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Questions for Life Cycle Inventory (LCI)

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Abstract
In product-oriented Life Cycle Assessment (LCA) studies, obtaining reliable and accurate data during the Life Cycle Inventory (LCI) analysis is challenging due to security concerns of industrial enterprises. In this study, a question catalogue inventory was intended to be developed to obtain accurate data in LCI processes and to overcome this challenge. The LCA process consists of four main stages: "Raw Material – Production – Use – Disposal." Within this process flow, the LCI inquiry focuses on system boundaries, energy, and transportation at each stage of the LCA process. While deriving the questions, the categories of "Definition – Raw Material – Production – Point of Sale and Distribution – Consumption – Recycling – Disposal" were taken as the basis. A total of 50 questions were developed in the study. This study aims to enhance the environmental sustainability of newly developed technological products by applying the LCI inquiry filter during the project phase, in the context of global industrial competition. Additionally, it will serve as a guiding light for those who are new to conducting LCA studies.

Keywords*: LCA, LCI, LCI process, LCI question catalog, question inventory, questions,*

Introduction

Life cycle assessment (LCA) is a well-established methodology to holistically evaluate the environmental impact associated with products or services, by quantifying environmental pressure of all processes over their entire life cycle from raw material acquisition to disposal. This helps identify environmental hotspots and potential opportunities to mitigate environmental consequences. LCA has been widely applied in sectors such as agriculture, construction, energy, and manufacturing to guide government decision-making on environmental policies and development plans, and assist researchers and businesses in designing sustainable products and technologies (Hellweg and Mil`a i Canals, 2014). LCA's holistic nature is twofold: it encompasses a process or product's entire life cycle from resource and energy acquisition to production, utilization, and eventual disposal, while also addressing various environmental impacts (Chebaeva *et al.*, 2021). LCA leads to identifying environmental hotspots in systems, thereby aiding in the selection of environmentally sustainable production methods (Kleinekorte *et al.*, 2023). In this regard, LCA requires substantial data in the shape of accessible records of material and energy flows for individual materials or processes (Martínez-Ram´on *et al.*, 2024). Although Life Cycle Inventory (LCI) analysis constitutes the fundamental step of life cycle assessment (LCA), it faces many challenges during its development. The primary problem is the complexity of the data collection process. The inputs (energy, raw materials, water use, etc.) and outputs (emissions, waste) required for LCI are often obtained from different sources, and the reliability and compatibility of these data can be questionable. Lack of standardization of data, especially in sectors such as agriculture, energy and industrial production, makes the analysis of LCI studies difficult (Finnveden *et al.*, 2009). Other challenges associated with industry-specific LCI development are identifying and gaining

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access to the specific persons/organizations within a given industry, selecting a representative sample from the industry, managing confidentiality concerns, incomplete information, dynamism of industries, etc. These challenges can often lead to using secondary data from literature and/or industry reports or other data sources, which requires validation, as poor and inconsistent data can result in unrealistic findings and conclusions (Elomaa *et al.*, 2020a ; Li *et al.*, 2018 ; Ferdous *et al.*, 2024). One of the main problems with using secondary data is dealing with missing/incomplete data (Zargar *et al.*, 2022 and Ferdous *et al.*, 2024). LCI data can be obtained from company surveys, industrial databases, published reports, verbal interviews with field experts, and other sources. What matters most is that the data, which is often challenging to collect, is of high quality and reliability. Therefore, to develop an effective LCI, a thorough inquiry and a systematic approach to the process are essential. In LCI development studies, asking consistent and relevant questions to the representative of the related sector is a crucial aspect in obtaining accurate data. A review of the literature shows that there is no existing study on a question catalogue related to this topic. This article aims to fill that knowledge gap. Especially for researchers who are new to LCA studies, the question catalogue will serve as a guiding tool in creating the LCI inventory.

