Applied Environmental Research
- RESEARCH FOR SUSTAINABLE PLANET -

Research Article

Life Cycle Assessment of Plastic Resin: A Case Study of the Petrochemical Industry in Thailand for the Production of HDPE Resin

Natthapong Wichaiutcha[1], Abhishek Dutta[2], Orathai Chavalparit[2,*]

[1] Interdisciplinary program of Environmental Science, Graduate School, Chulalongkorn University, Bangkok, Thailand
[2] Department of Environmental Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok, Thailand

*Correspondence Email: orathai.c@chula.ac.th

Abstract

Life cycle sustainability is an important tool for assessing product performance based on the three pillars of environment, economy and society. This study examined the life cycle impact, cost and social implications of high-density polyethylene (HDPE) resin. Environmental assessment revealed nonrenewable energy as the greatest impact followed by carcinogens, respiratory inorganics and global warming while economically, the operational cost of HDPE resin production was significantly highest. The social impact assessment following the United Nation Environmental Programme (UNEP)/ Society of Environmental Toxicology and Chemistry (SETAC) guidelines demonstrated optimal performance for all indicators except for gender ratio and disabled employee criteria which were lower human rights indicators than other companies. The subcategory of occupational health and safety should be specified in future aspects, such as rate of disease from company operation. Energy efficiency and material acquisition should be improved to reduce the environmental impact and positively redress declining costs, leading to decrease in disease rate among workers in the local community. Results suggested that improving environmental impact would increase economic performance through optimal energy efficiency, while the social life cycle assessment indicator should mainly focus on health and safety in the event of disease arising from business operations.

ARTICLE HISTORY

Received: 1 Nov. 2022
Accepted: 1 Mar. 2023
Published: 23 Mar. 2023

KEYWORDS

Life cycle sustainability assessment; Life cycle cost; Social life cycle assessment; Actor network analysis

Introduction

The global population surpassed 7 billion during the past decade and technologies and innovations are constantly being developed to support our comfortable way of life [1]. Anthropogenic development has resulted in the depletion of natural resources and deteriorating environmental quality. Beginning with the industrial revolution, uncontrolled release of CO_2 into the atmosphere has become a global issue impacting climate change [2]. The concentration of CO_2 in the atmosphere reached 413.2 parts per million in 2020, 149% higher than pre-industrial (before 1750) levels [3]. International cooperation through the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol has attempted unsuccessfully to relieve, mitigate and resolve these problems [4–5]. Climate change is caused by human activities including agriculture, transportation and the use of fossil fuels. Release of CO_2 into the atmosphere is the most significant cause of global warming, with industrial activity the major source of carbon emissions [6].

https://doi.org/10.35762/AER.2023004

The petrochemical industry emits significant amounts of greenhouse gases, mainly when producing plastic resin for downstream applications [7]. The plastics industry is very important in the modern world economy and plastic production and consumption rates have steadily increased [8]. In 2020, global plastic production reached 367 million tons. The primary plastic producing region is Asia, with China accounting for 32% of total global plastics production [9]. In Thailand, the petrochemical sector output was 33.3 million tons in 2018, the largest in Southeast Asia and 16th globally. Thailand is the world's 11th largest exporter of plastics and ASEAN's second largest [10]. Plastics accounted for 6.1% of Thai GDP, acting as a vital link between the petrochemicals sector which supplies upstream inputs and end-user industries [10]. Packaging consumes 42% of all plastic resin [11]. High-density polyethylene (HDPE) is a thermoplastic made from ethylene and used in a wide variety of plastic products due to its transparency, stability, durability and malleability [12–13]. Thailand's ethylene production, which is used to make HDPE, was 4.7 million tons in 2020 [14].

In 2020, during the COVID-19 pandemic, the global economy experienced a recession which reduced plastic pellet production, particularly in the first six months, with the exception of single-use plastic related to medical supplies; however, exports of plastic resin are expected to increase by 2–3%, [10]. Because of the complex production processes, the effect of petrochemical resin can be found in various pathways and undoubtedly contributes to natural resource depletion and wastewater, air and water pollution through macro and microplastics [15]. Plastics accumulate in food chains at all trophic levels, including in many types of birds and fish [16], eventually leading back to humans. Microplastics, in particular, can be found in marine creatures [17]. Microplastic pollution induces physiological problems such as in oyster reproduction [18], metabolism rate changes [19] and behavioural changes [20]. Plastic resin leaches into harmful environments at various stages of its life cycle, including storage, transportation and manufacturing. For example, a recent study reported an annual loss of 5 to 53 billion plastic resin pellets from industries in the United Kingdom [21], while approximately 300 million tons of plastic waste are being dumped globally annually [22].

Life cycle sustainability assessment (LCSA) has broadened the scope of life cycle assessment (LCA) to include three aspects of sustainability rather than only environmental impacts (environmental, economic and social). LCSA is a more comprehensive approach to all pillars of sustainability [23–25] because it combines environmental protection, economic considerations and social equity. LCSA methodology is still in its infancy but the concept has been used in many studies (Shrivastava & Unnikrishnan, 2021). Primary drivers of LCSA development are a shift in perspective from environmental protection to economic and social protection as three dimensions of sustainability [23, 26–27]. LCSA is a tool that assesses all aspects of sustainability to achieve sustainable development goals (SDGs). LCSA is a systematic framework for the quantitative evaluation of environmental impacts of a product system, starting from raw material acquisition, production, use of the products and finishing with end-of-life management. The Society of Environmental Toxicology and Chemistry (SETAC) has created a number of practical LCA recommendations [28]. In 1994, the International Organisation for Standardization (ISO) issued ISO 14040:2006 and ISO 14044:2006 which set the standards and principles for performing LCAs. Affluent nations have recognised the need to prevent environmental deterioration and, as a result, have taken aggressive measures. China is actively involved in monitoring and managing the environmental implications of plastic resins [29]. LCAs are used to create case studies that show the environmental effects caused by activities such as operation, organisation and total product [30]. One critical point in developing case studies is to consider the right indicators according to their importance in the analysis. Life cycle costing (LCC) is a concept that has been developed to understand the significant economic dimensions of sustainability [31]. LCC evaluates various aspects of business value, environmental impact and societal value in monetary terms and can be integrated with LCA as eco-efficiency to measure environmental impact and product system value at various scales [1, 32–33]. The final dimension of sustainability concerns the impact on society after integrating the environmental and economic assessments. Social life cycle assessment (SLCA) is used as a tool to evaluate the social dimensions of products and organisations [34]. There are no standardised SLCA methodologies. UNEP/SETAC Guidelines for Social Life Cycle Assessment of Products, 2009, is a methodology that may eventually become standardised [35]. SLCA, unlike LCA and LCC, involves stakeholders in goal and scope definitions, data collection and interpretation. Usually, SLCA is distinct due to the criteria and unit of impact and numerous studies have conducted separate SLCA [36].

