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Life Cycle Sustainability Assessment for Sustainability Improvements: A Case Study of High-Density Polyethylene Production in Alberta, Canada

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Abstract: Life cycle sustainability assessment (LCSA) is a still relatively new technique. One of its main application challenges is interpreting the three dimensions of its results in combined fashion. This paper presents the first attempt at an integrated solution-oriented approach in the LCSA, while simultaneously interpreting the results of the three assessments in a combined fashion toward improving the sustainability performance of product systems. It is based on a case study of high-density polyethylene (HDPE) production in Alberta, Canada. The methodology is characterized by five steps: (1) goal and scope definition; (2) inventory analysis; (3) impact assessment; (4) interpretation where the results of the three tools of LCSA are presented and an integrated analysis of the sustainability results following the strong sustainability model and using the Driver–Pressure–State–Impact–Response (DPSIR) framework, is conducted to propose sustainability improvements for the case study product; (5) discussion and conclusion. The integrated approach developed was able to propose some sustainability improvement proposals along the life cycle of HDPE. Yet, challenges exist in interpreting the interrelationships between the three assessment results. Moving from comparative integrated assessment approach in LCSA to solution-oriented approach still faces challenges. This work highlighted some of the research tasks that need more focus from the LCSA community to demonstrate how LCSA can contribute to sustainable development by improving the sustainability performance of product systems.

Keywords: life cycle sustainability assessment; sustainability improvements; high density polyethylene; integrated analysis; strong sustainability model; Alberta

1. Introduction

Sustainability has been the subject of an intense debate since 1987 with the Brundtland report on Environment and Development "Our common Future" which presented the first well-known definition of "sustainable development": "*A development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" [1]. Sustainable development comprises balancing the three pillars: environment, economy and society. A life cycle thinking approach to sustainable development is needed to consider sustainability aspects along the whole life cycle of the product and avoid any transfer of negative impacts from a part of the life cycle to another. The life cycle sustainability assessment (LCSA) is considered the best approach to evaluate the environmental, economic and social sustainability of product systems [2]. LCSA embraces the three techniques: environmental life cycle assessment (LCA), environmental life cycle costing (LCC) and social life cycle assessment (S-LCA) [3,4].

LCA is the only tool already standardized by ISO 14040-44. It is defined as a procedure for "*addressing the environmental aspects and potential environmental impacts throughout a product's life cycle from raw materials acquisition through production, use, end-of-life treatment, recycling and final disposal*" [5]. However, LCA is only based on environmental parameters. The LCC is not yet standardized though it is older than LCA and it has been used since 1930s [6]. According to a SETAC working group on LCC, there are three types of LCC: conventional, environmental, and societal [6]. Environmental LCC was considered the most suitable to be applied with LCA and integrated in LCSA as it has been shaped using the same approach of LCA. It covers all real money flows associated with a product along its life cycle. Environmental LCC is defined as "*an assessment of all costs associated with the life cycle of a product that are directly covered by any one or more of the actors in the product life cycle (e.g., supplier, manufacturer, user or consumer, or end of life actor) with complementary inclusion of externalities that are anticipated to be internalized in the decision-relevant future*" [7]. LCC is used throughout this paper to refer to environmental life cycle costing. The last component of LCSA is the S-LCA, which is still not a well-developed methodology. S-LCA is defined as "*the assessment of all social and socio-economic aspects of products and their potential positive and negative impacts along their life cycle*" [8]. Despite the guidelines for S-LCA and the recently published methodological sheets by UNEP/SETAC [8,9], this approach needs further clarification and research [10].

LCSA is still a relatively new technique and needs further development in terms of case studies and methodological developments [11]. One of the main challenges of the application of LCSA remains in the interpretation phase where the results of the three tools should be interpreted in a combined fashion based on the LCSA guidelines [10]. This systematic and holistic approach of looking at the results goes back to the roots of sustainability science as explained by Sala et al. [12,13]; where the emphasis is on understanding the interrelations between the three pillars of sustainability and not the separate parameters of each of those. Yet, integrating the three dimensions of sustainability in LCSA is still an emerging field and needs additional case-study-based contributions in advancing it further [13]. Although according to Sala et al. [12], "integrated assessment" may be used in different contexts, it is used here to refer to "combining the three parts of sustainability assessment".

Approaches to interpret the results of LCSA in a combined way are emerging in the literature (i.e., Basurko and Mesbahi; Foolmaun and Ramjeawon; Traverso et al.; Vinyes et al.) [14–18]. Traverso et al. [16,17] have proposed the use of life cycle sustainability dashboard (LCSD) to present and integrate the results of LCSA and to provide an overall index of sustainability performance for products useful in a comparison between different options while using a ranking score and a color scale. The life cycle sustainability triangle (LCST) which is a graphical tool was proposed by Finkbeiner et al. [19] to combine the results of the three dimensions of sustainability. Foolmaun and Ramjeawon [15] and Zhang and Haapala [20] have used the analytical hierarchy process to assign weights and rank the LCSA results. The solutions proposed were able to integrate the three dimensions of sustainability by aggregating the results of LCSA and assist decision-making in comparing the sustainability performance of different options or alternatives. The integration conducted in these studies solely means aggregating the quantitative results of the environmental, economic and social dimensions of sustainability. As concluded by Sala et al. [13], the goal of the integrated assessment in the LCSA studies was mainly "comparative oriented" toward choosing the products with less sustainability negative impacts.

However, to date, to our knowledge there have been no sustainability studies with the aim to analyze the LCSA results in an integrated way toward proposing strategies for improving the sustainability performance of products.

This study addresses this challenge by introducing the first attempt to interpret the results of the three dimensions of sustainability in a combined/integrated fashion with a solution-oriented approach in mind in order to propose sustainability improvements for the case study product. After performing the LCSA through its three tools on a specific case study, the paper presents an integrated approach to analyze the results of the three dimensions of sustainability following the strong sustainability model and using the Driver-Pressure-State-Impact-Response (DPSIR) framework. "Integration" in this paper means looking at/analyzing the results of the environmental, economic and social dimensions of sustainability in a combined way while interpreting the interrelations and linkages that occur between these results, toward proposing sustainability improvements for the case study product. The integrated approach proposed in this study is a qualitative approach based on analysis and interpretation of the results and doesn't imply any aggregation of the results in a quantitative way.