Materials

The first Life Cycle Assessment (LCA) study was conducted in the 1960s in packaging studies, primarily focused on energy use rather than emissions (Hauschild *et al.*, 2017). Since then, it has been introduced as a methodology (Br¨andstr¨om and Saidani, 2022; Pe˜na *et al.*, 2021), a method (Bastianoni *et al.*, 2023; Elia *et al.*, 2017; Schulte *et al.*, 2021; van Stijn *et al.*, 2021), or a tool (Corona *et al.*, 2019; Hauschild *et al.*, 2017; van der Giesen *et al.*, 2020). (Civancik-Uslu *et al.*, 2018) highlight that LCA is defined as a tool by the United Nations Environment Program (UNEP) and as a methodology by the ISO standard. Evaluation of the environmental impacts attributed to the production, use and disposing of a product is the prime motive of Life Cycle Analysis (LCA) (Bhosale *et al.*, 2023). LCA is a process for assessing and evaluating the environmental and occupational health and resource consequences of a product through all phases of its life, i.e., extracting and processing raw materials, production, transportation and distribution, use, remanufacturing, recycling, and final disposal (Paulraj *et al.*, 2022). This approach allows the comparison of the environmental impact on different areas, and the different impact categories are weighted and unified into a single value (Galve *et al.*, 2022). According to ISO, an LCA is divided into four interdependent phases: Goal and scope definition, Life Cycle Inventory, Life Cycle Impact Assessment and Interpretation (Figure 1) (Temporelli *et al.*, 2022). LCA is an extensively used tool for quantifying the environmental impacts and resource consumption associated with a product or production activity throughout its life cycle (Liu *et al.*, 2024). In the context of the mining industry, the life cycles of mining projects and the life cycles of minerals can be differentiated (Hodge, 2011). From one perspective, the life cycle of a mining project essentially consists of the following stages: exploration, design and construction, operation, closure, and postclosure (Hodge, 2011). In addition, the life cycle of minerals often includes the following phases: mining (underground, open pit, and in situ), mineral processing (comminution, flotation, filtration, physical separation, and dense media separation), and metal production (pyrometallurgy and hydrometallurgy) (Haque, 2024). The Life Cycle Inventory (LCI) phase is pivotal in an LCA study, as the reliability of the analysis depends heavily on the accuracy and quality of the LCI data. High-quality, precise data ensures that the results effectively represent the environmental impacts being assessed. LCI utilizes both primary and secondary data sources. Primary data, or foreground data, is directly collected from mining sites, beneficiation plants, and related operations. In contrast, secondary data, or background data, is derived from established databases like Ecoinvent (Burhan Memon *et al.*, 2025).

Figure 1 *Life cycle assessment method*

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Preparation of research questions within the scope of LCA

Life Cycle Assessment (LCA) is a scientific process that evaluates the environmental impacts of products in a comprehensive manner and is aligned with ISO 14040 and ISO 14044 standards. The accuracy of research questions in managing the process depends on clearly and systematically defining the goal and scope of the study. Methodological variables such as system boundaries, functional unit, and assumptions are key factors in the formation of these questions. Research questions should establish a strong connection between general environmental impacts and process stages. The research questions should be characterised in alignment with the four main components of LCA: goal and scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and interpretation. For example, in the LCI phase, a question like "What is the amount of energy consumed during the raw material procurement process of the product?" or in the LCIA phase, "What is the contribution of the production stage to Global Warming Potential (GWP)?" can assist in analysing functional environmental impact categories. Additionally, these questions should be connected to impact assessment methods (such as TRACI, ReCiPe, CML, etc.) to ensure consistent results. The preparation of questions is directly influenced by data sources (primary vs. secondary data). For example, a question such as "What percentage of total CO_2e emissions generated throughout the product's life cycle is attributed to the distribution phase?" requires comprehensive inventory data and aims to investigate the variation of these data based on regional conditions. The applicability of statistical methods such as uncertainty analysis and sensitivity analysis also depends on the structure of the questions. Questions should not be superficial only, but also interconnected across modelling processes. LCA research questions should support decision-making processes aimed at sustainability optimisation while also guiding environmental impact assessment. In this context, questions such as "How does the use of alternative raw materials affect the GWP?" or "How do consumer usage habits influence the life cycle impacts of the product?" should be developed to enable scenario building and comparative analyses. In this way, the outcomes of the process can shed light on academic data, policy development, eco-design, and the perspective of sustainable living.