Most research assessing the environmental impact of plastic pellets has focused on economic and social dimensions but environmental impacts on ecosystems are also severe. LCSA combines the three sustainability pillars of environmental, economic and social aspects in business operations. The main study objective assessed the sustainability of plastic pellets using LCSA methodology and including LCA, LCC and SLCA. Interpreting the interrelationship between the three pillars in the realm of plastic pellets and assessing sustainability is challenging but requires urgent attention. In LCSA, scope and system boundaries are accepted to be different from the boundaries of LCA, LCC and SLCA, following the procedure of life cycle sustainability assessment of product [26, 37]. There are different kinds of LCSA scope and concept following the guidelines of LCSA Methodology. Some researchers integrated the sustainability of the three pillars [38–40], while others investigated the sustainability of individual pillars [41–43].

Materials and methods

The LCSA system boundaries covered all areas related to the plastic pellets business, while LCC focused on operational and maintenance costs of an olefin and the HDPE plant, excluding the refinery plant or capital cost for gas separation. The SLCA focused on the entire system boundary. The study area was located in Rayong Province and indicators used were selected using the LCA method and adapted according to ISO 14040-44:2006. The ISO 15686-5 and 15663-1 guidelines were used for LCC, while the product social life cycle assessment (SLCA) followed the United Nation Environmental Programme (UNEP)/SETAC [44] guidelines and LCSA used UNEP/SETAC guidelines [27]. System boundaries are shown in Figure 1, with indicators of LCA, LCC and SLCA shown in Figure 2.

1) Life cycle assessment process

Life cycle assessment can be evaluated in four steps as 1. Definition of the goal and scope, 2. Inventory, 3. Evaluation of the impact and 4. Interpretation. This research quantified the environmental impact of HDPE plastic resin and identified hotspots of environmental performance in the HDPE manufacturing process using 1 kg of HDPE resin as the functional unit for study. The system boundary was from material acquisition (cradle) to HDPE production (gate). In this case study, HDPE was produced from the monomer of ethylene. Ethylene is produced via steam cracking of ethane and naphtha. All steps in the production process, from material acquisition in the olefin plant at the HDPE factory, were assessed at a factory gate. The data inventory consisted of raw material, chemical usage, energy consumption, wastes and others to assess the environmental impact. All input and output data in the inventory were allocated to 1 kg of HDPE resin. The IMPACT 2002+V2.12 method was used with Simarpro V.8.2 software for evaluation and determined 15 midpoint impact categories per one functional unit. A normalisation step was used to facilitate comparison of the LCA results. Results of environmental performance showed the hotspots and critical points. Options for improving environmental performance were proposed.

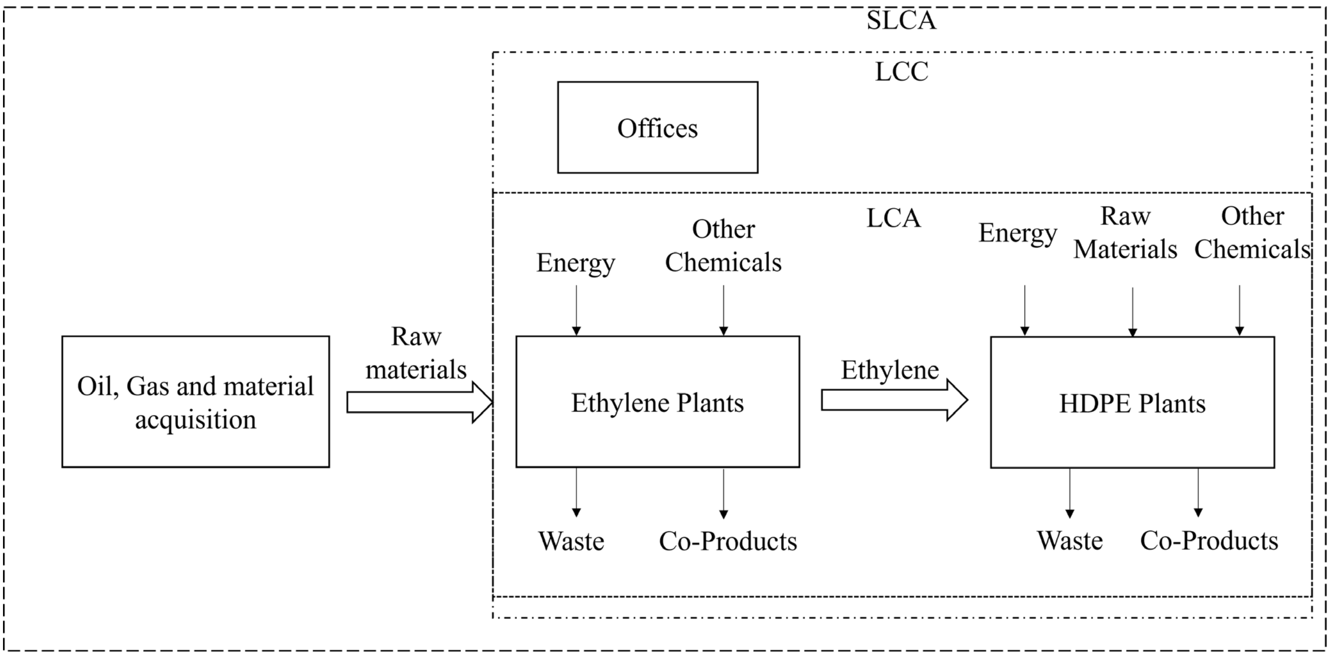

Figure 1 Study system boundaries.

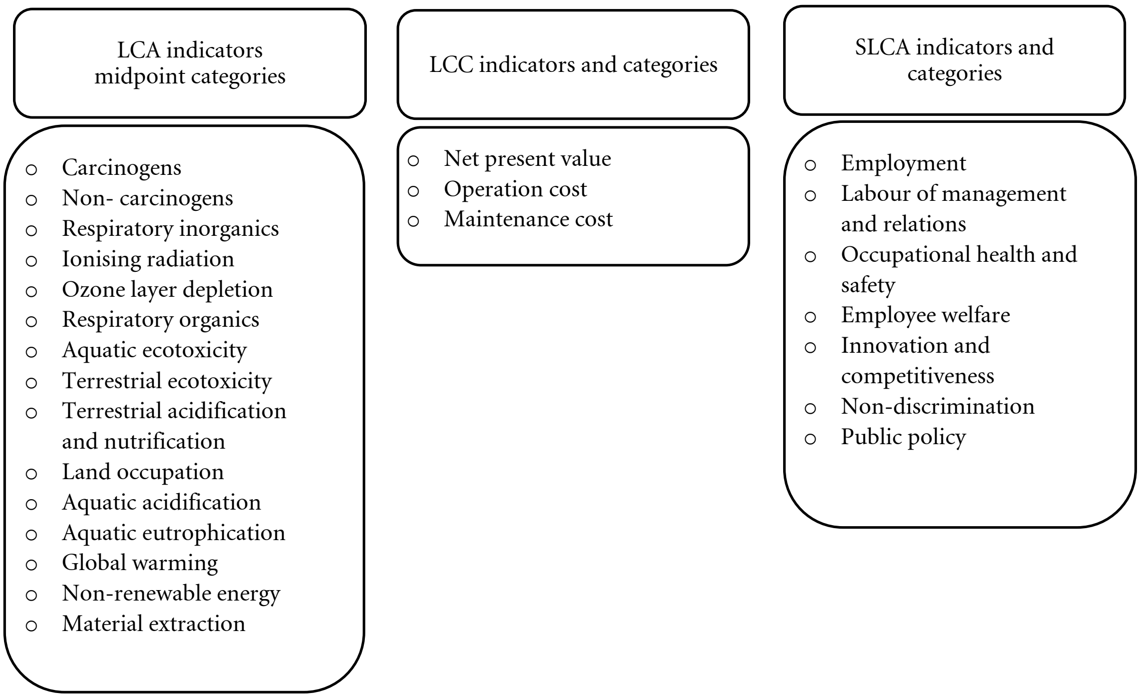

Figure 2 Indicators and categories of LCA, LCC and SLCA.

