Utilisation of Life Cycle Assessment in Environmental Management: Review

Petronella Nyakudya, Daniel M. Madyira and Nkosinathi Madushele
University of Johannesburg
Auckland Park, 2006
Johannesburg, South Africa
pettienyakudya@gmail.com, dmadyira@uj.ac.za, nmadushele@uj.ac.za

Abstract

Many industries face the challenge of coalescing economic development with a decrease in environmental burden that has brought more stress on life support systems, pushing the environmental impacts closer to the threshold limits of tolerance. Therefore, it is fundamental that the industrial system focuses on the consideration of the whole life cycle of the products, processes, infrastructures, and other industrial activities during the designing and restructuring of processes through Life Cycle Thinking (LCT). The theoretical and methodological aspects in research is reviewed in literature where Life Cycle Assessment (LCA) was applied to environmental management. LCA is a useful (though labour intensive) tool in analysing environmental benefits of synergies in an industrial system. Literature reveals that there is a need to research more on the possibility of LCA methods that are less complex especially in Inventory Analysis (IA). The methods should be affordable but giving reliable data that can be used for decision making. Another area of research is the development of a framework that is region specific especially in the African region considering that most tools used are European based.

Keywords

Environmental Management; Industrial Ecology; Industrial Symbiosis; Life Cycle Assessment

1. Introduction

Industrialisation, a pivotal process of any country's economic development (Zafar et al. 2020) has been associated with an altered environment as well as increased environmental impact. The challenge many industries face today is to coalesce economic development with a decrease in environmental burden. The burden on the environment has brought more stress on life support systems thus pushing the environmental impacts closer to the threshold limits of tolerance (Bhandan & Garg 2016) (Patnaik 2018). These impacts include global warming, climate change, diminishing natural resources and waste management. This calls for industries to be proactive in the design of new products, improve those that exist and develop cleaner manufacturing processes as the world is moving towards a Circular Economy (CE), a model where resource use is improved by extracting minimal natural resources, reducing waste generation through optimising, material environmental, social, and economic values throughout a product's life cycle (Velenturf & Purnell 2021). In doing this, industries reduce raw material and energy consumption minimising amount of waste generated thus increasing productivity and the organisation's financial benefits in the long term (Rankin 2014). Globally, environmentally responsible organisations are being incentivised as the market is increasingly becoming interested in environmental issues as strategic variables in business (Mazzi 2020). Therefore, it is fundamental that the industrial system focuses on methods that assess their processes and systems (Mazzi 2020). This includes the consideration of the whole life cycles of the products, processes, infrastructures and other industrial activities during the designing and restructuring or processes through Life Cycle Thinking as described on Figure 1.

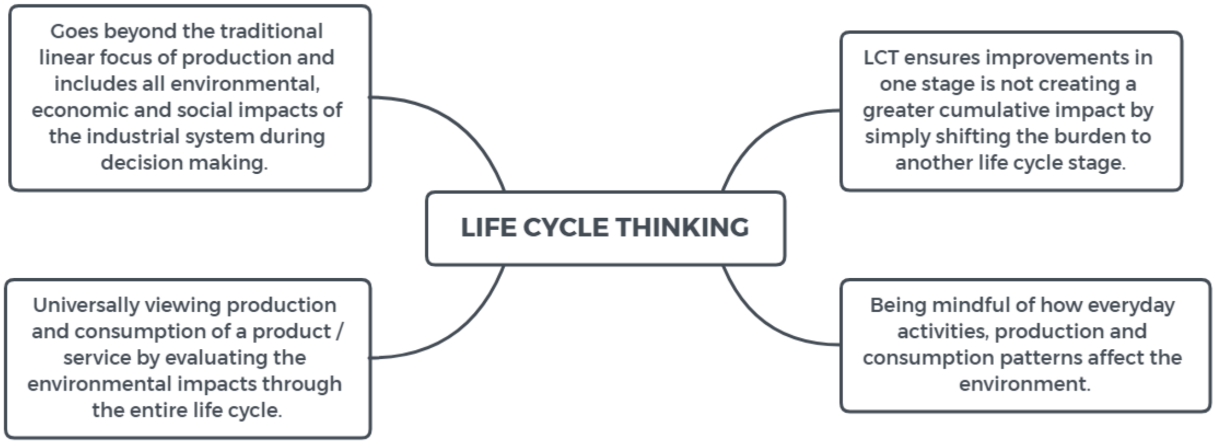

Figure 1. Life Cycle Thinking, adapted from (UNEP/SETAC, 2012)

In Life Cycle Thinking, potential environmental impacts from production to the end user are evaluated and measures put in place to mitigate and minimize them. This is mainly achieved through the method of Life Cycle Assessment (LCA). ISO 14040 highlights that LCA is "a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the functioning of a product throughout its life cycle (International Organisation for Standardisation (ISO) 2006). LCA has been used to assess the environmental impact of products and services in many different sectors. For instance, in Municipal Solid Waste Management, (Menikpura, *et al*. 2012) and environmental decision making for commercial buildings (Means & Guggemos 2015). It has also been used to assess the potential of industrial symbiosis implementation (Neves *et al*. 2019). This paper aims to investigate and present an overview of LCA as a tool in environmental management. The following section discusses LCA.