Open-pit metallic mining: general system boundaries

Open-pit metallic mining involves a series of stages designed to ensure the safe and economical extraction of ore from the earth's crust (Figure 2). The process begins with geological surveys and drilling studies to determine the location, reserve size, and grade of the ore. Based on these data, mine planning and pit design are carried out. Subsequently, overburden removal (stripping) is performed as part of the preparation phase, in which the economically non-valuable layer covering the ore is removed. Once the ore is reached, the rock is fragmented through drilling and blasting methods. Following this operation, the ore is separated from the waste rock. During the loading and hauling stage, the ore is transported to the processing plant, while the waste material is hauled to designated dumping sites. At the plant, the ore undergoes crushing and screening to achieve suitable particle sizes, and is then subjected to grinding to liberate the minerals. In the next stage, beneficiation techniques are applied depending on the mineralogical characteristics of the ore. For instance, flotation is commonly used for sulfide ores, magnetic separation for magnetic minerals, gravity separation for minerals with density differences, and leaching methods (heap or pressure leaching) for low-grade ores. These processes result in the production of a concentrate. The concentrate is subsequently treated in the metal production stage through either pyrometallurgical methods (smelting and refining) or hydrometallurgical methods (precipitation, solvent extraction, electrowinning) to yield pure metal. Throu-

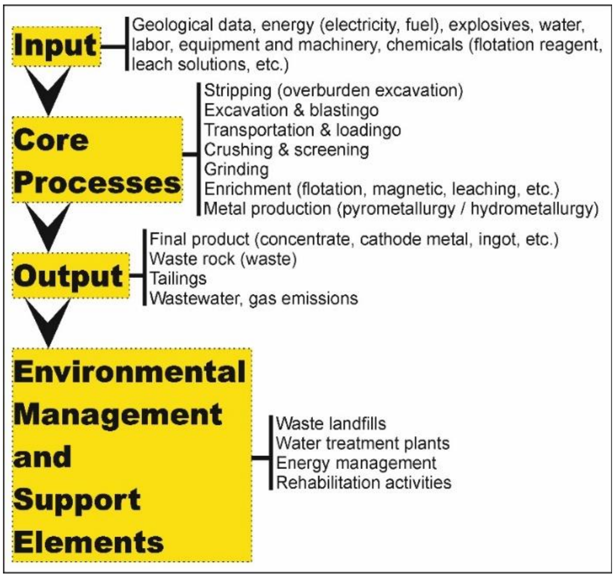

Figure 2 *General system boundaries of open-pit metallic mining*

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ghout the entire process, waste materials generated (waste rock, wastewater, and flotation or leaching residues) are managed using appropriate environmental control measures. Waste rock is deposited in dumping areas, tailings from beneficiation are stored in engineered tailings dams, and wastewater is directed to treatment facilities. In this way, both environmental sustainability is maintained and mining operations continue safely and responsibly (Figure 2).

General system boundaries of the production process

The production processes of a factory manufacturing metallic products vary depending on the type of product produced (e.g., automotive parts, kitchenware, construction elements), the type of metal used (steel, aluminium, copper, titanium, etc.), and the scale of production. However, in general, they include the following processes (Figure 3). Raw Material Input: At this stage, the factory procures the metals to be processed (e.g., steel sheets, aluminium ingots, metal rods). The incoming raw materials are inspected for compliance with technical specifications and are stored in the warehouse, ready for production. Pre-Processing: The raw material is brought to the required dimensions for production. Sheets are cut, rods are sliced, oils are removed, and sandblasting or pickling is applied if necessary. This step prepares the material for the subsequent processing stages. Forming: At this stage, the basic shape of the product is created. This is done using methods such as machining (CNC), forging, casting, or sheet metal forming (pressing, bending). The specific process applied is determined based on the function of the product. Heat Treatment (Optional): Some products undergo heat treatment to gain strength or durability. Processes such as annealing, hardening, and tempering are used to improve the metal's microstructure and mechanical properties. Surface Treatments: Surface treatments are applied to enhance both the aesthetic appearance and corrosion resistance of the product. At this stage, processes such as painting, electroplating (galvanising, chrome, etc.), polishing, or passivation are carried out. Assembly (If Applicable): For products consisting of multiple parts, assembly is carried out on the assembly line. In this step, techniques such as welding, screwing, and riveting are used to combine the components into a complete product. Quality Control: Dimensional and visual inspections of the produced parts are carried out. When necessary, non-destructive testing methods are used to detect internal structural defects. This step ensures compliance with customer quality standards. Packaging and Shipment: Products that pass quality approval are adequately packaged, labelled, and prepared for shipment. This stage is aimed at preventing damage to the products during transportation.