2) Life cycle costing (LCC) evaluation

The method for evaluating life cycle costing consisted of the following steps.

This study was defined by cost elements as:

$$\text{LCC of manufacturing} = LCC_{OP} + LCC_{MA} \quad \text{(Eq. 1)}$$

where, LCC_{OP} = Operational cost in year T

LCC_{MA} = Maintenance cost in year T

$$LCC_{OP} = LC_W + LC_E + LC_{EL} + LC_{MA} + LC_{FE} + LC_T + LC_R + LC_{MH} + LC_{SE} + LC_{OT} \quad \text{(Eq. 2)}$$

where, LC_W = Water cost in year T

LC_E = Energy cost in year T

LC_{EL} = Electricity cost in year T

LC_{MA} = Material cost in year T

LC_{FE} = Fee and tax cost in year T

LC_T = Transportation cost in year T

LC_R = Rental cost in year T

LC_{MH} = Operational man hour cost in year T

LC_{SE} = Service cost in year T

LC_{OT} = Other operational costs in year T

All LCs are present values (P: present value) with depreciation cost provided in place of capital cost. After converting all cost data to current values, the unit cost was assigned by weight as 1 kg of HDPE resin.

$$\text{Life cycle cost per 1 tonne of HDPE} = {\text{LCC of HDPE}}/{\text{Amount of HDPE production for whole life (tonne)}} \quad \text{(Eq. 3)}$$

Data collection for LCC analysis can either use real costs or estimated costs. The real cost can be calculated directly if available. The accounting departments of the olefin and HDPE factories were approached for all costs. However, some cost data were not available so estimated cost data were used following the international standard ISO15686-2:2001 by employing direct cost estimation and historical data analysis to develop models based on expected performance, future technology trends and market applications.

3) Social life cycle assessment (SLCA)

Two types of social life cycle impact assessment have been defined as (1) Reference Scale Based Social Life Cycle Impact Assessment (RS S-LCIA) and (2) Impact Pathway Social Life Cycle Impact Assessment (IP S-LCIA) [44]. Various constraints were encountered in IP SLCA, resulting in the analysis of only one stakeholder or worker. RS S-LCIA, on the other hand, could analyze all stakeholder groups and associated effects in all categories and facilitates handling multi-actor situations and was, therefore, best suited for this study [45]. Both primary and secondary data were gathered from various sources including company sustainability reports, research and official reveal reports at national and international levels. Social effects of plastic pellet production were studied for social life cycle evaluation. The SLCA system boundaries comprised ethylene production and HDPE pellet manufacture but did not include material acquisition, disposal or plastic consumption. Social life cycle inventory indicators were taken from the Global Reporting Initiative (GRI) and guidelines for social life cycle product assessment (UNEP/SETAC). Sixteen social indicators were chosen harmoniously by considering the necessity to cover all activities of petrochemical industries and connect with various social stakeholders following the UNEP/SETAC guidelines for social life cycle assessment and subcategories in social life assessment [46]. Details are shown in Table 1.

For data collection, 40 workers were interviewed including officers and engineers from each organisational division. Workers were chosen by length of service as 1-5 years, 6–10 years, 11–15 years and 15 years and above (5 officers and 5 engineers were selected from each age range) The 5 consumer companies were corporations that purchased HDPE pellets to manufacture various types of plastic products. For society, the stakeholders included government employees, local government officials and non-governmental organisations (NGOs). Central government officials in the Department of Industrial Works are directly related to the corporation. Local government officials are employees of the Municipality of Maptaphut. Data were collected from NGOs with previous company experience, while local community data were acquired from five year residents. The performance reference points (PRP) were calculated by dividing the number of events in each social indicator and comparing them to worldwide standards, local registration and organisation best practices [45]. In this example, the researcher used secondary data from [36] collected from 45 bio-chemical and biodiesel firms in Europe to develop benchmarks, as well as sustainability reports from 19 companies, including seven companies that participated in the GRI standards. These secondary variables were used to ascertain the lowest and maximum quantitative performances and PRP were determined as the average between the highest and lowest of each indicator.

Table 1 Types of social GRI standards

Endpoint	Midpoint [44]	Sub-midpoint categories [46]	GRIs [36, 47]
Labour practice and decent work	Employment	Number of direct employees	405-1
		Turnover rate	401-1
	Labour relations management	Full time worker	102-8
	Occupational health and safety	Total recordable injury frequency	403-9
		Process safety event	-
		Number of accidents with an irreversible consequence	403-9
		Number of fatal accidents	403-9
		Site with OHSAS certification	-
	Employee welfare, innovation and competitiveness	Number of vacation days	-
		Training hours	404-1
Human rights	Non-discrimination	Gender ratio	-
		Percentage of disabled employees	405-1
		Code of conduct training ratio	-
Society	Public policy	Legal obligation on public sustainability reporting	-
		Presence of laws regulating company transparency	-

Results

1) Life cycle environmental impact

The resin life cycle assessment results of HDPE indicated the critical effect categories including non-renewable energy, global warming, carcinogens, non-carcinogens, respiratory inorganics and respiratory organics. The other effect categories had a negligible influence. Ethane and naptha as raw materials used in HDPE manufacturing are derived from gas and petroleum separation and nonrenewable energy had a significant environmental impact. Furthermore, ethane is a carcinogenic substance with greater environmental impact. Therefore, the most significant examination step was material acquisition. This began with drilling for natural gas and gas separation, followed by processes to obtain ethylene as the end material.

Midpoint analysis results revealed six important environmental effect categories as nonrenewable energy, global warming, carcinogens, non-carcinogens, respiratory inorganics and respiratory inorganics. The remaining environmental effect categories were insignificant with values less than 5% of the total, following the ISO14040 insignificant criteria cut-off. The environmental effect of material acquisition was the highest.

Activities that had the most significant influence on the environment are shown in Figure 3. Material acquisition had the highest effect in all impact categories except for global warming. Material acquisition, chemical substances, power consumption, waste disposal and transportation had the largest share of all important impacts. The fraction of material acquisition categorised activities had the highest rating of all plastic pellet production activities. Environmental impacts were improved by using recycled materials for plastic production as the primary aspect of reducing the environmental impact of material acquisition. The efficiency of HDPE manufacturing was also enhanced by reducing the number of materials used in production by applying a circular economy to the system, such as increasing production efficiency and using renewable raw resources. These efficient approaches showed potential to decrease all environmental consequences. Power consumption also has an impact on the environment. Electricity consumption is responsible for only 2–3% of all environmental impacts but the impact on global warming is estimated to be 10%. To minimise the use of petroleum-based fuel, renewable energy could be employed to improve energy efficiency in manufacturing. Production plants can create electricity using hydrogen gas generated during manufacturing as a substitute for natural gas to boil water in a co-generator to obtain steam and electricity. However, the supply of power during production is limited. Renewable energy, such as solar energy, should be continually developed to reduce the environmental effect of electricity use. Other production activities such as chemical substances constituted under 5%. Non-toxic materials and chemical substance, harmless solvents and efficient methods should be studied and used in the production process to decrease respiratory organics.