This paper is using Dow Chemical Canada's facility in Fort Saskatchewan as a case study with the high-density polyethylene (HDPE) as a specific product. The company is one of the large greenhouse gas (GHG) emitters in Alberta, Canada that are faced with a growing challenge related to searching for cost-effective opportunities to reduce GHG emissions and thus, meet environmental compliance. In addition, petrochemical industry is considered one of the largest manufacturing industries in the province of Alberta with the largest polyethylene production facilities in Canada [21,22]. The purpose of this case study is to demonstrate how LCSA can be used by decision-makers to identify possible areas of sustainability improvements along the product life cycle where GHG emissions can be reduced while achieving economic and social benefits.

The sustainability performance evaluation of HDPE has followed the UNEP/SETAC guidelines. The methodology used to conduct this evaluation and interpret the results in a combined fashion involves five steps: (1) Goal and scope definition where the goal of the study, functional unit, reference flow, system boundaries and impact categories under the three LCSA tools are determined; (2) Inventory analysis where data collection for LCA, LCC and S-LCA is conducted; (3) Impact assessment where the results of the three tools are evaluated; (4) Interpretation where first the results of the three dimensions are presented and second an integrated approach is developed and conducted to interpret the results in a combined way based on the strong sustainability model and using the DPSIR framework; (5) Discussion and conclusion where the limitations of this study and further research required from the LCSA community are highlighted.

The S-LCA part of this case study was conducted and presented in details by the authors in a separate paper [23]. In the current paper, the evaluation of the other two sustainability dimensions (environmental and economic) are conducted to complete the LCSA study of HDPE. Therefore, the main focus of the goal and scope definition, inventory analysis and impact assessment in this paper is on LCA and LCC. The S-LCA results are summarized for the purpose of presenting all sustainability results and interpreting these results in a combined way using the integrated approach proposed in the current paper.

2. Goal and Scope Definition

The goal of this study is to assess the sustainability performance (environmental, economic and social impacts) of the HDPE life cycle by Dow Chemical Canada facility in Alberta, Canada. The assessment is based on the application of the three techniques: LCA, LCC and S-LCA. The common goal is to improve the sustainability performance of the product system. Therefore, in this study, each of these tools is applied while considering an integrated approach in mind. The impact results for the three dimensions are identified. Then, an integrated/combined analysis is conducted to analyze the synergies and tradeoffs between the three dimensions' impact results and propose recommendations of sustainability improvements for the case study product.

All details on the functional unit, reference flow, system boundaries and impact categories are presented in Supplementary Material 1.

3. Inventory Analysis

3.1. LCA Methodology

The environmental life cycle inventory (LCI) of HDPE production is developed taking into account the inputs (e.g., natural gas, crude oil) and outputs (e.g., carbon dioxide (CO_2), methane (CH_4) and

(N_2O)) of the stages of HDPE production. The climate change is the only impact category considered in this study as the goal of this research is to guide one of the large GHG emitters in Alberta, Canada "Dow Chemical Canada facility" to develop sustainability improvements along their product life cycle that can reduce GHG emissions while achieving sustainability goals.

For detailed information on the LCA inventory analysis including data collection, material inputs in all unit processes for the production of 1000 kg HDPE and for a description on the types of inputs and outputs, please refer to Supplementary Material 2.

3.2. S-LCA Methodology

As previously mentioned in the introduction, the S-LCA part of this study was developed and presented in details by the authors in a separate paper [23]. Social data was collected at three levels considering all stakeholder groups (i.e., local community, value chain actors, consumers, workers and society) and types of data (i.e., quantitative, qualitative, semi-quantitative): company level data for foreground processes, sector level data (using Product Social Impact Life Cycle Assessment (PSILCA) database) for all background and foreground processes and country level data for Canada.

3.3. LCC Methodology

In this study, we determined the costs from the perspective of the producer of processed natural gas, refined petroleum product and HDPE in order to assess the costs along the cradle-to-gate of HDPE as identified in the goal and scope definition. One of the critical challenges in conducting an LCC study is to capture all cost categories [24]. In this study, three types of cost categories are considered: raw materials costs, energy costs and labor costs. Due to data availability issues, all other internal costs such as financial costs, research and development costs, maintenance costs etc. are not considered.

According to Hunkeler et al. [7], external costs expected to be internalized in the decision relevant future have to be monetized. But these "costs should reflect only real monetary flows that are covered by one or more actors in the product system" [24]. However, as LCC is applied with S-LCA and LCA within LCSA, LCC should assess "microeconomic, real money flows only, excluding external or macroeconomic costs; it thereby avoids overlaps with environmental LCA, but also with socioeconomic impacts addressed in S-LCA" as stated by Klöpffer and Ciroth [25]. Therefore, only internal microeconomic real money flows from the perspective of producer along the cradle-to-gate life cycle of HDPE are taken into account here.

In addition, revenues are not taken into account in this study as data was not available on net revenues generated by the companies specifically from the HDPE production along its life cycle. Please refer to Supplementary Material 3 for a detailed description of LCC inventory data collection.

4. Impact Assessment

The impact analysis for LCA has followed the classification and characterization phases based on ISO 14044 [5]. GHG emissions in CO_2e are calculated following the characterization factors provided by the 2013 Intergovernmental Panel on Climate Change (IPCC) 100 years.

For LCC, according to UNEP/SETAC guidelines, impact assessment is not applicable as the aggregation of costs is considered enough to evaluate the economic impacts [10].

For S-LCA, a new subcategory assessment method (SAM) was developed for foreground processes in a separate paper for this case study [23]. A comparison between the company's performance and sector (using PSILCA) or country performance was conducted for foreground processes. For background processes, PSILCA database subcategory performance evaluation or country performance evaluation conducted in the S-LCA study were used [23].

5. Interpretation

The results of the three dimensions are presented and an integrated analysis has been conducted to interpret the results in a combined fashion and thus, propose recommendations of sustainability improvements along the life cycle of HDPE production.

5.1. Results Presentation

This subsection presents the environmental, economic and social dimension of the results.

5.1.1. Environmental Dimension Results

Based on Figure 1 below, we can see that the ethylene production step is responsible for the largest amount of GHG emissions "43%" in the HDPE manufacture life cycle. The natural gas extraction follows being responsible for 27% of total GHG emissions.