Figure 3. *General system boundaries of the production process*

Results

Questions for LCI

In this study, a seven-stage interrogation process was developed to derive questions, incorporating an initial "definition" phase into the six stages of a product's life cycle from cradle to grave: "Raw Material, Production, Distribution and Sales Point, Consumption, Recycling, Disposal." A total of 50 question derivatives were generated (Table 1). The questions primarily focus on concepts such as system boundaries, energy, transportation, emissions, and environmental burdens. In the definition phase, six question derivatives were developed, focusing primarily on the name of the industry, the description of the product, and the identification of the expert who will conduct the study. In the raw material phase, eleven question derivatives were developed, generally addressing the definition of the raw material, the auxiliary materials used, system boundaries, energy consumption, emissions, and waste quantities. In this phase, new question derivatives can particu-

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Table 1. *Question catalog for LCI*

Description
What is the name of the industry?
What type of industry is it?
What is the name and surname of the expert?
What is the role of the expert?
What is the name of the product and its standard production quantity?
What is the functional unit of the product?
Raw Materials
What is the name of the raw material?
Where is the source of the raw material?
What are the types and quantities of auxiliary raw materials?
What are the system boundaries of the raw material?
What are the equipment and tools used in raw material extraction?
What are the types and amounts of energy consumed in raw material extraction?
What is the amount of natural gas consumed during raw material extraction?
What is the amount of water consumed during raw material extraction?
What are the emissions, waste types and quantities generated during raw material extraction?
What is the distance of the raw material to the factory?
How are raw materials transported and what are the vehicle features?
Production
Where is the product produced?
What are the system limits of production?
What are the daily energy types and amounts consumed in production?
What is the amount of natural gas consumed in production?
What is the amount of water consumed in production?
What are the daily emissions and their amounts in production?
What are the daily waste types and amounts generated in production and how are they evaluated?
Point of sale and distribution
Where are the sales points where the product is distributed?
What are the vehicle features used in the distribution of the product?
What are the distribution conditions and distance?
What are the energy, fuel types and quantities consumed in distribution?
What are the emissions generated during distribution?
Consumption
Where are the product's consumption areas?
What are the distances to the product's consumption places?
What is the method of transporting the product to the consumption places?
What are the types and amounts of energy used in the consumption of the product?
What are the emissions, waste types and amounts generated during consumption of the product?
Recycle
Where is the recycling location?
What are the system limits of recycling?
What is the distance between the products and recycling areas?
What are the transportation methods and vehicle features of the products to recycling areas?
What are the types and amounts of energy consumed in recycling?
What is the amount of natural gas consumed in recycling?
What is the amount of water consumed in recycling?
What are the emissions, waste types and quantities generated in recycling?
Disposal
Where is the disposal location?
What are the system limits of disposal?
What is the distance between the products and disposal areas?
What are the transportation methods and vehicle features of the products to disposal areas?
What are the types and amounts of energy consumed in disposal?
What is the amount of natural gas consumed in disposal?
What is the amount of water consumed in disposal?
What are the emissions, waste types and quantities generated in disposal?

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larly be developed regarding the vehicles, equipment, and tools used in mining activities. Additionally, treatment processes aimed at reducing environmental burdens can lead to new questions. Furthermore, the transformation of mining sites into vital green areas after operations have ceased can characterise new types of question derivatives. As a result, the raw material phase is the most extensive and critical process in terms of question derivatives. In the production phase, seven question derivatives were developed. The questions were characterised by system boundaries, energy consumption, emissions released, and types of waste. In this phase, the characteristics of the equipment used within each system boundary will bring new question derivatives to the forefront. Treatment activities aimed at mitigating environmental burdens will also generate new questions. Industry 4.0 production methods and the influence of artificial intelligence on production in the future vision will lead to the development of highly variable question derivatives. The production phase is the section where second-degree question derivatives are found. In the distribution and sales point phase, five question derivatives were developed. In this process, the locations of sales points, the characteristics of the vehicles used for distribution, and the type of fuel used come to the forefront. In the consumption phase, five question derivatives were developed. In this section, the areas where the products are consumed were emphasized for question derivation. Additionally, in the future vision, users' consumption habits will effectively characterize new question derivatives. In the recycling phase, eight question derivatives were developed. In this section, the recyclability of the product, the energy used, and the location characteristics of the recycling process will contribute to the development of new question derivatives. In the disposal phase, eight question derivatives were developed. This phase can be considered as the reverse process of the raw material phase. While there is a product output at the raw material location, there is an environmental burden input at the disposal location. Therefore, many of the inquiries made in the raw material phase can also be applied to the disposal process. The most distinctive aspect of the disposal phase is the necessity of proper geological site selection and isolation. Otherwise, environmental health issues, groundwater leachate problems, and the measures to be taken may lead to the development of new and different question derivatives. The questions were developed based on the influence of the seven processes. One additional function of the total 50 questions is that they serve as a regulatory catalyst among "LCI, LCA, and LCIA" studies. In the future vision, the criteria that enable the development of different questions can be considered as: "economy, politics, global climate, urban planning, wars, migrations, sociological changes, artificial intelligence applications, renewable energy, consumer habits, new treatment technologies, and interdisciplinary studies".