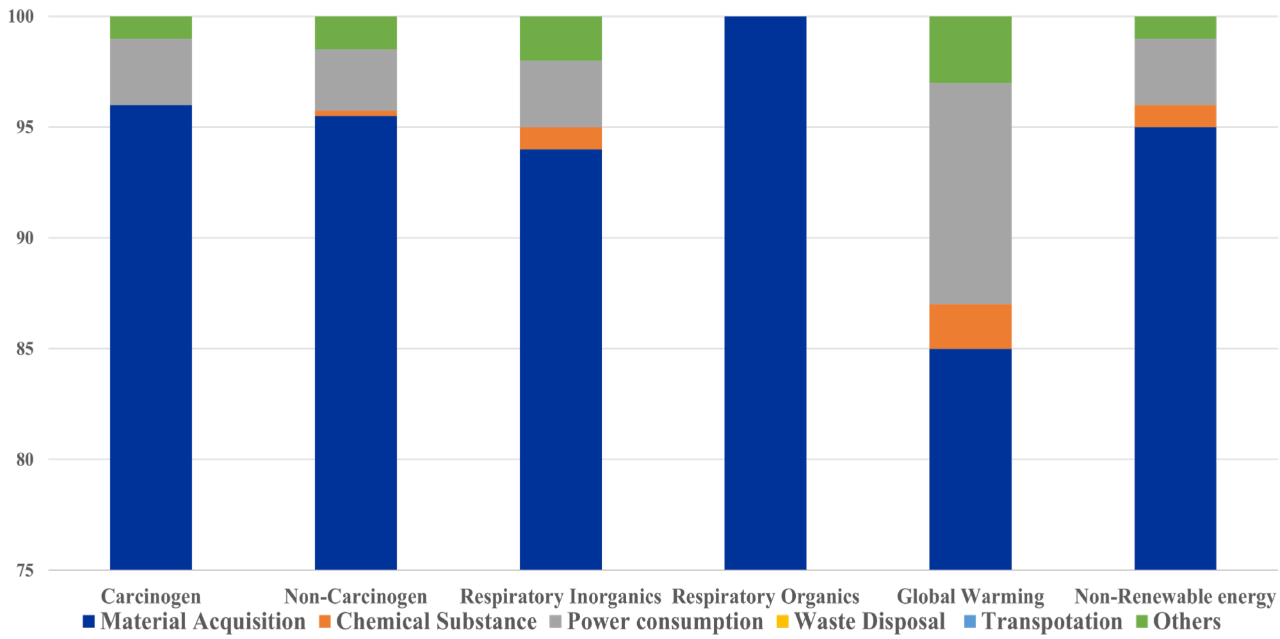

Figure 3 Classifying impact by activity type.

https://doi.org/10.35762/AER.2023004

Normalising impact category results are exhibited in Figure 4 by comparing the dominating impact proportions. Significant contribution at 46% represented nonrenewable energy such as gasoline, oil and natural gas used to manufacture ethane and ethylene for HDPE resin production. Carcinogens accounted for 19% of the total, followed by respiratory inorganics, global warming, respiratory organics and non-carcinogens. The remaining impact categories were less than 1% and had no major influence. These findings were consistent with Treenate et al. [48] and Ruangrit et al. [8] who reported that nonrenewable energy was a major issue in plastic bottle and bag packaging due to the use of natural gas as a raw material to produce ethylene for use in plastic packaging production. The phase of raw material acquisition and pre-processing was a hotspot.

2) Life cycle cost evaluation

The life cycle cost of HDPE resin was calculated as 0.15 USD per functional unit, excluding the investment cost, as the infrastructure required for a petrochemical plant is significant and impacts the operational cost. Investment cost was not included in life cycle cost of HDPE. Expenses for one year in USD. The olefin plant and the HDPE plant had higher operational costs than maintenance costs. Primary expenses were allocated into two groups based on the study method as operational and maintenance costs. Operational costs included water, energy, electricity, material, fees and taxes, transportation, renting, operational man-hours, service and maintenance costs. For the net present cost, the operating cost constituted the largest share in both the olefin and HDPE plants. Olefin plants create a variety of resin products and the allocation by weight approach was used to deduct the overall cost. The entire cost of HDPE resin per kilogram was separated into two major cost categories. The proportional of operational costs reached 80% of the total life cycle costs with maintenance costs at approximately 20%. The largest share comprised operating man-hours at 31% followed by energy, power and material costs. The ethylene manufacturing process is complicated and uses large amounts of raw materials and energy and requires more man-hours than the HDPE facility. Operational cost fractions are shown in Figure 5.

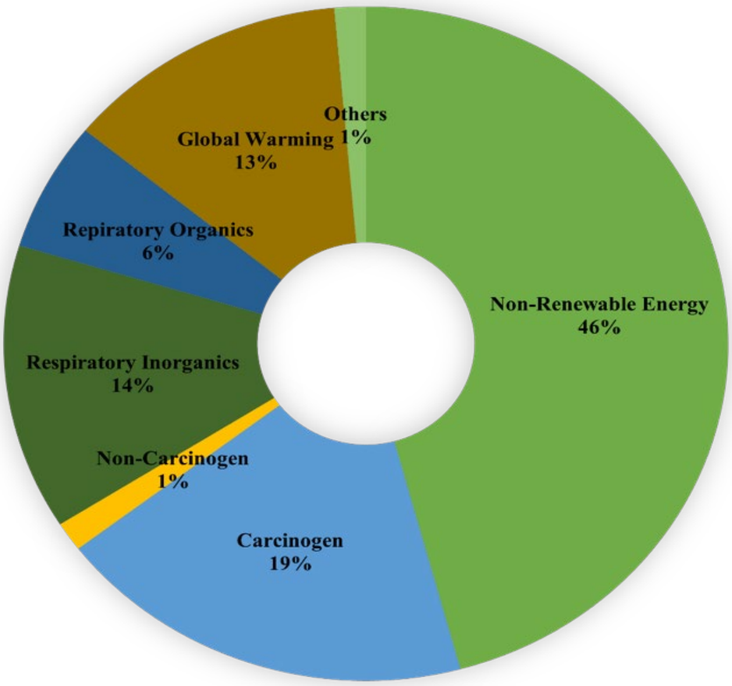

Figure 4 Proportional impact of HDPE resin.