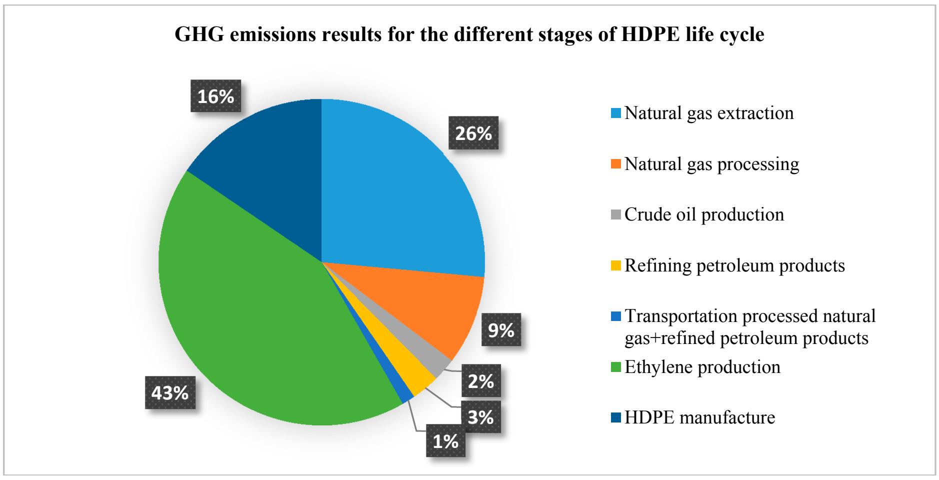

Figure 1. Greenhouse gas (GHG) emissions results for the different stages of HDPE production.

In Figure 2, we can see the substance contribution to GHG emissions under each unit process. Methane appears to be the largest contributor to GHG emissions in natural gas extraction and crude oil extraction with respectively 76.4% and 85% of total CO_2e. In addition, methane is responsible for 99.9% of total GHG emissions in transportation. However, for natural gas processing, refining petroleum products, ethylene production and HDPE manufacture, carbon dioxide dominates with a higher percentage of GHG emissions.

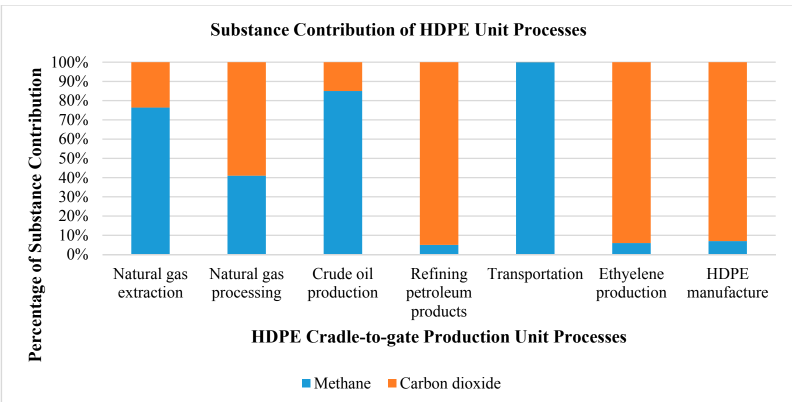

Figure 2. Substance contribution of HDPE unit processes.

5.1.2. Economic Dimension Results

Based on Figure 3, we can see that the ethylene production is responsible for 53% of total costs. In addition, the natural gas extraction follows being responsible for 22% of total costs.

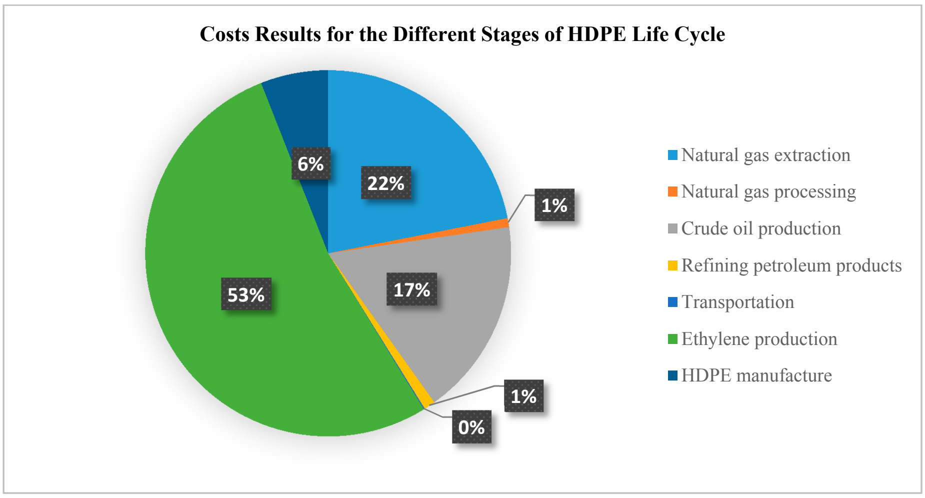

Figure 3. Costs results for the different stages of HDPE production.

The LCC results can also be presented from the different perspectives taken into account along the HDPE life cycle and by cost category (See Figure 4 below). Figure 4 presents the costs from the perspective of the producer of processed natural gas, producer of refined petroleum product and producer of HDPE (while considering that the transportation is paid by the producer of HDPE). As well, Figure 4 presents the results by cost category, raw materials, energy and labor costs.

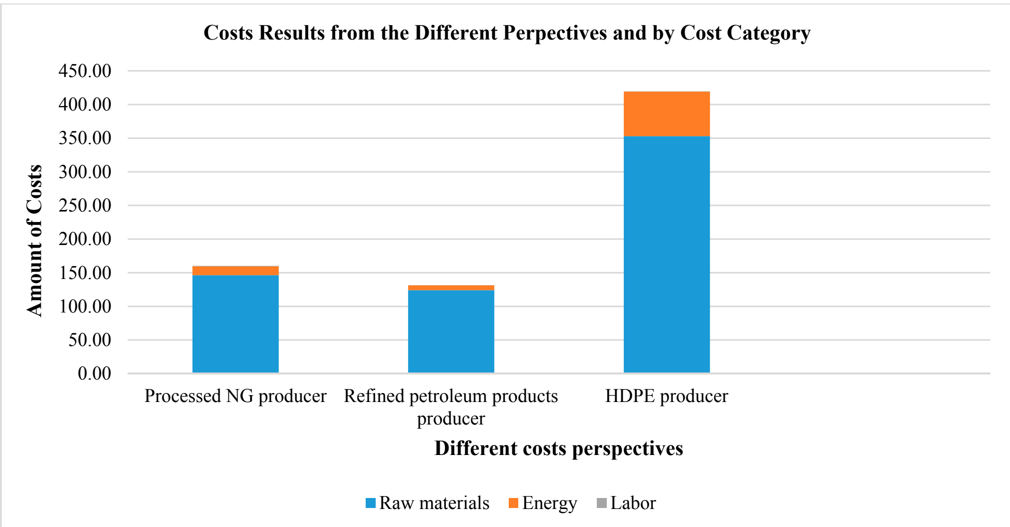

Figure 4. Costs results from the different perspectives and by cost category.