2. Life Cycle Assessment

Life Cycle Assessment is an evaluation of relevant environmental impacts of a material, process or product across its life from raw material extraction, manufacturing, transport, use and disposal (Karkour, et al. 2021; Madushele 2017; Dong, et al. 2013). The broad scope of LCA is aimed at reducing the environmental impacts by shifting the focus from end of pipe solutions to dealing with them before they are manifested (Mazzi 2020). The life span of a product and or system is assessed to determine the product's contribution to the environmental load for continual improvement of the product/ process ultimately avoiding and mitigating the impacts at a lower cost through product development and process improvement as well as identifying potential tradeoffs from transitioning one stage to another or from one environmental problem to another. As set out in the ISO Standards 14040 (2006) and ISO 14046 (2006), LCA is carried out in four basic, interdependent stages viz:

- Goal and Scope Definition
- Life Cycle Inventory Analysis
- Life Cycle Impact Assessment
- Life Cycle Interpretation

2.1 Goal and Scope Definition

The definition of the goal and scope is the most critical phase of LCA as it sets out the intent of the assessment outlining the intended purpose of the study. This stage defines what is being analysed and to what extent is the analysis. It is at this stage that system boundaries are set to determine the unit processes to be included in the LCA This is known as the Functional Unit. It is a fundamental element of LCA which must be clearly defined though difficult as it enables comparison of two essential different systems (Furberg et al. 2021).

In a study to define the Functional Unit in the mining sector Bongono, Elevli, & Laratte (2020) concluded that if the Functional Unit is not properly defined as it might not reflect on the pivotal elements in the final utility of the product (or process) and stakeholders' interests. They highlighted that, it is difficult to compare, for example, the production of copper or alumina in two regions, as this requires considering the whole environment around production rather than the production process. The definition should be precise and comparable enough so that the unit can be used throughout the study as reference. Defining system boundaries is partly based on a subjective choice, made during the scope phase when the boundaries are initially set as it defines what and quantifies how much will be assessed. It is at this stage that the product life cycle and analysis implications will be defined through identification of impact categories the assessment will focus on. For instance, if the goal of the assessment is the development of an industrial waste management strategy, the assessment should be based on the provisions of the environmental legislation as well as policies by industrial bodies towards pollution prevention and reduction in resource consumption. Thus, it is through LCA that the decision makers will determine the appropriate Waste Management Option to consider (Yadav & Samadder 2014).

It is also vital to determine what the assessment will not consider as certain depth of the value chain may not be relevant to the assessment. Moreover, in-depth assessment of the raw materials and the social implications of the product may be omitted in the analysis. An assessment can also be done to quantify the environmental benefits of an Industrial Symbiosis (a process where wastes, or by-products of an industry or industrial process become the raw materials for another) network as studied by Daddi et al. (2016) in an industrial cluster of SMEs thus defining the context of the assessment. This phase also defines why the LCA is being done compared to other approaches for instances the end of pipe approach which is reactive hence industries prefer the proactive and progressive approach in tackling environmental impacts as specified in Goal 12 of the United Nations Sustainable Development Goals (Srinivas. 2015; Weidema et al. 2020). This is the most critical phase of LCA as it sets out the intent of the assessment outlining the intended purpose of the study.

2.2 LCA Inventory Analysis

The LCA Inventory Analysis is the "compilation and quantification of inputs and outputs for a product throughout its life cycle (International Organisation for Standardisation (ISO) 2006). In simple terms, it is the accounting of everything involved in the Product System of interest, consisting of detailed tracking of all the flows in and out of the product system, including Raw Materials, Energy, and Waste as depicted in Figure 2.