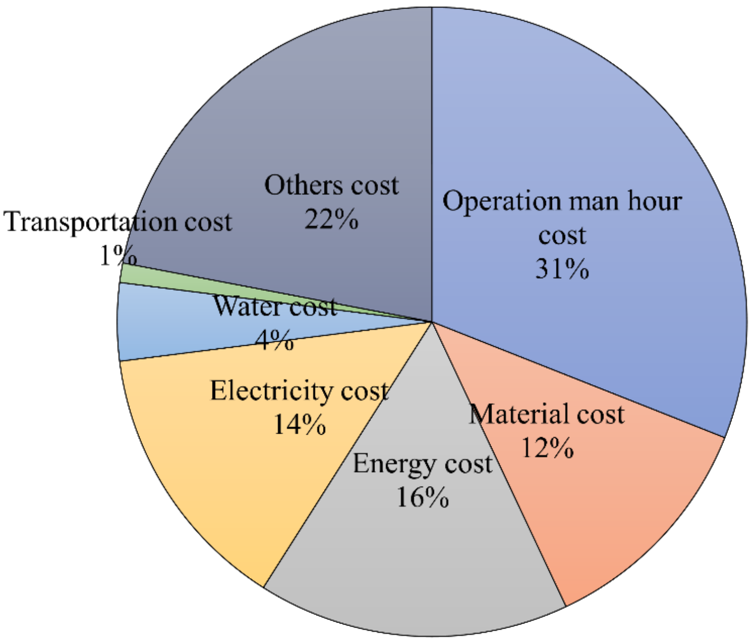

Figure 5 Operational cost proportions.

3) Social life cycle impact assessment

Since 2012, the plants have been running all the indicators in accordance with Thai laws that are extremely stringent for industrial operations, particularly those affecting stakeholders such as the Department of Labour Protection and Welfare and Industrial Work, Pollution Control Department, Provincial Public Health Office, Thailand Greenhouse Gas Management Organisation, Industrial Estate Authority of Thailand and the Department of Alternative Energy Development and Efficiency. Furthermore, the plants operate at high quality standards. Plant operations are based on the principles of the United Nations Global Compact, which are taken from the Universal Declaration of Human Rights and the International Labour Organisation Declaration on Fundamental Principles and Rights at Work. The Global Reporting Initiative (GRI) standard and the Dow Jones Sustainability Indices (DJSI) were also used. Plant policies determine the human rights of employees, occupational health and safety, environment, commercial ethics and supply chain management. In-depth interview results concluded that while the firm consistently promoted welfare and benefits and linked social indicators regarding workers, there were some discrepancies in benefits for hired workers. Most employees were happy with aspects of company sustainability. Local and federal government officials urge that corporations focus more on communication sustainability, while closely managing environmental incident protection. Certain environmental occurrences from associated businesses in the value chain satisfied sustainable policy and operational requirements but could be more effective. Similarly, non-governmental organisations (NGOs) voiced concerns regarding effective mitigation methods, including compensation and justice. Company customers revealed the willingness to support sustainable policies with reasonable pricing of plastic resin. They also requested a reduction in plastic resin price but maintained faith in the company's sustainability policy and operations. Table 2 and Figure 6 depict the GRI standards and the important aspects of societal interviews.

Social performance results were mostly higher than the benchmarks, with the exception of midpoint indicators in gender ratio and percentage of disabled employees that were lower than the PRP score, while percentage of disabled employees was lower than the minimal score of this social indicator compared to other factories. The company focused on the promotion of indicators connected to labour and welfare, with many social operations occurring in employment.

When the outcomes of social performance were compared with the same type of plant (biorefinery plant), the majority of social performances in the case study were better than the results of social performances, except for the percentage of disabled employees and gender ratio [36]. The case study social performance outcomes were similar to results of the biorefinery plants, as shown in Figure 7.

https://doi.org/10.35762/AER.2023004

Table 2 Types of social GRI standards

Midpoint [(1)]	Sub-midpoint categories [(2)]	Result of this study	Reference case [36]
Employment	Number of direct employees	4486	378.5
	Turnover rate	6.87	16.79
Labour relations management	Full time worker	100	95.5
Occupational health and safety	Total recordable injury frequency	0.33	5.64
	Process safety event	0	1.55
	Number of accidents with irreversible consequences	0	1.5
	Number of fatal accidents	0	0.6
	Site with OHSAS certification	100	72.5
Employee welfare	Number of vacation days	20	20
Innovation and competitiveness	Training hours	37.64	27.8
Non-discrimination	Gender ratio	74.65	72.5
	Percentage of disabled employees	0.11	5.5
	Code of conduct training ratio	100	87.5
Public policy	Legal obligation on public sustainability reporting	100	50
	Presence of laws regulating company transparency	100	50

Note: The reference cases were filtered and chosen from 45 companies that participated in GR 3.0. Out of 7 companies that were selected, 2 companies focused on the upstream life cycle stage (biodiesel production), 4 companies focused on the downstream stage (green chemical and bioplastic) and 1 company had a diversified portfolio including both product categories (complete life cycle).

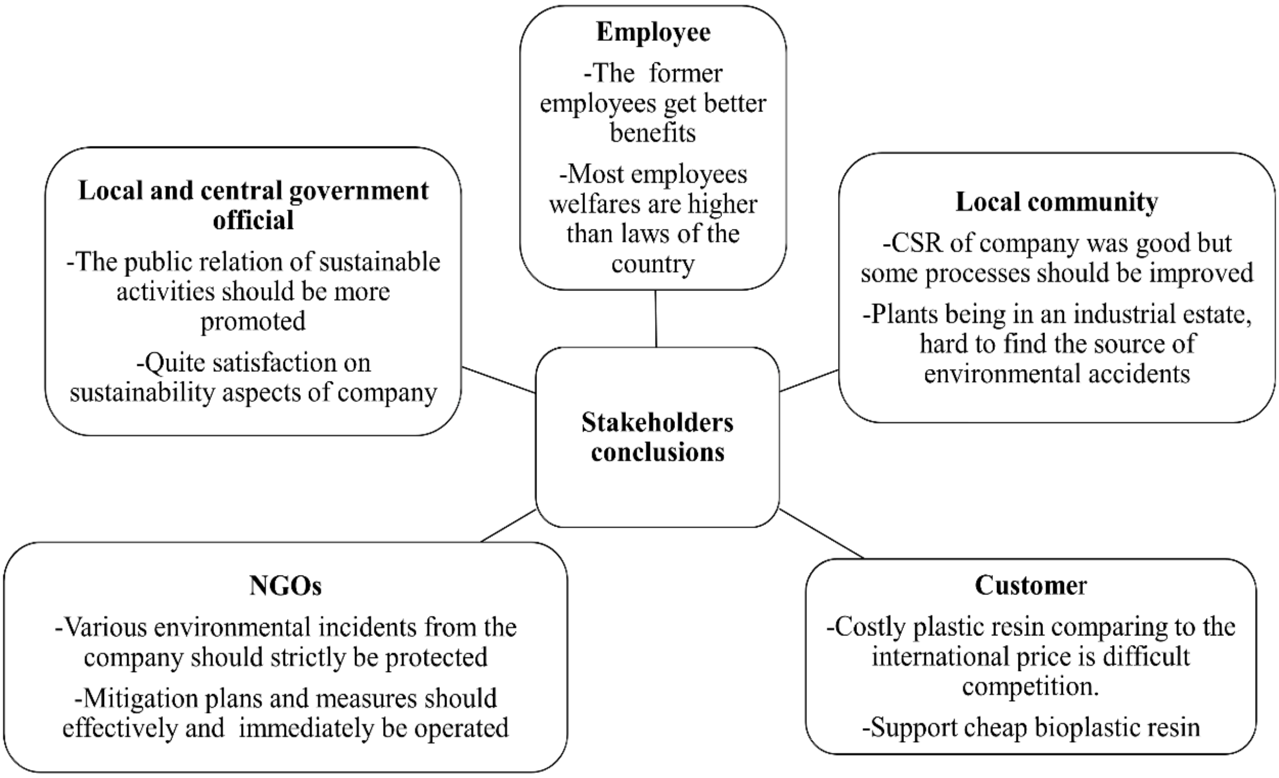

Figure 6 Important aspects of societal interviews.