Based on Figure 4, we can see that the HDPE producer has the largest costs along the life cycle of HDPE, with the raw materials costs responsible for approximately 84% of these costs. In addition, by looking at the results by cost category, we can see that the raw materials costs are responsible for the largest percentage of total costs along the cradle-to-gate life cycle of HDPE.

5.1.3. Social Dimension Results

For the social dimension, the results are divided between foreground and background processes.

The important results of the S-LCA study by Hannouf and Assefa [23] are summarized in Table 1. The table identifies the subcategories that need high level and moderate level of improvements in all foreground and background processes as well as those subcategories where improvement is not required. "Moderate level of improvements" is used in this article to correspond to what is presented as "Some level of improvements" in Hannouf and Assefa [23]. Due to data availability issues, no evaluation was conducted for some subcategories as indicated in Table 1.

Table 1. Results of subcategories' evaluation for all foreground and background processes (based on Hannouf and Assefa [23]).

	Life Cycle Stages				
	Foreground Processes	Background Processes			
Subcategories	Ethylene Production and HDPE Production	NG Extraction and Crude Oil Extraction	Refining Petroleum Products	NG Processing	Transportation
Freedom of association and collective bargaining		HI	MI	MI	HI
Child labor					
Forced labor					
Equal opportunities/discrimination		MI	MI	MI	MI
Health and safety (workers)	HI		HI		
Social benefits/social security		MI			
Fair salary	HI				
Working hours	-				
Health and safety (consumers)	HI				
Feedback mechanism	-	-	-	-	-
Privacy		MI	MI	MI	MI
Transparency	HI				
End of life responsibility	HI				
Supplier relations	-	-	-	-	-
Promoting social responsibility	-	-	-	-	-
Fair competition	MI	HI			
Respect of intellectual property	HI				
Cultural heritage	HI				
Respect of indigenous rights		HI	HI	HI	HI
Local employment	MI	MI	MI	MI	MI
Delocalization and migration	-	MI	MI	MI	MI
Access to immaterial resources		HI	HI	HI	HI
Access to material resources			HI	HI	MI
Secure living conditions	HI				
Community engagement					
Safe and healthy living conditions	HI				
Public commitment to sustainability issues		HI	HI	HI	HI
Contribution to economic development					
Technology development		HI	HI	HI	HI
Prevention and mitigation of conflicts	HI				
Corruption	HI	HI	HI		HI

HI: high level of improvements; MI: moderate level of improvements; "-": No evaluation; Note: empty cells are those subcategories with no required improvements based on evaluation conducted by Hannouf and Assefa [23].

5.2. Integrated Analysis of the Sustainability Results

Understanding the interrelationships between the three dimensions of sustainability is a necessary part to achieve the goal of this study which is to present the first attempt of an integrated solution-oriented approach in LCSA toward improving the sustainability performance of product systems. This subsection presents first a brief discussion of the sustainability concept with different interpretations and views of the interrelationships between the three dimensions of sustainability. This discussion is used to choose the sustainability model that will be followed in the integrated approach proposed in the second part of this subsection.

5.2.1. Sustainability Concept

Even though there has been an agreement about the existence of the three dimensions of sustainability (i.e., environment, economy and social), there are still differences in the philosophical interpretations of the interrelationships between these three dimensions. This section presents a brief of two different existent paradigms or models of sustainability. Each model explains the interrelationship or structure of the three dimensions of sustainability from a different perspective.

The first model is an economic principle called the weak sustainability model mainly derived from the neoclassical theory. Based on this model, the three dimensions of sustainability are interlinked and any degradation of one group of assets (environment, economy, society) can be compensated by an improvement in another [26,27]. This model supports the substitutability between natural and man-made capital where sustainability is measured as an aggregated value of the improvement of all three dimensions without a special attention given to the environmental dimension. Specifically, following this model, a sustainability improvement can lead to a degradation in the environmental system as long as the improvement in the economic and/or social systems can compensate this degradation.

The second model called the strong sustainability model which is derived from the ecological economics paradigm. This model gives a special attention to the environmental dimension which is considered as the foundation of sustainability. Economic and social systems cannot exist without the environment [26]. Therefore, any sustainability improvement should lead first to a refinement in the environmental dimension before it achieves any progress in the other two dimensions. This goes back to the main principle of this paradigm which is the non-substitutability between natural and man-made capital [28].

Choosing a sustainability model can determine the values and the particular world view followed in understanding and analyzing the interrelationships between the three dimensions of sustainability. As mentioned by Ott [29], choosing between strong and weak models of sustainability can be done based on different arguments discussed in previous literature. Ott [29] has summarized these arguments: (1) the right of future generations to enjoy equal lifestyles that require all types of capital including natural capital; (2) using the precautionary principle, the uncertainty associated with the assumption of substitutability of natural capital in the future; (3) the need to preserve a constant amount of natural capital due to the different functions of ecosystems and for human survival. This opposed the unlimited substitutability principle of weak sustainability; (4) the failure of real life examples of weak sustainability such as the case of Pacific Island of Nauru to increase the average quality of life, while ignoring important parameters of human welfare. Following these arguments of Ott [29], we are using the strong sustainability model in this study as the guiding vision and perspective to interpret and analyze the three dimensions' results and propose recommendations for sustainability improvements in the next section.

5.2.2. Integrated Solution-Oriented Approach

The approach proposed to analyze and interpret the results of the three dimensions of sustainability and to use these results to develop recommendations for sustainability improvement proposals, is explained here.

It starts with setting an objective to pursue, followed by identification of the social life cycle subcategories to prioritize as part of developing sustainability improvement proposals based on key life cycle sustainability assessment results.

1- Setting the objective

To propose sustainability improvements along HDPE life cycle that reduce GHG emissions while reducing costs/increasing revenue and improving the social conditions along the product systems' life cycle.

2- Identifying key life cycle sustainability assessment results

This study has assessed the sustainability performance of HDPE production in Alberta, Canada using the three tools of LCSA: LCA, LCC and S-LCA. Our key life cycle sustainability assessment results indicate that (1) the ethylene production stage, which is part of foreground processes, is responsible for the largest amount of GHG (43%) and the largest costs (52%) (2) the natural gas extraction stage, which is part of background processes, is responsible for the second largest amount of GHG (27%) and costs (22%). (3) An evaluation of the social subcategories' results and a relative comparison to sector performance evaluation from PSILCA have identified that the company in foreground processes needs high level of improvements in 11 subcategories and moderate level of improvements in two subcategories. In addition, specific subcategories that need improvements in the background processes were identified.