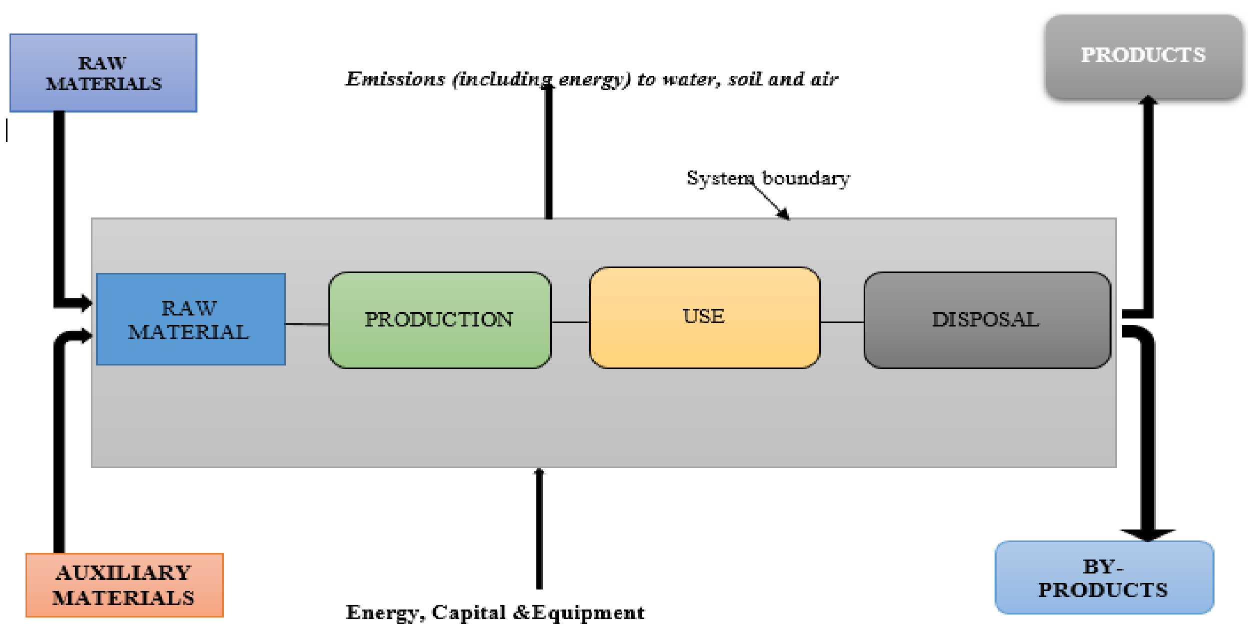

Figure 2. Inventory Analysis as adapted from (Rinawati,. et al. 2018)

The inputs as in energy and raw materials consumed, emissions to air, water, soil, and solid waste produced by the system are calculated for the entire life cycle of the product or service. This phase is complex (Crawford 2008) and may involve numerous individual unit processes (e.g., raw material extraction, primary and secondary production processes, transportation etc.) as well as hundreds of tracked substances. The analysis may be made simpler by splitting the system under study into sub systems or processes. The data obtained is then grouped into different categories to form an LCI table. For instance, the LCI table for a chair may be grouped as in table 1.

Table 1. LCI Table for a Chair as adapted from (Rinawati et al. 2018).

Type	Class	Volume Unit
Input	Material Energy	XKg Timber YkWh Electricity
Output	Product Output Non- Product Output	Xkg Chair Xkg Waste X ppm Emission (Gasses)

From the above simplified table the data for the manufacture of a chair is grouped as inputs in the form of raw materials which could be timber in kilograms and energy (electricity measured in kilowatt hours' kWh). The output would be the product in this instance. the chair and the non-product output, the waste (sawdust, woodchips etc.) and gaseous emissions into the environment. It is crucial to calculate data used in the entire life cycle. Therefore, choosing the appropriate procedure, as highlighted by Singh et al. (2007) is vital otherwise, one may end up using unreliable and incomplete data (Crawford. 2008). Past LCA studies have used traditional LCA methods where, all the loadings are aggregated, and impacts are calculated at the regional or global scale and indicates a more extensive data collection exercise. As highlighted by Singh et al. (2007) and Thomas, et al. (2003 different studies adopt different methods of inventory analysis depending on the purpose, time, and resources (both financial and human). Recent work has developed Hybrid Inventory Analysis Methods by combining these two methods developing 4 hybrid methods namely, tiered hybrid, path exchange, matrix augmentation and integrated hybrid. The hybridized methods maintained the strengths of the traditional methods (Crawford 2008; Crawford, et al. 2017).

Life cycle inventory data can be used to quantify per unit Life Cycle emissions and energy consumption in a material reuse or material exchange industrial system as well as a hypothetic alternative (Daddi et al. 2016). In this study, LCI was used to quantify the environmental benefits of material and by-product reuse in an industrial system. The virgin material that could have been used if there was no material reuse was also quantified. However, even though life cycle inventory data is adopted, it is not a Life Cycle Assessment of the synergies within the industrial system, as the procedure to quantify did not follow the procedure as set out by Chertow (Chertow 2000) and in the ISO standards (International Organisation for Standardisation (ISO) 2006).

2.3 Life Cycle Impact Assessment

The next phase is the Life Cycle Impact Assessment which estimates and calculates the potential impacts to the environment. The environmental burdens quantified in the Inventory Analysis are aggregated into impact categories such as climate change, ozone depletion, eutrophication, acidification, toxicological stress on human health and ecosystems, water use, land use and others (Crawford 2008). According to Crawford, the transition from Inventory Analysis to Impact Assessment is the most difficult stage of LCA, and this is where inconsistencies among practitioners arise and has been a cause for concern and cited as one of the limitations of LCA methodology. This has led to the development of many impact assessment methodologies to ease the burden (Islam et al. 2016). Although these methods differ, distinction is made between midpoint and endpoint methods that look at diverse phases in the cause-effect chain to compute the impact. A midpoint method looks at the impact at the beginning of the cause-effect chain, before the endpoint is reached whilst an endpoint method looks at environmental effect at the end of this cause-effect chain (Bare et al. 2000). Endpoint results are usually shown as human health impact, quality of the ecosystem and depletion of resources. Figure 2 illustrates Midpoint impact categories and the corresponding areas of protection when turned into Endpoints.