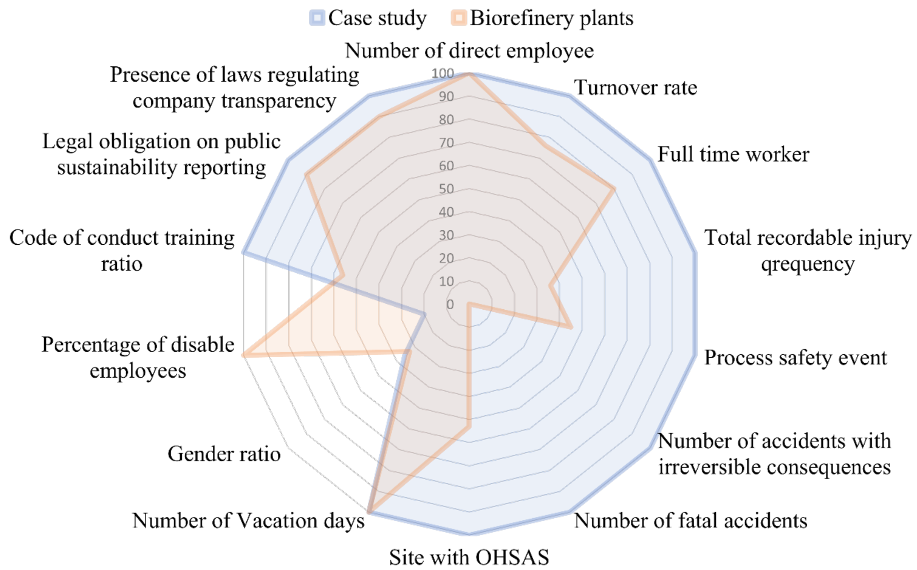

Figure 7 Social performance of case study compared with biorefinery plants.

4) Life cycle sustainability assessment of HDPE pellets

The LCSA evaluation results showed that the most important issue was the environment as the critical point of this study. A comparison with previous research on the same products [49] found that the LCC result was better. The SLCA result was also significantly better compared with the reference case. Therefore, the LCA result should be improved, particularly the nonrenewable energy impact category, which had the highest proportion of all environmental indicators, followed by carcinogens with the second highest ranking. These large impacts were caused by raw material acquisitions. Global warming is caused by energy usage. If the company can enhance its environmental performance, particularly the usage of renewable energy, this will improve the SLCA results because the indicators are linked to the local community and general public perceptions based on company environmental performance. The largest proportion of LCC was operational cost, with the highest proportion as operational man hours. The company has created and refined manufacturing technologies and concentrated on numerous ways to reduce total costs. Stakeholders were happy to extremely satisfied with most SLCA indices but results reflected certain needs and difficulties from the local community, NGOs, government and staff. The sustainability assessment results using LCA, LCC and SLCA methodologies highlighted several environmental and social concerns requiring improvement. Operational indicators demonstrated efficiency including environmental improvement, cost reduction and social responsibility. All stakeholders agreed that the company should improve and promote sustainability. One of the biggest problems of using bio-based plastic resin is the higher cost compared to fossil-based resin. However, some consumers accepted the increased expense because of product sustainability, while other supply chain companies gained less profit from using higher cost plastic resin which adversely impacted business survival.

Customers supported and desired the sustainable concept if it was affordable. The company is constantly improving on environmental impacts, particularly in developing closed-loop systems but contamination in plastic waste was identified as a critical issue. This can be attributed to high plastic production costs. The company must promote value-added environmentally friendly products. Figure 8 shows the relationship between indicators and impacts of each aspect of sustainability. Internal and external factors both influenced sustainability as follows:

1) Internal factors affecting environmental performance

The most essential aspect of environmental performance is material acquisition, with highest impacts being nonrenewable energy, carcinogens, respiratory inorganics, respiratory organics and global warming. Energy consumption, particularly during the manufacturing process, is a substantial element as the second rank, while its fraction of significant influence is small. Chemical use accounts for around 33% of all activities that impact the environment, while utilities, waste management, transportation and water use in production are roughly 2%.

2) Internal factors contributing to improved sustainable development

The company should increase the efficiency of ethylene production and plastic pellet manufacture by exploring and creating new technologies and breakthroughs to gain a competitive advantage. Improved technology will result in less energy consumed, less material used and reduced pollution. This might lead to cheaper operating and material costs. The quality of employees' lives should also be improved through various measures such as maintaining the quality of the environment and counselling about mental health. Competitive trading advantages must be achieved. The company must enhance all elements by reducing production costs and boosting output while maintaining a green operation.

3) External factors leading towards sustainable development

The company must be compliant with all Acts and ministerial regulations through governmental offices such as the Department of Industrial Work, Department of Pollution Control, Energy Policy and Planning Office. The Securities and Exchange Commission (SEC) Office encourages companies to continuously improve standards by adopting the right strategies to achieve business excellence, follow national plans and seek international cooperation through the World Business Council for Sustainable Development (WBCSD). Sustainable development goals (SDGs) are critical indicators that the SEC has implemented following Thailand's national policy of a Bio-Circular-Green Economy (BCG) through involvement in volunteer national and worldwide organisations to promote environmentally friendly businesses. This might involve registering as a sustainability index, DJSI of the chemical industry, or UN Global Compact LEAD with the Securities and Exchange Commission. These national and international organisations influence future company sustainability, with favourable impact on stock market valuation.

The environmental effect revealed that nonrenewable energy and carcinogens account for the majority of all environmental consequences, while the LCC result indicated highest expense as the cost of operating man hours. The SLCA is concerned with human rights and effective actions must be implemented on a continuous basis as follows:

1) Reduction of nonrenewable energy by promoting alternative energy development such as solar, biomass and hydrogen gas.

2) Conservation of energy by improving energy efficiency at the plant. Saving energy reduces the impact of global warming.

3) Closed loop recycling of plastic products and trash as raw materials for the manufacture of plastic pellets. This will reduce fuel usage and waste generation.

4) Use improved technology to replace some jobs and lower the cost of operating man hours.

5) Increase the number of women employed and hire more disabled people in suitable job positions.

6) Raw materials used to make plastic pellets are crude oil and natural gas. To comply with the national strategy of reducing GHGs, the company should publicise its long-term supply chain management strategy, ensuring that businesses do not support any harmful environmental activities. Forced child labour and discrimination are prohibited, while corporate social responsibility (CSR) allows no conflict of interests. The company operates in an industrial park with other plant operations and industries within a confined area. Local residents should be immediately informed of any pollution leaks to ensure company dependability and responsibility

7) A circular economy can be beneficially integrated with LCSA to offer a sustainable future.