3- Developing sustainability improvement proposals

As we are using the strong sustainability model, the environmental dimension should be considered the foundation of sustainability. So, sustainability improvements should lead mainly to a reduction in GHG emissions while it achieves any progress in economic or social dimensions. Therefore, we first identify the possible options available to reduce GHG emissions along HDPE production and then look for strategies where these reductions could be implemented while achieving economic and social benefits. The focus here is on ethylene production and natural gas extraction stages responsible for the largest amount of GHG emissions.

We are using here the possible options for reduction of GHG emissions along ethylene production and upstream process of natural gas extraction proposed by Yao et al. [30] (please see Table 2 below).

Table 2. Greenhouse gas (GHG) emission reduction opportunities for ethylene production from natural gas (extracted from Yao et al. [30]).

GHG Emission Reduction Opportunities in Ethylene Production Process	GHG Emission Reduction Opportunities in Natural Gas Extraction Process
• Maintain optimal operational conditions (process optimization) • Reduce equipment leakage: for example maintenance and repair of pressure safety valves and automated controls for combustion • Operations and maintenance improvements in steam system efficiency • Maintenance to improve heat recovery rates.	• Reduce equipment leakage: Install/retrofit equipment with better emission control features such as valve controllers and regular equipment repair • Improving well operations: for example through optimized operation settings.

In this step, we go back to the key sustainability results of S-LCA and LCC for a combined analysis.

Table 3 below presents the potential GHG emission reduction opportunities (with the approximate amount of reduction whenever possible) in foreground (specifically ethylene production) and background processes (specifically natural gas extraction) and through the collaboration between both types of processes with the potential connections that could be established with social and economic improvements.

We have identified the social life cycle subcategories to prioritize as part of developing sustainability improvements proposals based on the key sustainability assessment results. Table 3 does not provide an exhaustive list and it is meant to be a starting example of sustainability recommendations that could be formulated based on the connections between the three assessment results.

Table 3. Greenhouse Gas (GHG) emission reduction opportunities in foreground, background processes and through the collaboration between both types of processes with possible social and economic improvements.

HDPE Production Processes	GHG Reduction Options—Approximate Amount of GHG Reduction in CO_2e	Social Subcategories	Economic Opportunities
Foreground processes (i.e., ethylene production)	• Maintain optimal operational conditions (process optimization)—reduction of approximately 0.05 kg CO_2e/kg ethylene [30]	• *Fair salary* • *Health and safety*	• Reduction in costs of raw materials (i.e., ethane and refined petroleum products) and overall production costs (such as energy and labor costs) • Increase in revenue
Background processes (i.e., NG extraction)	• Install/retrofit equipment with better emission control features—reduction of approximately 0.2 to 0.6 kg CO_2e/kg ethylene [30] • Improving well operations: for example regularly scheduled leak detection and optimized operation settings—reduction of approximately 0.05 kg CO_2e/kg ethylene [30]	• *Technology development* • *Public commitment to sustainability issues* • *Social benefits* • *Freedom of association* • *Discrimination/equal opportunities*	• Reduction in costs of raw materials (i.e., raw natural gas) and overall production costs (such as energy and labor costs) • Increase in revenue
Collaboration between foreground and background processes	• Emission reductions opportunities along the life cycle of the product	• *Supplier relations* • *Promoting social responsibility*	• Reduction in overall costs along the life cycle of the product (such as raw materials costs, energy costs, labor costs) • Increase in revenue

(Abbreviations NG: Natural gas).

Table 3 is explained further by presenting schematic examples for some cause-effect relationships that could be established between the three dimensions of sustainability that will be used in developing sustainability improvement proposals. The schematic examples are presented using the DPSIR framework. The DPSIR established by the European Environment Agency (EEA) is used in this work for environmental analyses and to present the sustainability recommendations proposed to be undertaken by the companies responsible for the production of HDPE. The DPSIR is a systematic framework for structuring the cause-effect relationships in connection with environmental problems [31,32]. It takes into account the interacting components of economic, social and environmental systems. The scheme helps to provide an overview of the environmental problems while connecting their origin to the results and developing the efficient responses that could participate in resolving the problems [31,32]. While DPSIR mainly focuses on the environmental impacts of socio-economic development [31], in this work we take into account all effects from the three dimensions of sustainability to facilitate the development of sustainability solutions and responses. The DPSIR schematic examples provided in this section show how the responses proposed to be undertaken by the companies are crafted to minimize the un-sustainability impacts of the drivers and pressures on ecosystems, while maximizing the welfare of human beings (companies' stakeholders in this study) and reducing the companies' economic costs. The schematic examples presented below extend the DPSIR model to present the sustainability outcomes of the responses proposed. To build the schematic examples in Figures 5–8, and specifically present the sustainability responses with their outcomes on the three dimensions of sustainability, we looked at the potential connections that exist between the potential GHG reduction opportunities in Table 2 and the social subcategories that require improvements in foreground and background processes in Table 1. In addition, in building these connections, we have done analysis based on previous studies (e.g., [9,33–35]) related to corporate sustainability performance and life cycle approaches and supported it with plausible arguments. The schematic examples of the sustainability improvement proposals in Figures 5–8 are explained in details as follows by identifying the process used to determine the sustainability measures and outcomes.

For foreground processes (i.e., ethylene production):

Based on Table 1, we have chosen the subcategories that could have a connection with the potential GHG emission reduction opportunities among the 11 subcategories that require high level of improvements and the two subcategories that require moderate level of improvements for foreground processes. Some analysis based on previous studies (e.g., [33,34]) related to corporate sustainability performance and life cycle approaches and some plausible arguments has been done to establish these potential connections. For example:

- A reduction of GHG emissions (approximately 0.05 kg CO_2e per kg ethylene [30]) could be achieved by maintaining optimal operational conditions through for example process optimization that could be associated with an improvement in the working conditions for employees. For instance, providing better working conditions for employees could lead to an improvement in the subcategories related to worker's stakeholders in S-LCA. Norris [33] has discussed the importance of information provided by S-LCA and has presented some of the benefits that companies can generate using this information. Among these advantages, Norris [33] has stated that an improvement in working conditions in the company can increase labor productivity. In addition, Nicolaescu et al. [34] have similarly argued that improving the social responsibility of companies increase the satisfaction of their employees and can ensure their long-term run.