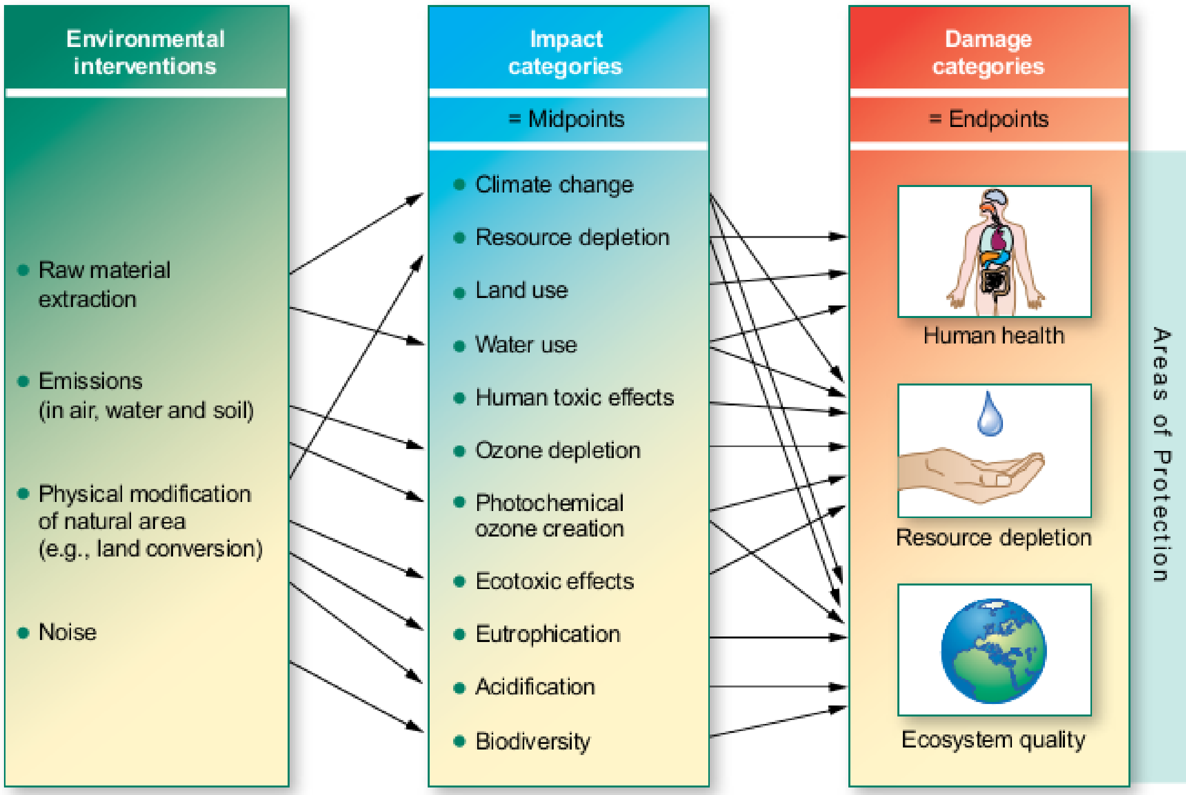

Figure 3. Midpoint impact categories and the corresponding areas of protection when turned into Endpoints (UNEP/SETAC 2012)

The ISO standard on LCA makes it mandatory to quantify impact categories and normalisation and weighting optional. However, weighting is the most standardising part of the LCIA method as it applies to the ranking, grouping, and weighting of the impact categories. According to Finnveden & Potting, (2014) there is no objective way to execute weighting and therefore, no 'correct' set of ranks or weighting factors. They further highlight that the ISO standard for LCIA does not allow weighting in comparative assertions for studies that are unveiled to the public.

2.4 Interpretation Phase

This phase allows for conclusions and recommendations to be drawn with respect to the environmental impacts generated by the system based on results obtained from the impact assessment phase. These are evaluated checking for consistency, completeness, and sensitivity in line with the ISO standard. In a report to the Water Research Commission (Friedrich, Goga, & Buckley 2017) managed to determine the environmental burden that arise as a result of water treatment processes. As a result of using LCA methodologies they managed to draw conclusions on environmental performances for technologies used in water treatment. They concluded that the use of renewable energy is critical for water treatment in order to reduce the environmental burden that arise from water purification processes. Moreso, it is at this phase that one checks if the conclusions are well-substantiated as described in the ISO 14040 standard (ISO 2006). There is a need to understand the accuracy of the results and ensuring they meet the goal and scope of the study as the purpose of Life Cycle Interpretation is to determine the level of confidence in the results and communicate them in a fairly complete and accurate manner (Skone 2004).

3. Life Cycle Assessment in Environmental Management

Globally, organisations have progressively become aware that their operations may have far reaching impacts as their operations have become increasingly diverse, both technically and geographically, that is, from sourcing raw materials, through processing and product assembly, to usage, and finally to end of life. Considering this, awareness in terms of global environmental management has become vital in production and consumption patterns. Therefore, it is imperative that companies and governments alike look at products and services in a holistic approach to identify and quantify the potential impacts of a product or process throughout its life cycle. This means that Environmental Management strategies have evolved from end-of-pipe treatment to considering all stages of operations thus closing all the loops (Circular Economy) for sustainable development as depicted in Figure 4.