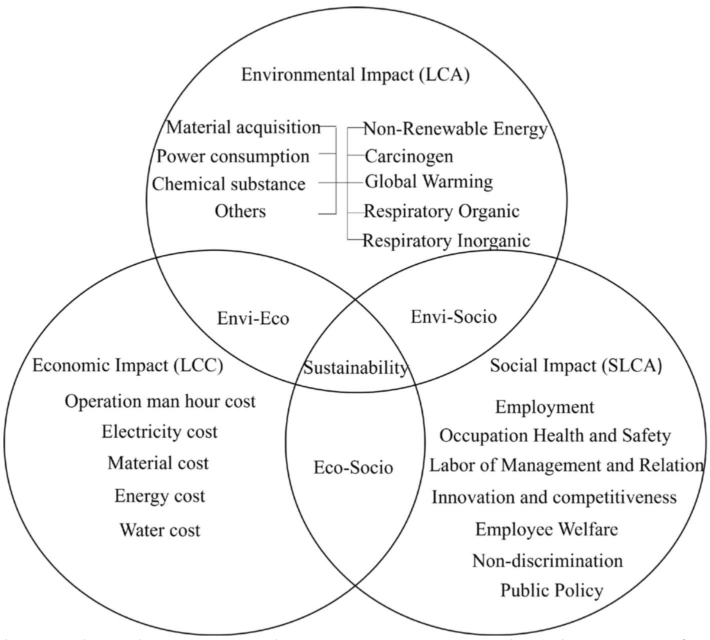

Figure 8 Relationships between indicators, impacts and each aspect of sustainability.

Conclusions

The LCSA findings of in-depth stakeholder analysis differed from the actor-network analysis in all areas, particularly in company policies. Stakeholders, as economic players, have driven companies to pursue sustainability. Policy networks are required, such as rules and regulations which primarily concern environmental indicators and labour laws. By contrast, economic networks can promote sustainability since the perceptions of sustainable sectors are critical in international commerce and the stock exchange. Voluntary operations imply that companies are willing to lower trade barriers and enhance added value to goods. This research differs from previous studies and presents a new challenge to stakeholders connected to policy, economics and society. Stakeholder analysis revealed factors that affected company sustainability by reducing trade barriers and enhancing access to international markets.

Acknowledgment

The research was funded by the 90th Anniversary of Chulalongkorn University Fund (Ratchadaphiseksomphot Endowment Fund).

References

[1] Guo, Y., Liu, W., Tian, J., He, R., Chen, L. Eco-efficiency assessment of coal-fired combined heat and power plants in Chinese eco-industrial parks. Journal of Cleaner Production, 2017, 168, 963–972.

[2] Rшnning, A., Brekke, A., Life cycle assessment (LCA) of the building sector: Strengths and weaknesses, *In:* F. Pacheco-Torgal, L.F. Cabeza, J. Labrincha, A. De Magalhres, Eco-efficient construction and building materials. Woodhead Publishing: UK, 2014, 63–83.

[3] Organization, W.M. WMO greenhouse gas bulletin: The state of greenhouse gases in the atmosphere based on global observations through 2020. World Meteorological Organization, 2021, 17, 1–10. [Online] Available from: https://static.poder360.com.br/2021/10/boletim-gases-efeito-estufa-omm-25-out-2021.pdf [Accessed 20 May 2021].

[4] Lagaros, N.D., Karlaftis, M.G. Life-cycle cost structural design optimization of steel wind towers. Computers & Structures, 2016, 174, 122–132.

[5] Lagaros, N.D., Karlaftis, M.G., Paida, M.K. Stochastic life-cycle cost analysis of wind parks. Reliability Engineering & System Safety, 2015, 144, 117–127.

[6] Daylan, B., Ciliz, N. Life cycle assessment and environmental life cycle costing analysis of lignocellulosic bioethanol as an alternative transportation fuel. Renewable Energy, 2016, 89, 578–587.

[7] Takht Ravanchi, M., Sahebdelfar, S. Carbon dioxide capture and utilization in petrochemical industry: Potentials and challenges. Applied Petrochemical Research, 2014, 4(1), 63–77.

[8] Ruangrit, C., Usapein, P., Limphitakphong, N., Chavalparit, O. Evaluation of the environmental impact of portion bag for food packaging: a case study of Thailand. IOP Conference series: Earth and Environmental Science, 2017, 67(1), 012001.

[9] PlasticsEurope, EPRO. Plastics - the Facts 2021 An analysis of European plastics production, demand and waste data. Brussels-Belgium: PlasticsEurope, 2021, 34. [Online] Available from: https://plasticseurope.org/wp-content/uploads/2021/12/Plastics-the-Facts-2021-web-final.pdf [Accessed 18 May 2021].

[10] Khanunthong, A. Thailand Industrial Outlook 2020-22 PETROCHEMICALS. Krungsri Research, 2020. [Online] Available from: https://www.krungsri.com/getmedia/cb439bc6-cb88-42f2-82df-0f1ec18e0df8/IO_Petrochemicals_200610_EN_EX.pdf.aspx [Accessed 21 May 2022].

[11] Group, W.B. Market study for Thailand: Plastics circularity opportunities and barriers. World Bank, 2020.

[12] Khonakdar, H., Morshedian, J., Wagenknecht, U., Jafari, S. An investigation of chemical crosslinking effect on properties of high-density polyethylene. Polymer, 2003, 44(15), 4301-4309.

[13] Kumar, S., Panda, A.K., Singh, R.K. A review on tertiary recycling of high-density polyethylene to fuel. Resources, Conservation and Recycling, 2011, 55(11), 893–910.

[14] Department of Trade Negotiations. Plastic and plastic products Nonthaburi, Thailand: Department of Trade Negotiations, 2020. [Online] Available from: https://api.dtn.go.th/files/v3/5e86e559ef414020671cd0e4/download [Accessed 21 May 2022].

[15] Karlsson, T.M., Arneborg, L., Brostrцm, G., Almroth, B.C., Gipperth, L., Hassellцv, M. The unaccountability case of plastic pellet pollution. Marine Pollution Bulletin, 2018, 129(1), 52–60.

[16] Baltz, D.M., Morejohn, G.V. Food habits and niche overlap of seabirds wintering on Monterey Bay, California. The Auk, 1977, 94(3), 526–543.

[17] Setдlд, O., Norkko, J., Lehtiniemi, M. Feeding type affects microplastic ingestion in a coastal invertebrate community. Marine Pollution Bulletin, 2016, 102(1), 95–101.

[18] Sussarellu, R., Suquet, M., Thomas, Y., Lambert, C., Fabioux, C., Pernet, M.E.J., ..., Huvet, A. Oyster reproduction is affected by exposure to polystyrene microplastics. Proceedings of the National Academy of Sciences, 2016, 113(9), 2430–2435.

[19] Lu, Y., Zhang, Y., Deng, Y., Jiang, W., Zhao, Y., Geng, J., ..., Ren, H. Uptake and accumulation of polystyrene microplastics in zebrafish (*Danio rerio*) and toxic effects in liver. Environmental Science & Technology, 2016, 50(7), 4054–4060.

[20] Mattsson, K., Ekvall, M.T., Hansson, L.-A., Linse, S., Malmendal, A., Cedervall, T. Altered behavior, physiology, and metabolism in fish exposed to polystyrene nanoparticles. Environmental Science & Technology, 2015, 49(1), 553–561.