Fair salary and *health and safety* (workers) subcategories are found to be the two subcategories related to workers' stakeholder group that need high level of improvements in foreground processes. Therefore, we are arguing that companies can successfully and beneficially link an improvement in the working conditions of the employees to lead to a reduction in GHG emissions through operational improvements, and at the same time improving the subcategories related to worker's stakeholder and reducing overall production costs.

Figure 5 depicts the DPSIR chain for the problem of climate change and GHG emissions with the sustainability response proposed to be undertaken by Dow Chemical Canada.

As can be seen in Figure 5 the response can affect any part of the chain between driving force and impacts. The specific outcomes of the response proposed on the three dimensions of sustainability are also presented.

For background processes (i.e., Natural gas extraction):

Based on Table 1, we have chosen the subcategories that could have a potential connection with the possible GHG emission reduction opportunities in background processes among the subcategories that require high level and moderate level of improvements in natural gas extraction process. Some analysis based on previous studies related to corporate sustainability performance and life cycle approaches and some plausible arguments has been done to establish these potential connections. For example:

- A reduction of GHG emissions (approximately 0.2 to 0.6 kg CO_2e per kg ethylene [30]) could be achieved by installing new equipment with better emission control features that could be associated with partnerships in research and development, investment in technology development and collaboration along the supply chain. For instance, these strategies could lead to an improvement in the technology development subcategory. *Technology development* subcategory is found to be one of the subcategories that require high level of improvements in natural gas extraction process. Therefore, we are arguing that companies need to frame developing new technologies or equipment with better emission control features through partnerships and investment in research and development as leading to a reduction in GHG emissions, and at the same time improvement in the *technology development* subcategory and reduction in long-term costs.

Figure 6 depicts the DPSIR chain connecting the multiple parts with the solution proposed that could have sustainability outcomes on the three dimensions.

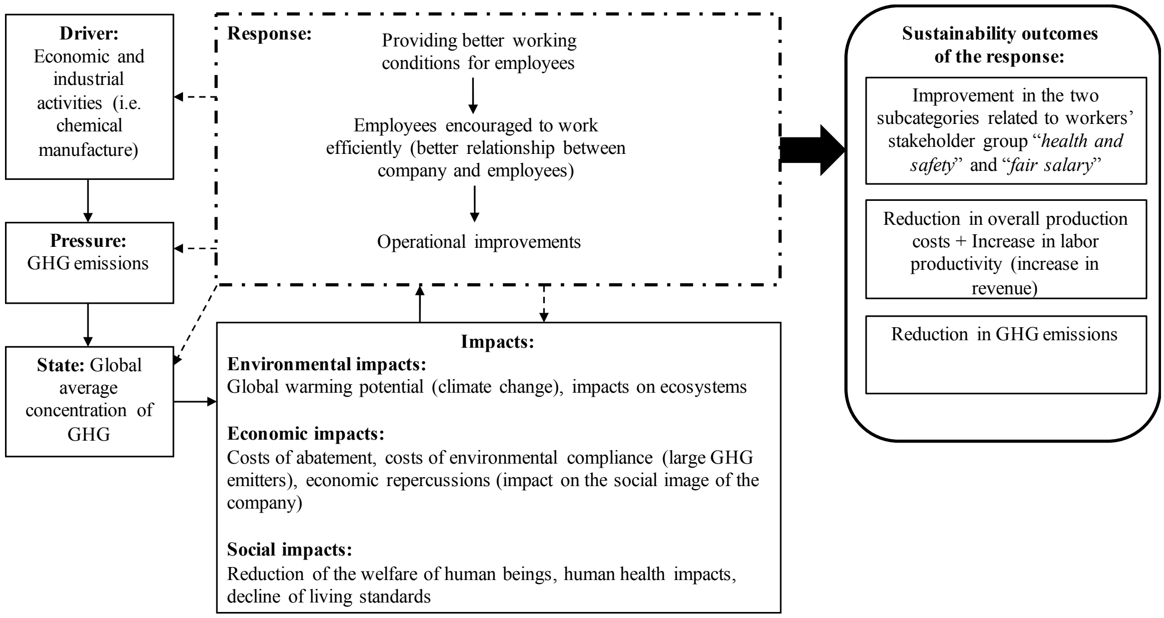

Figure 5. Schematic example #1 of sustainability improvement proposal in a DPSIR framework.

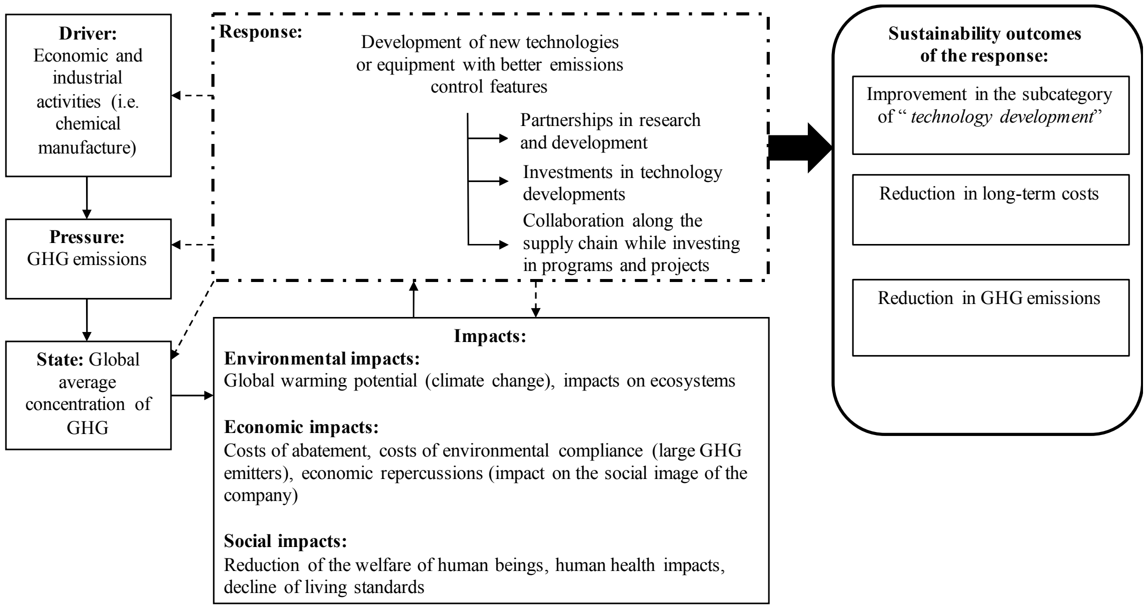

Figure 6. Schematic example #2 of sustainability improvement proposal in a DPSIR framework.