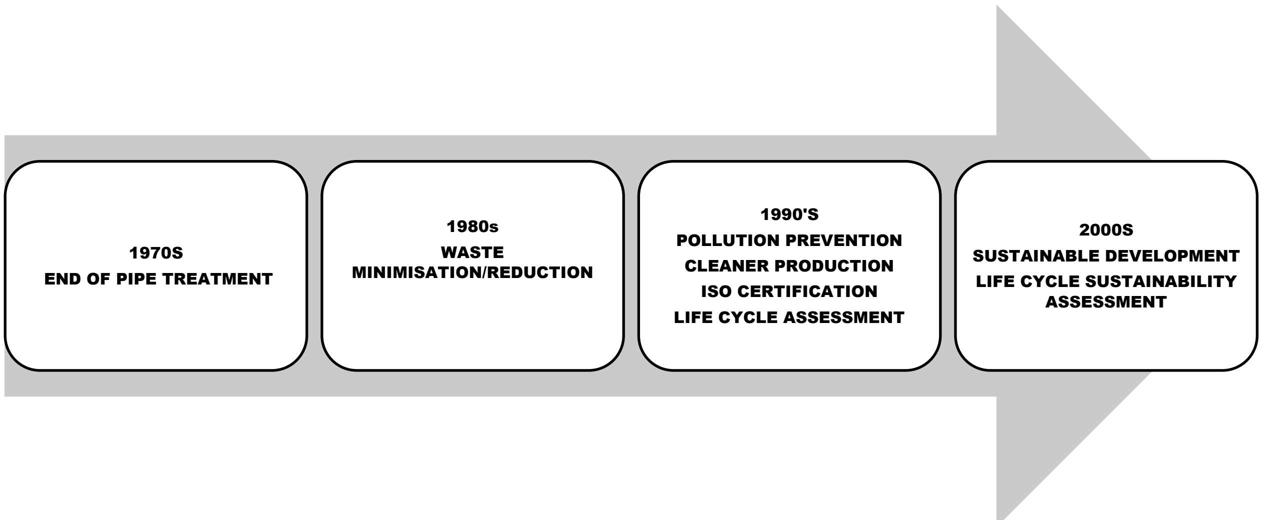

Figure 4. Evolution of Environmental Management Strategies adapted from **(Curran, 2015)**

Understanding a product life cycle will help organisations move from the traditional linear methods to a Circular economy thus improve on environmental management strategies. In essence, LCT helps in considering respective impact generation rates. LCA initiatives have been used in environmental management especially in quantifying the amount of impact that different sources of pollution have on the environment (Esnouf *et al*. 2018). In China, (Dong *et al.* 2013) used LCA to assess the carbon footprint of an Industrial Park due to intensive energy consumption and dependence on fossil fuels that led to increased greenhouse gas emissions. It was critical to quantify the carbon footprints of resident organisations in the Industrial Park so that appropriate emission reduction policies can be raised. In doing this, they investigated carbon dioxide emissions produced by companies in the park as well as the product systems using the hybrid tiered LCA method. The total Carbon footprint measure was 15.29Mt (Figure 5) and this was measured onsite, upstream and downstream. They concluded by recommending policies aimed at reducing the carbon dioxide emissions.

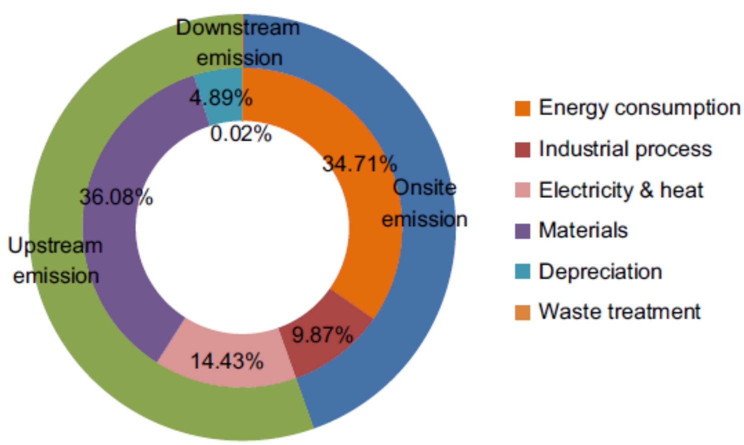

Figure 5. Life Cycle Carbon Footprint in SETDZ (Dong et al. 2013)

In a related study, (Chen, et al. 2013) analysed the lifecycle of Greenhouse Gases CO_2, CH_4 and N_2O in a high-end industrial park in Beijing. They quantified the gases as emitted from direct and indirect processes from the consumption of primary energy and secondary energy. They also considered direct emissions from the industrial production process as well as the material transportation, equipment used in the high-end industrial park and the emission from the sewage treatment and solid waste disposal. Based on the results, they were able to give suggestions to guide the low-carbon development of the high-end industrial park viz;

- Use of locally available l construction materials to minimise the GHG emission from the transportation processes
- Substituting traditional materials with regenerated and low-carbon construction materials thus managing the GHG emission from the upstream production process and downstream disposal.
- Promoting safe and low-carbon form of construction engineering through optimisation of the construction progress

