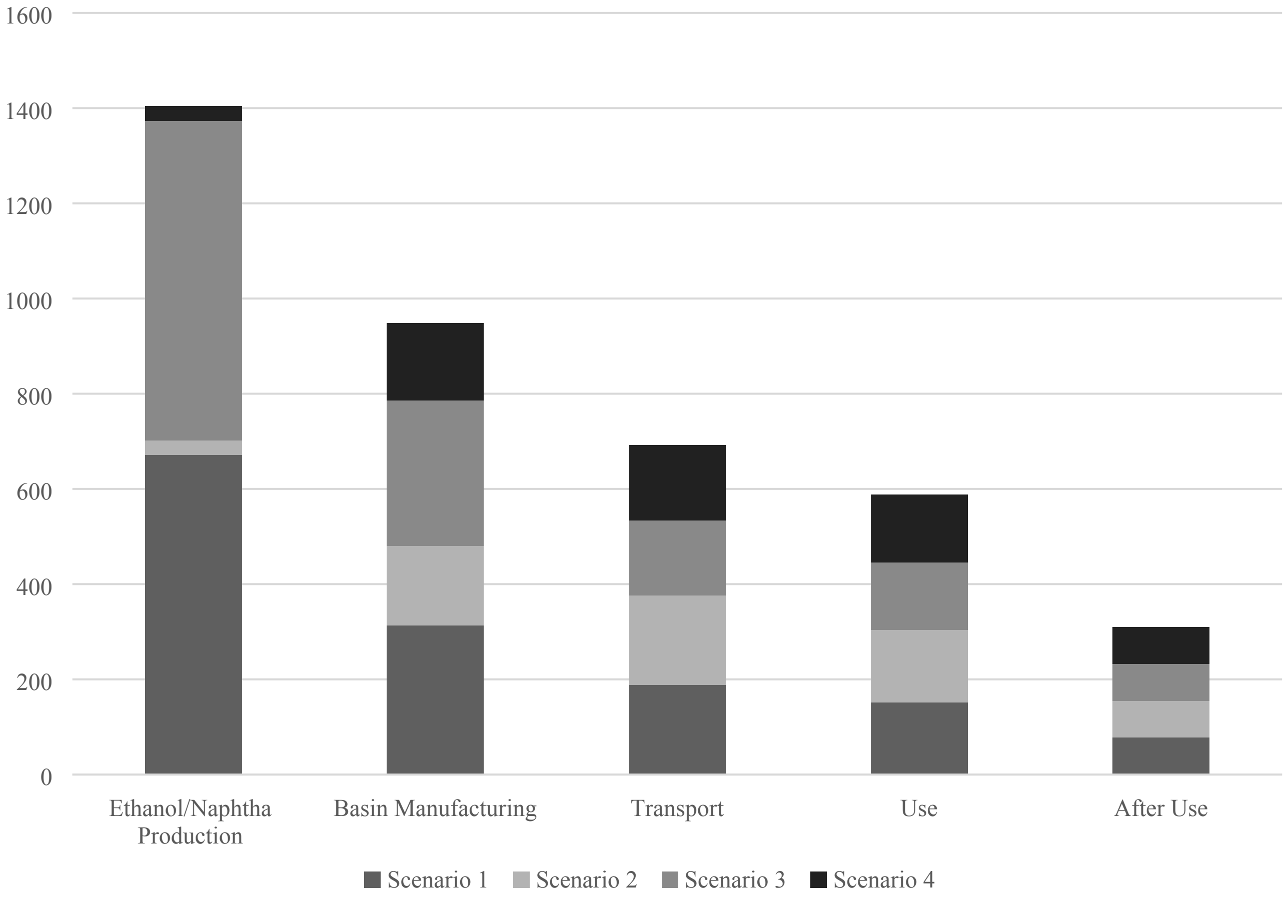

Figure 6 Total emissions from the life cycle stages of each scenario

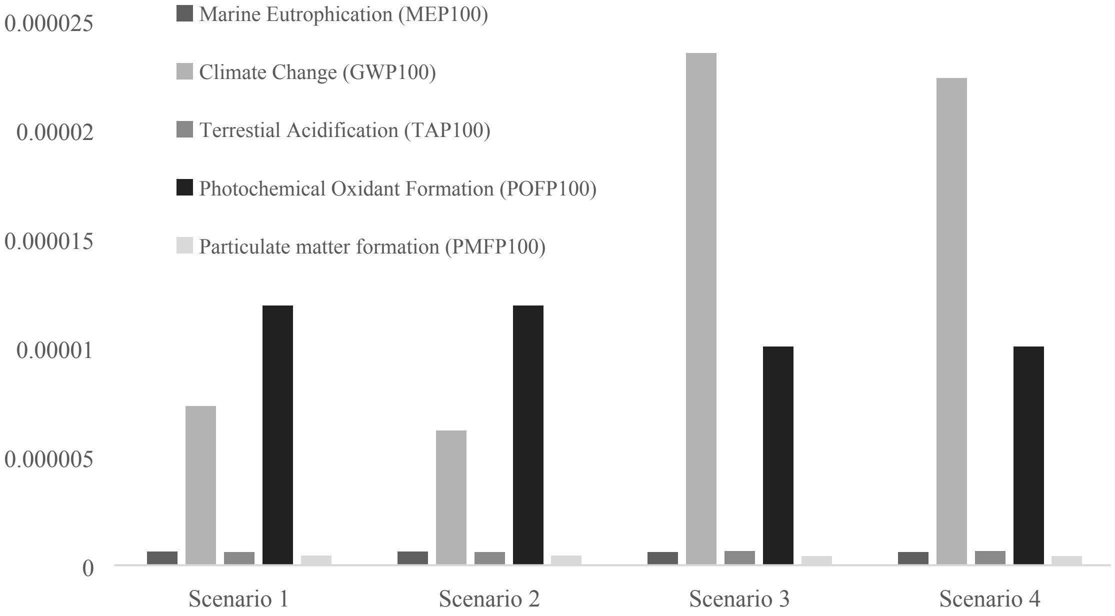

Figure 7 Overall environmental impacts of each scenario (ReCiPe Midpoint World Value/Egalitarian)