Even though this proposal can require some capital cost, some collaboration between the producers along the life cycle of HDPE, for example between the supplier of natural gas and the producer of ethylene can distribute the capital cost burden and benefit to both parts in terms of reduction in costs and GHG emissions. This could be part of Dow Chemical Canada's collaboration with suppliers that will be discussed further in the next section.

- On the other hand, any reduction of GHG emissions that could be achieved in background processes using any option mentioned in Table 2 or any other option is part of improving the social performance of the company and its social image in market. Therefore, this could lead to an improvement in the *public commitment to sustainability issues* subcategory which is found to be one of the subcategories that require high level of improvements in natural gas extraction process. One of the advantages that companies can gain while improving their social performance is to benefit from higher share in market and long-term profitability due to the increased demand for sustainable products [33,34]. Therefore, we are arguing that companies can successfully link any reduction in GHG emissions to lead to an improvement in the social performance of product systems and increase in the company's revenues.

Figure 7 depicts the DSPIR framework that shows how the sustainability response proposed can affect the different parts of the climate change analysis chain.

- Similar to the example presented in Figure 5, a reduction in GHG emissions (approximately 0.05 kg CO_2e per kg ethylene [30]) in natural gas extraction process could be achieved by improving well operations through as well process optimization that could be associated with an improvement in the working conditions for employees. As previously explained, providing better working conditions for employees could lead to an improvement in the subcategories related to worker's stakeholders in S-LCA. *Social benefits, freedom of association and discrimination* subcategories are found here to be the three subcategories related to workers' stakeholder group that need high or moderate level of improvements in natural gas extraction process. As the schematic example in this case is similar to the one presented in Figure 5, this won't be repeated here again.

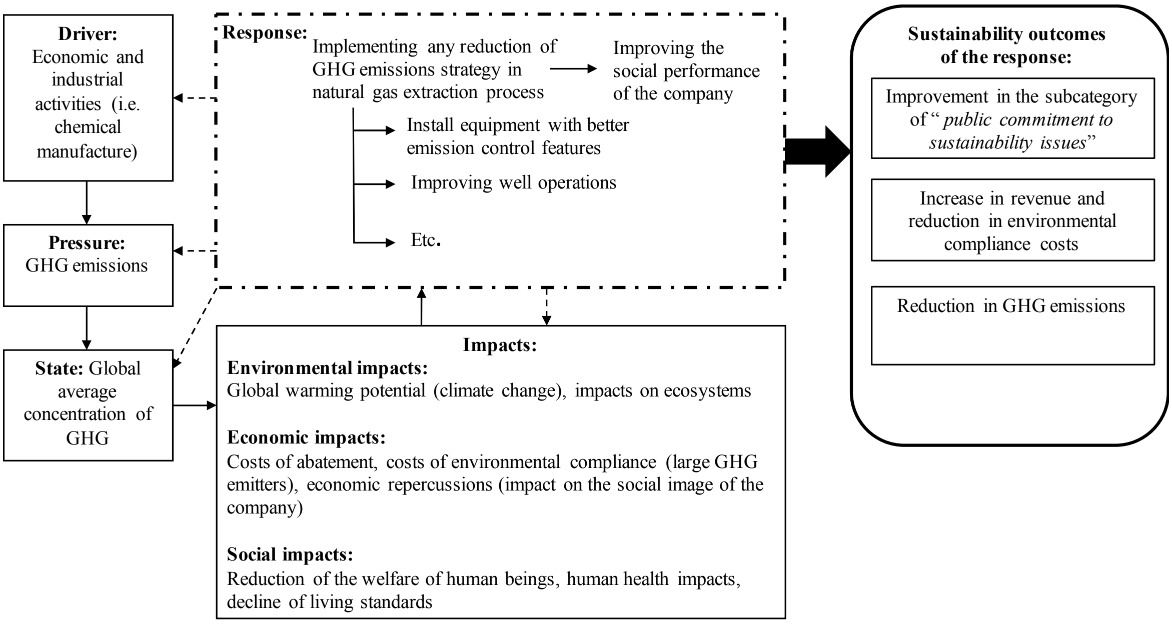

Figure 7. Schematic example #3 of sustainability improvement proposal in a DPSIR framework.

For collaboration between foreground and background processes:

Hunkeler et al. [7] have shown that reducing environmental impacts along the life cycle of a product is a challenge within the conflicting interests of the actors that exist along the life cycle. The authors have conducted a combined case study using LCC and LCA on waste water treatment and have proposed some win-win recommendations that can improve the environmental and economic performance along the life cycle of waste water treatment. However, Hunkeler et al. [7] have found that implementing these recommendations is hard to achieve without a collaboration between the actors.

Solving this problem of different interests in supply chain was the main discussion of Slagmulder [35]. The author proposed the interorganizational cost management, which is *"a structured approach to coordinating the activities of firms in a supply chain so that total costs in the chain are reduced"*. Slagmulder [35] has not included environmental impacts reductions in his discussion. However, the same strategies proposed can include emission reductions objectives.

Slagmulder [35] has proposed general strategies to identify win-win situations such as increase information sharing between buyer-supplier, coordinating the product development process through round tables etc. But for these interorganizational management practices to succeed, the relations between the company and its suppliers need to be based on high trust, stability and share mutual benefits [35].

This collaboration could easily achieve an improvement in the two social life cycle subcategories related to suppliers (i.e., *supplier relations* and *promoting social responsibility*). Going back to the social subcategories' results in foreground processes for Dow Chemical Canada, we can find that supplier relations and promoting social responsibility are among the subcategories not evaluated due to data availability issues. These two subcategories are of high importance for the development of sustainability improvements along the life cycle of the product. They help avoid the shift of negative impacts from a part of the life cycle to another, which is the basis of the life cycle thinking perspective taken by LCSA.

Hence, even though no information was available on the quality of performance of Dow Chemical in these two subcategories, we are arguing that Dow Chemical can benefit from the cause-effect relationship that could be established while prioritizing the social subcategories of *supplier relations* and *promoting social responsibility* as part of developing sustainability improvements proposals.

Figure 8 presents the DPSIR framework for the problem of climate change and GHG emissions with the sustainability response proposed and its outcomes on the three dimensions.