LCA can also be applied in quantifying the environmental benefits of an industrial system operating in an Industrial Symbiosis (IS) network. The IS concept focuses on the flow of material and energy in Industrial Systems using the systems approach (Chertow 2000) (Brent, Oelofse 2008). Sokkh et al. 2010 assessed the environmental impacts such as acidification, eutrophication, and climate change from a Finnish Forest industrial complex. Symbiotic relationships between the pulp and paper mill, power plant, chemical plants and waste treatment plants were assessed. The functional unit was clearly defined as the "annual production of the IS Case (in tonnes or GWh during 2005) at the gate of the park" and the boundary as "cradle to gate", where upstream activities as well as the activities within the park were analysed. Downstream impacts of the products were not taken into consideration as according to the authors they are mainly intermediate products for other firms.

The interpretation of the LCA concluded that Industrial Symbiosis resulted in net improvements in the overall environmental impacts. Net improvements ranged between 5% and 10% with acidification, climate change impacts and particulate matter formation having the largest reduction. The reduction was attributed to symbiotic exchanges for energy production in Kouvala town. They highlighted that Life Cycle Assessment is a very useful, albeit labour intensive tool. It helps in detecting flows whose utilization could provide the greatest environmental benefit. On that regard, monitoring and evaluation of the network can ensure sustainability of the LCA tools. In another study, Eckelman and Chertow (Eckerma et al. 2009) used LCA to identify the best design of an eco-industrial park. The authors compared different designs and identified the potential trade-off in different environmental impact categories identified through an LCA. Consequently, LCA results will provide vital information about the overall environmental sustainability of an industrial ecosystem. This information plays an instrumental role in assessing and improving the environmental sustainability of industrial processes (Eckerman & Chertow 2009) (Jacquemin et al. 2011).

4. Conclusion

This paper centered on an overview of LCA methodology and its application in environmental management. LCA is a method to understand the potential/possible environmental impacts of products (manufactured, supplied, consumed.) throughout their life cycle. Practitioners in an industrial system have the flexibility of implementing LCA as prescribed by the international standard which provides the framework consisting of four interrelated phases:

- Clearly defining the goal and scope of the study (including selecting a functional unit).
- Compiling a (LCI) that is, an inventory of relevant energy and material inputs and environmental releases.
- Evaluating the potential environmental impacts associated with the identified inputs and releases.
- Interpreting the results to enable more-informed decision-making.

The ISO standard provides a general framework for conducting an LCA (International Organisation for Standardisation (ISO) 2006), with interpretation from the practitioner. LCAs can yield different results even if the same product is the focus of the study. These differences may be attributed to several factors such as different goal statements, functional units, boundaries, and different assumptions used by the practitioner in modelling the data. These include, the use of cut-off rules, co-product allocation, assigning credit for avoided burden, and applying consequential LCA (Curran 2015). These differences can be dealt with by keeping assumptions to a minimum and clearly reporting them and values on which the LCA is centered on. The onus will then lie on the users whether to recognize the judgments and make decisions to accept, qualify, or discard them and the study.

LCA implementation provides information that can be used in a comprehensive decision-making process. Moreso application of LCA methodologies as well as engaging experts assist in identifying ecological impacts of a product or system. In line with sustainable Development goal 12, businesses need to comprehend the environmental and social effects of their system and products as well as their life cycles. Consequently, industry is obliged to identify hotspots within the value chain to come up with interventions to improve the system in line with the pillars of sustainability (Economic, Social and Environmental). Given the continued industrial evolution impacting on the environment, there is need for a deliberate and rational approach to maintain sustainability. From an industrial ecology perspective, the application of LCA is useful (though labour intensive) in analysing environmental benefits of synergies in an environmental system as it is an ISO standardised tool that examines the impacts of a product or service throughout its life cycle.

The reviewed literature revealed that a life cycle view should be considered which gives a better insight into the impacts of an industrial system. LCA has become widely recognised as an effective tool for assessing the resource consumption, environmental as well as and human health impacts connected with the complete life cycle of products, processes, and activities. The approach allows decision-makers to identify environmental areas of concern and enhance industrial systems without burden shifting. Initially LCA started as a strategy to compare the environmental friendliness of products but has evolved to a systemic, standardized tool for environmental sustainability in industry and government. LCA methodologies, especially in the LCI phase, are so complicated, there is potential for new scientific findings and improvements.

5. Suggestions for Future Research

Life Cycle Assessment is a valuable decision-making, though labour-intensive tool in Environmental Management and sustainable development. Therefore, it is suggested that more research be done on the possibility of making LCA methods less complex and affordable but giving reliable data. Another area of research is the development of a framework that is region specific especially the African region considering that most tools used are from the European region. As a way of ensuring sustainability of LCA tools, monitoring and evaluation methodologies of the tools need to be explored.

REFERENCES

Bare, J. C., Hofstetter, P., Pennington, D. W., & Udo de Haes, H. A., Midpoint Versus Endpoints: The Sacrifices and Benefits. *International Journal of Life Cycle Assessment, 5*(6), 319-326, 2000.

Bhandan, D., & Garg, R. K., Effect of Industrialisation on the Environment. *Global Journal for Research Analysis, 4*(12), 2016.