[21] Cole, G., Sherrington, C. Study to quantify pellet emissions in the UK. Bristol, UK: Eunomia, 2016.

[22] Geyer, R., Jambeck, J.R., Law, K.L. Production, use, and fate of all plastics ever made. Science Advances, 2017, 3(7), e1700782.

[23] Alejandrino, C., Mercante, I., Bovea, M.D. Life cycle sustainability assessment: Lessons learned from case studies. Environmental Impact Assessment Review, 2021, 87, 106517.

[24] Costa, D., Quinteiro, P., Dias, A. A systematic review of life cycle sustainability assessment: Current state, methodological challenges, and implementation issues. Science of the Total Environment, 2019, 686, 774–787.

[25] Visentin, C., Trentin, A.W., Braun, A.B., Thomй, A. Life cycle sustainability assessment: A systematic literature review through the application perspective, indicators, and methodologies. Journal of Cleaner Production, 2020, 270, 122509.

[26] Klцpffer, W. Life cycle sustainability assessment of products. The International Journal of Life Cycle Assessment, 2008, 13(2), 89–95.

[27] Valdivia, S., Ugaya, C.M., Hildenbrand, J., Traverso, M., Mazijn, B., Sonnemann, G. A UNEP/SETAC approach towards a life cycle sustainability assessment—our contribution to Rio+ 20. The International Journal of Life Cycle Assessment, 2013, 18(9), 1673–1685.

[28] Heijungs, R., Guinйe, J., Huppes, D., Lankreijer, R.M., Udo de Haes, H.A., Sleeswijk, A.W., ..., de Goede, H.P. Environmental life cycle assessment of products: Guide and backgrounds (part 1). Netherlands: Multicopy, 1992. [Online] Available from: https://scholarlypublications.universiteitleiden.nl/access/item%3A3137515/view [Accessed 20 May 2022].

[29] Alhazmi, H., Almansour, F.H., Aldhafeeri, Z. Plastic waste management: A review of existing life cycle assessment studies. Sustainability, 2021, 13(10), 5340.

[30] Zamagni, A., Pesonen, H.-L., Swarr, T. From LCA to life cycle sustainability assessment: Concept, practice and future directions. The International Journal of Life Cycle Assessment, 2013, 18(9), 1637–1641.

[31] Liapis, K.J., Kantianis, D.D. Depreciation methods and life-cycle costing (LCC) methodology. Procedia Economics and Finance, 2015, 19, 314–324.

[32] Zhang, C., Hu, M., Dong, L., Gebremariam, A., Miranda-Xicotencatl, B., Maio, F.D., Tukker, A. Eco-efficiency assessment of technological innovations in high-grade concrete recycling. Resources, Conservation and Recycling, 2019, 149, 649-663.

[33] Ehrenfeld, J.R. Eco-efficiency. Journal of Industrial Ecology, 2005, 9(4), 6–8.

[34] Agyekum, E.O., Fortuin, K.K., van der Harst, E. Environmental and social life cycle assessment of bamboo bicycle frames made in Ghana. Journal of Cleaner Production, 2017, 143, 1069–1080.

[35] Larsen, V.G., Tollin, N., Sattrup, P.A., Birkved, M., Holmboe, T. What are the challenges in assessing circular economy for the built environment? A literature review on integrating LCA, LCC and S-LCA in life cycle sustainability assessment, LCSA. Journal of Building Engineering, 2022, 50, 104203.

[36] Erasmo, C., Francesco, R., Jose, A.G., Ana, C. Social life cycle assessment methology for evaluating production process design: Biorefinery case study. Journal of Cleaner Production, 2019, 238.

[37] Finkbeiner, M., Schau, E.M., Lehmann, A., Traverso, M. Towards life cycle sustainability assessment. Sustainability, 2010, 2(10), 3309–3322.

[38] Akhtar, S., Reza, B., Hewage, K., Shahriar, A., Zargar, A., Sadiq, R. Life cycle sustainability assessment (LCSA) for selection of sewer pipe

materials. Clean Technologies and Environmental Policy, 2015, 17(4), 973–992.

[39] Atilgan, B., Azapagic, A. An integrated life cycle sustainability assessment of electricity generation in Turkey. Energy Policy, 2016, 93.

[40] Ekener, E., Hansson, J., Larsson, A., Peck, P. Developing life cycle sustainability assessment methodology by applying values-based sustainability weighting-tested on biomass based and fossil transportation fuels. Journal of Cleaner Production, 2018, 181, 337–351.

[41] Li, T., Roskilly, A.P., Wang, Y. Life cycle sustainability assessment of grid-connected photovoltaic power generation: A case study of Northeast England. Applied Energy, 2018, 227, 465–479.

[42] Ma, J., Harstvedt, J.D., Dunaway, D., Bian, L., Jaradat, R. An exploratory investigation of additively manufactured product life cycle sustainability assessment. Journal of Cleaner Production, 2018, 192, 55–70.

[43] Blundo, D.S., Ferrari, A.M., del Hoyo, A.F., Riccardi, M.P., Muica, F.E.G. Improving sustainable cultural heritage restoration work through life cycle assessment based model. Journal of Cultural Heritage, 2018, 32, 221–231.

[44] Benoot Norris, C., Traverzo, M., Neugebauer, S., Ekener, E., Schaubroeck, T., Russo Garrido, S. Guidelines for social life cycle assessment of products and organizations 2020. Paris, France: United Nations Environment Programme, 2020. [Online] Available from: https://shorturl.asia/EVko0 [Accessed 20 May 2022].

[45] Bouillass, G., Blanc, I., Perez-Lopez, P. Step-by-step social life cycle assessment framework: A participatory approach for the identification and prioritization of impact subcategories applied to mobility scenarios. The International Journal of Life Cycle Assessment, 2021, 26(12), 2408–2435.

[46] Norris, C.B., Traverso, M., Valdivia, S., Vickery-Niederman, G., Franze, J., Azuero, L., ..., Aulisio, D. The methodological sheets for sub-categories in social life cycle assessment (S-LCA). Paris, France: United Nations Environment Programme (UNEP) and Society for Environmental Toxicology and Chemistry (SETAC), 2013. [Online] Available from: www.lifecycleinitiative.org/wp-content/uploads/2013/11/S-LCA_methodological_sheets_11.11.13.pdf [Accessed 20 May 2022].

[47] PTT Global Chemical Public Company Limited. Sustainability Performance Data. Bangkok, Thailand: PTT Global Chemical Public Company Limited, 2021, 30. [Online] Available from: https://sustainability.pttgcgroup.com/en/flipbook/344/sustainability-performance-data [Accessed 6 May 2022].

[48] Treenate, P., Limphitakphong, N., Chavalparit, O. A complete life cycle assessment of high density polyethylene plastic bottle. IOP Conference Series: Materials Science and Engineering, 2017, 222, 1–6.

[49] Czaplicka-Kolarz, K., Burchart-Korol, D., Krawczyk, P. Eco-efficiency analysis methodology on the example of the chosen polyolefins production. Journal of Achievements in Materials and Manufacturing Engineering, 2010, 43(1), 469–475.