Conclusions

LCA studies determine the quantitative definition of environmental burdens arising from the functional process stages of mining. Therefore, by identifying the criteria that lead to energy waste and harmful emissions, efficient strategic processes can be implemented. For example, waste management processes and the energy costs of a facility can be assessed using the LCA method. These evaluations enhance operational efficiency and form the foundation of green and sustainable development. LCA is an effective catalyst in reducing environmental impacts in mining activities. In studies based on LCA, the carbon footprint can be reduced, natural resources can be used more efficiently, and energy efficiency can be achieved, contributing to green and sustainable goals. The LCA method evaluates environmental impacts and also supports the development of environmentally friendly technologies. In this way, mining activities contribute positively to public health and ecological awareness. Industrial facilities are the sources of environmental burdens throughout the processes involved in producing a product, from raw material consumption to waste generation. Elements such as greenhouse gas emissions, fossil fuel use, and water and energy consumption increase the carbon footprint of factories. Therefore, to evaluate the environmental impacts of production processes from a holistic perspective, the development of sustainable production strategies is a necessity. LCA enables the identification of environmental "hotspots" within production processes, allowing the detection of areas with high carbon emissions, energy inefficiencies, or concentrated waste generation. In this way, facilities can reduce their environmental burdens while simultaneously increasing resource and energy efficiency, thereby achieving economic gains. LCA processes play a significant role in monitoring environmental performance within factory production systems. Manufacturers recognise that increasing economic gains will be shaped by improvements in environmental quality. This approach enhances corporate ecological awareness wi-

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thin society. The Life Cycle Inventory (LCI) analysis is a key factor in building the quantitative database of LCA and in verifying the accuracy of the flow process. LCI enables the detailed measurement and recording of all inputs (such as energy, raw materials, water) and outputs (such as emissions, waste, products) within the defined system boundaries (ISO 14044, 2006). Since LCI forms the foundation of the Life Cycle Impact Assessment (LCIA), it is regarded as the backbone of the LCA process. The central theme of LCI is to organize environmental "input-output" relationships through systematic data collection. This organization allows for the identification of where environmental burdens are concentrated and facilitates the development of solution proposals. For example, in the plastic production process, which consumers widely use, LCI studies can determine in which process energy consumption is most intense or which raw materials contribute most to the carbon footprint. Therefore, over time, LCI processes can guide the development of sustainability strategies and help minimize environmental burdens. In the development of LCA studies, LCI analysis functions like photosynthesis, enhancing the accuracy of LCA results. Moreover, the use of LCI databases (e.g., Ecoinvent, GaBi) provides realistic assessments across different products and sectors. At the same time, it serves as a bridge between industrial practices and environmental policies. Before conducting an LCA study, it is vital to define clear and goal-oriented research questions that align with the purpose of the study. These questions shape the study's boundaries, objectives, and methodological approach, ensuring consistency throughout the assessment process. An LCA study conducted without research questions would be of poor quality, have low accuracy, and be insufficient. Research questions play a crucial role in accurately defining system boundaries and the functional unit. For example, clear questions such as "At which stages is the carbon footprint of this product most concentrated?" or "How do the environmental impacts of alternative packaging methods differ?" help guide data collection strategies. This prevents waste of time and resources. Additionally, it allows for the clear identification of which environmental impact categories to focus on (e.g., greenhouse gas emissions, water consumption, acidification, etc.). Well-defined research questions of high quality help establish a consortium among decision-makers, enabling different stakeholders (academics, industry representatives, environmental engineers, and policymakers) to align around common goals. This creates coherence in the "input and output" relationships within LCA studies. As a result, the outcomes become clear and transparent, ensuring the proper functioning of external auditing mechanisms.

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