Bongono, J., Elevli, B., & Laratte, B., Functional Unit for Impact Assessment in the Mining Sector. *Sustainability, 12*(22),2020.

Brent, A. C., Oelofse, S., & Godfrey, L., Advancing the Concepts of Industrial Ecology in South African Institutions. *South African Journal of Science, 104,2008*.

Chen, B., He, G., Qi, J., Su, M., Zhou, S., & Jiang, M., Greenhouse Gas Inventory of a Typical High-End Industrial Park. *The Scientific World Journal, 2013*, 1-7, 2013.

Chertow, M. R., Industrial Symbiosis: Literature and Taxonomy. *Annual Review of Energy and the Environment, 25*, 313--337,2000.

Crawford, R. H. (2008). Validation of a Hybrid LCI Analysis Method. *Journal of Environmental Mnagement, 88*(3), 496-506.

Crawford, R. H., Bontinck, P. A., Stephan, A., & Wiedman, T., Towards an Automated Approach for Compiling Hybrid Life Cycle Inventories. *Procedia Engineering, 180*, 157-166, 2017.

Curran, M. A. (2015, October 1). Life Cycle Assessment : A Systems Approach to Environmental Management and Sustainability. New York , USA. Retrieved June 15, 2022, from https://www.aiche.org/resources/publications/cep/2015/october/life-cycle-assessment-systems-approach-environmental-management-and-sustainability

Daddi, T., Nucci, B., & Iraldo, F. (2016). Using LCA to Measure the Environmental Benefits of Industrial Symiosis in an Industrial Cluster of SMEs. *Journal of Cleaner Production, 147*, 157-164.

Dong, H., Geng, Y., Xi, F., & Fujita, T., Carbon Footprint Evaluation at Indistrial Park Level: A Hybrid Life Cycle Approach. *Energy Policy, 57*, 298-307, 2013.

Eckerman, J. M., & Chertow, M. R. (2009). Quantifying the Life Cycle Environmental Benefits from the Reuse of Industrial Materials in Pennyslyvania. *Environmental Science and Technology, 43*(7), 2250-2256.

Esnouf, A., Latrille, E., Steyer, J. P., & Helias, A., Representativeness of EIA Methods Regarding LCI. *Science of the Total Environment, 621*, 1264-1271, 2018.

Finnveden, G., & Potting, J., Life Cycle Assessment. In P. Wexter (Ed.), *Encyclopaedia of Toxicology* (pp. 74-77). Academic Press, 2014.

Friedrich, E., Goga, T., & Buckley , C., *A Comparative Life Cycle Assessment for the Provision of Potable Water from Alternative Sources in South Africa.* Water Research Commission,2017.

Furberg, A., Arvidsson, R., & Molander, S., A Practice -based Framework for defining Functional Units in Comparative LLife Cycle Assessment of Materials. *Journal of Industrial Ecology*, 1-13,2021.

International Organisation for Standardisation (ISO). (2006). *ISO 14040 : Environmental Management ; Life Cycle Assessment, Principles and Framework.* Switzerland: ISO.

International Organisation for Standardisation (ISO). (2006). *ISO 14044: Environmental Management; Life Cycle Assessment, Requirements and Guidelines.* Switzerland: International Organisation for Standardisation.

Islam , S., Ponnambalam, S. G., & Lam, H. L., Review of Life Cycle Methods: Methods Examples and Application. *Journal of Cleaner Production, 136*, 266-278,2016.

Jacquemin, L., Pantalier, P. Y., & Sablayrolles, C. (2011). Life Cycle Assessment (LCA) Applied to the Process Industry: A Review. *French Sociaety of Process Engineering (SFGP)*.

Karkour, S., Itsubo, N., Rachid, S., Maaoui, M., & Lin, C.-C. (2021). Status of Life Cycle Assessment in Africa. *Environments, 8*(2).

Madushele, N. (2017). Life Cycle Assessment : A Review. *Proceedings of the World Congress in Engineering.* London , UK.

Mazzi, A. (2020). Introduction : Life Cycle Thinking. In J. Ren, & R. Toniolo (Eds.), *Life Cycle Sustainability Assessementb for Decision Making : Methodologies and Case Studies.* Elsevier.

Means, P., & Guggemos, A. (2015). Framework for LCA Based Environmental Decision Making During the Conceptual Design Phase for Municipal Buildings. *International Conference on Sustainable Design, Engineering and Construction. 118*, pp. 802-812. Elsevier.

Menikpura, N., Gheewala, S. H., & Bonnet, S., Framework for Life Cycle Sustainability Assessment of Municipal Solid Waste Management Systems with an Application to a case Study in Thailand. *Waste Management and Research*, 709-719, 2012.

Neves, A., Godina, R., Azevedo, S. G., Pimentel, C., & Matias, J. C. (2019). The Potential of Industrial Symbiosis: Case Analysis and Main Drivers and Barriers to its Implementation. *Sustainability*.