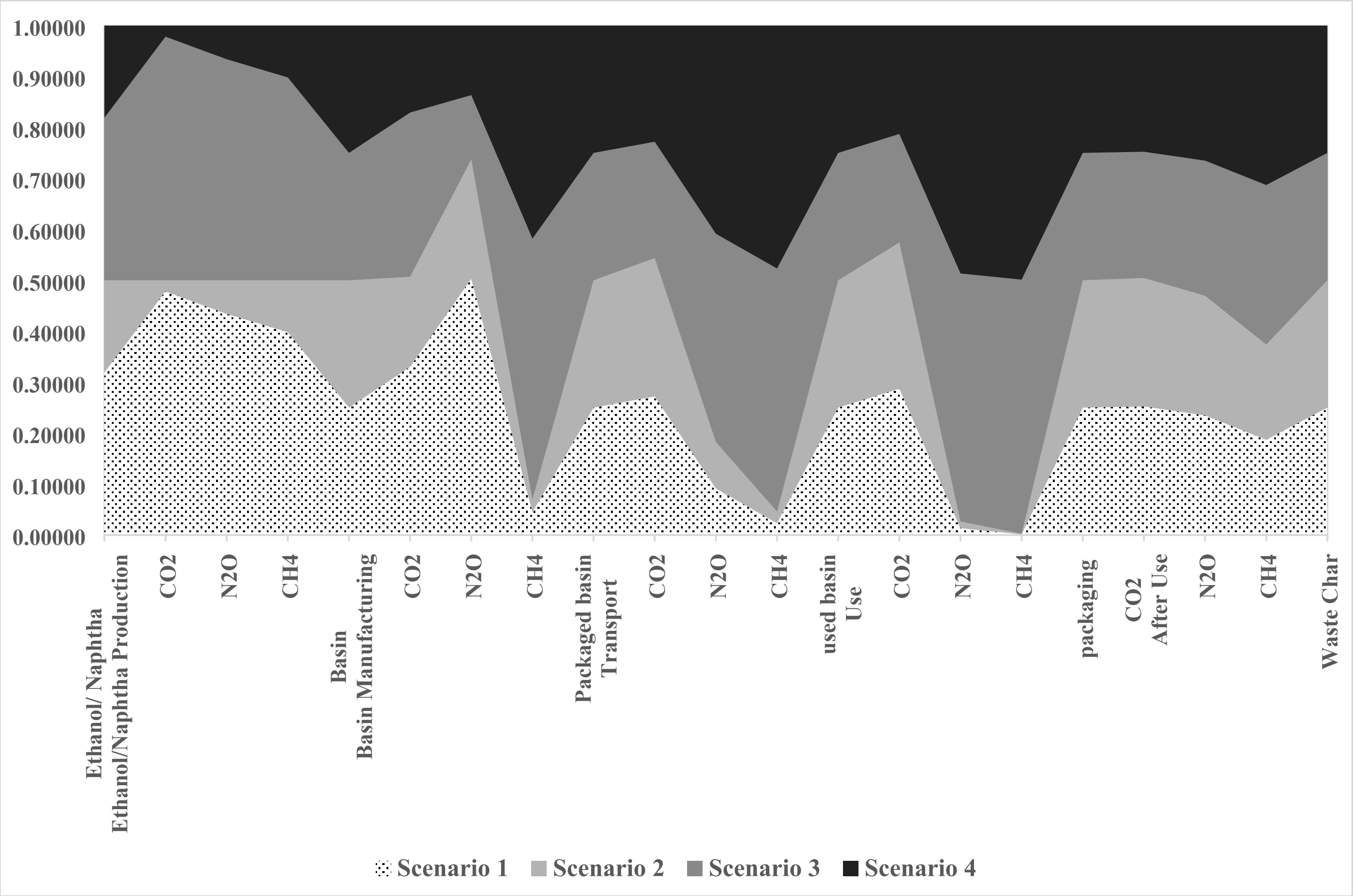

Figure 8 Percentage contribution to ecological impacts, with a change in supply chain strategy for each scenario

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