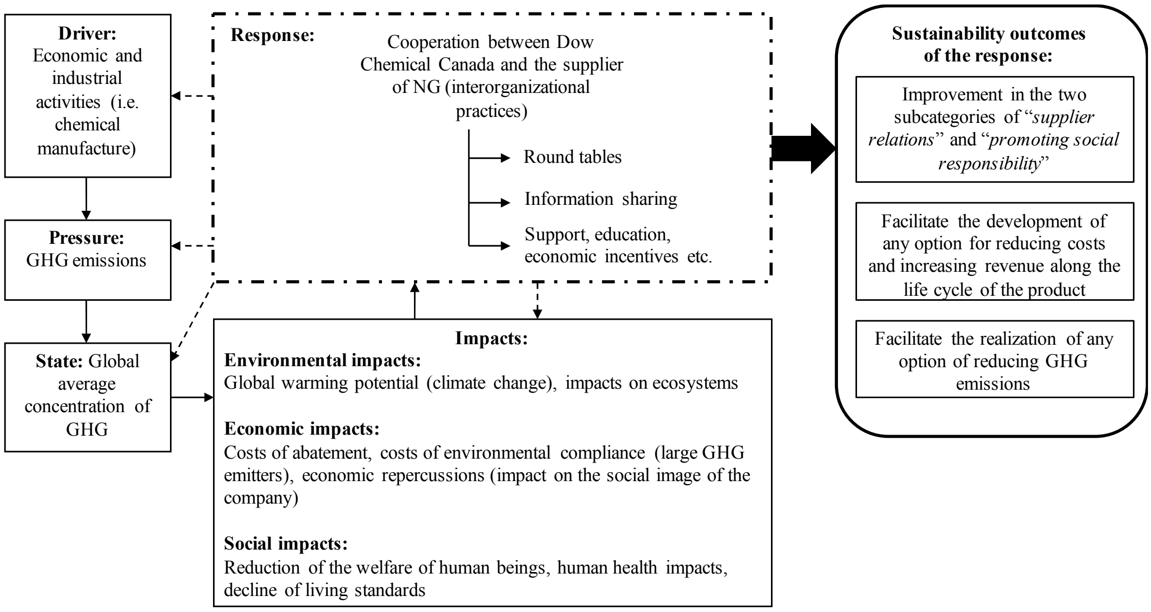

Figure 8. Schematic example #4 of sustainability improvement proposal in a DPSIR framework.

6. Discussion and Conclusions

The approach applied in this paper was able to propose the first attempt for an integrated solution-oriented approach in LCSA toward improving the sustainability performance of product systems. This paper has used a case study of LCSA of HDPE production by Dow Chemical Canada in Alberta, Canada. This case study shows that using the key sustainability assessment results, the integrated approach developed was able to propose some sustainability recommendations for the case study product. Data availability issues for some cost categories and social subcategories was one of the limitations of this case study. Regarding the cost categories not considered in this case study, this does not have an impact on the results due to their insignificance as the integrated approach was using the key sustainability results as an input. However, resolving the data availability issue especially for the social dimension can still open more opportunities for developing some linkages between the sustainability results and propose additional sustainability improvement proposals. This was the case for "*promoting social responsibility*" and "*supplier relations*" in this case study, where a sustainability improvement proposal was developed despite the data availability issue. One solution to the data availability limitation would be to collect primary data from the company using a questionnaire for foreground processes, as well as improve the data collection in generic databases for background processes.

Yet, other challenges and limitations remain in this work and demand additional research. As emphasized in Section 5.2.2, this article has only given a rough sketch of the possible linkages that could be established between the three assessment results and some possible sustainability recommendations for companies. Many other linkages and more specific opportunities are still to be clarified and require further research.

While it is easy and straightforward in some cases to interpret the interrelationships between the results of the three assessments to formulate sustainability improvement proposals, there is not yet a direct relationship in other cases. For example, some specific social life cycle subcategories that require high level of improvements in foreground processes could not be directly related to an environmental performance improvement; specifically, when it comes to some subcategories related to local community and society stakeholder groups such as *corruption*, *prevention and mitigation of conflicts*, *secure living conditions* etc. It is not clear yet how improving the social subcategories of S-LCA can affect the environmental performance of product systems or vice-versa in order to propose sustainability improvement proposals for the product system that cover all three pillars of sustainability.

These limitations are still due to the limited scientific knowledge about understanding:

- The interrelationships and linkages between the three groups of LCSA evaluation results in the context of achieving sustainability goals while adopting the strong sustainability perspective with a solution-oriented approach to sustainability.
- The connection between improving the social performance of the company toward increasing the well-being of its stakeholders which is the aim of S-LCA and increasing the environmental and economic performance at product system level.

As the development of LCSA is still ongoing, we are convinced that it is the right time to think about further improvements in the LCSA methodology. LCSA should be able to contribute to sustainable development from its level of assessment which is the product system level. However, contributing to sustainable development should not be only focused on avoiding negative impacts in decision-making through a comparative integrated assessment approach. The contribution should exceed that to also propose solutions and improvements to enhance the positive sustainability impacts of product systems. But this would require from the LCSA community to do research about the following questions:

(1). While adopting a strong sustainability perspective, how sustainability goals on product system level could be addressed in interpreting the results of LCSA using a solution-oriented approach to sustainability problems?

(2). How to use, link and interpret the LCSA results in decision-making to formulate sustainability improvement proposals in the context of strong sustainability model?

(3). How improving the social well-being of companies' stakeholders through the different subcategories presented in S-LCA is connected with improving the environmental and economic performance of product systems?

(4). What type of decision-making approach is capable to handle and analyze the interdisciplinary, and different types of assessment results in LCSA and develop sustainability solutions for product systems?

(5). Can a comprehensive theory about interpreting the three assessment results in an integrated approach to propose sustainability improvements in product systems be developed?

Making more and more LCSA case studies, can guide our understanding of the above questions and show how best the three components work in the context of different applications to achieve sustainability goals at product system level. This works best with a collaboration between the two parts responsible for the development, application and use of LCSA results "scientific community and business associations".

Supplementary Materials: The following are available online at www.mdpi.com/2071-1050/9/12/2332/s1, SM1: The detailed information on goal and scope definition of the study including the functional unit, reference flow, system boundaries and impact categories. SM2: The detailed information on the LCA inventory analysis including materials inputs in all unit processes for the production of 1000 kg HDPE and a description on the types of inputs and outputs, in addition to the transportation calculations. SM3: The detailed information on the LCC inventory analysis.

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