Patnaik, R. (2018). Impact of Industrialisation on the Environment and Sustainable Solutions. Reflections from a South Indian Region. *IOP Conference Series: Earth and Environmental Science, Volume 120, 2017 5th International Conference on Environment Pollution and Prevention (ICEPP 2017) 14–16 December 2017, .* Singapore: IOP Publishing Ltd.

Rankin, W. J. (2014). Sustainability. In *Treatise on Process Metallurgy* (pp. 1376-1424). Clayton , Australia: Elsevier.

Rinawati, D. I., Sriyanto, Sari, D. P., & Prayodha, A. C. (2018). Eco- Efficiency Analysis of Furniture Product Using Life Cycle Assessment. *ICENIS 2017.* Semarang , Indonesia: E3S Web of Conferences 31.

Singh, A., Lou, H. H., Yaws, C., Hopper, L., & Pike, R. W. (2007). Environmental Impact Assessment of Different Design Schemes of an Industrial Ecosystem. *Resources, Conservation and Recycling, 51*, 294-313, 2007.

Skone, T., What is Life Cycle Intepretation. *Environmental Progress and Sustainable Energy, 19*(2), 92-100, 2004.

Sokkha, l., Lehtoranta, S., Nissinen, A., & Melanen, M. (2010). Analysing the Environmental Benefits of Industrial Symbiosis. LCA Applied in Finnish Forest Industry Complex. *Journal of Industrial Ecology, 15*(1), 137-155.

Srinivas, H. (2015, March 08). Sustainable Developemnt Concepts - Life Cycle Analysis. Kobe, Japan. Retrieved June 23, 2022, from https://www.gdrc.org/sustdev/concepts/17-lca.html

Thomas, V., Theis, T., Lifset, R., Grasso, D., Byum, K., Koshland, C., & Pfahl, R., Industrial Ecology: Policy Poltential and Research Needs. *Environmental Engineering Science, 20*(1), 2003.

UNEP/SETAC. (2012). *Greening the Economy Through Life Cycle Thinking: Ten Years of the UNEP/SETAC Life Cycle Initiative.* Paris: UNEP.

Velenturf, A. P., & Purnell, P., Principles for a Sustainable Circular Economy. *Sustainable Production and Consumption*, 1437-1457, 2021.

Weidema, B., Goedkoop, M., Meijer, E., & Harmens. (2020). *LCA Based Assessment of the Sustainable Developemnt Goals - Developement Update and Preliminary Findingsof the Project "Linking the UN Sustainable Developement Goals to Life Cycle Impact Pathway Frameworks".* PRé Sustainability & 2.-0 LCA Consultants.

Yadav, P., & Samadder, S. R., Life Cycle Assessment of Solid Waste Management Options: A Review. *Recent Research in Science and Technology, 6*(1), 113-116, 2014.

Zafar, A., Ullah, S., Majeed, T. M., & Yasmeen, R., Environmental Pollution in Asian Econonomies: Does Industrialiastion Matter? *OPEC Energy Review, 44*(3), 227-248, 2020.

Biographies

Petronella Nyakudya is currently a PhD candidate at the Postgraduate School of Engineering Management, University of Johannesburg. Her research interest is on Industrial Symbiosis for the management of Industrial waste, Circular Economy, and Waste Management. She is a holder of a Master of Science in Environmental Management from the University of Johannesburg and a Bachelor of Environmental Science Honours Degree in Pollution Science from Bindura University. She has more than ten years of work experience in Environmental Management, Occupational Health and Safety and possesses advanced practical and technical knowledge in SHEQ Management Systems, Environmental Management Education, Training and Sustainability studies, recycling and public conservation projects and corporate sustainability reporting. She advocates for the development and implementation of efficient, targeted integrated SHEQ programs SHE initiatives and applying research to create effective sustainability projects.

Professor Daniel M. Madyira is currently a senior lecturer in the Department of Mechanical Engineering Science at the University of Johannesburg. He has taught a wide range of core mechanical engineering subjects including machine design, fluid dynamics, thermodynamics, and strength of materials. He is a highly experienced mechanical engineer and academic with more than 20 years of academic and industrial experience. He is passionate about engineering design with special expertise in machine component stress analysis. He has developed several mechanical designs ranging from contemporary societal problems such as biomass briquetting, solar crop drying to advanced mechanical systems such as rotating bending fatigue testing machines. His research interests range from high-speed machining of titanium, fatigue of titanium and composites, natural composites to biomass briquetting and biomass combustion modelling, fracture behaviour of materials produced using modern manufacturing techniques such as additive manufacturing and wire EDM including post weld heat treatment. He is also involved in several industry-based activities solving industry-based problems. This makes his academic work relevant to industry and fruitful to his students.

Dr. Nkosinathi Madushele is a Senior Lecturer in the Department of Mechanical Engineering Science and Co-Director of the Biomedical Engineering and Healthcare Technology (BEAHT) Research Centre at the University of Johannesburg. Dr. Madushele is a professionally registered engineer, with the Engineering Council of South Africa (ECSA), and he has worked in Industry as well as Academia. His research interests are in renewable energies modelling from both a Cycle Assessment (LCA) perspective, as well as from an Intelligent Systems Modelling perspective. His involvement in BEAHT serves to incorporate engineering technologies in the biomedical field.