Process impact assessment towards enhancing sustainability in three-dimensional sand printing

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Abstract. Three-dimensional (3D) sand printing process using additive manufacturing offers design flexibility and faster production but generates significant waste. This study applies a process impact assessment or partial life cycle analysis (LCA), to evaluate its environmental impact, identifying inefficiencies and areas for improvement. The analysis focused on material usage, waste generation, and energy-related CO_2 emissions. For the defined functional unit of 15 furan-based silica sand cores (2.50 kg each), results showed 92.5% of coated sand remained unused after a build, and electricity use over a 6.83 h cycle resulted in 1.09 t CO_2 (Scope 2) emissions. The findings highlight opportunities for renewable energy adoption, material reclamation, and landfill reduction. Integrating circular economy principles could enhance sustainability in sand printing. This approach underscores the need to rethink waste management practices and optimize resource efficiency in additive manufacturing.

1 Introduction

Binder jetting is a versatile additive manufacturing (AM) process that enables the creation of complex parts with high design freedom. It works by selectively depositing a liquid binder onto a powder bed, layer by layer, without requiring heat for material fusion. This allows for a broad range of materials, including metals, ceramics, sand and polymers, making it particularly valuable in industries like aerospace, automotive, and healthcare, where customized and intricate components are essential [1, 3, 2].

A significant advantage of binder jetting compared to other additive manufacturing processes lies in its cost efficiency, as it generally offers faster processing times and lower costs compared to powder bed fusion techniques like selective laser sintering or direct metal laser sintering [1]. However, as with all manufacturing processes, this innovative technique generates a significant amount of waste [4]. The waste sand generated during the production

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of sand moulds exhibits characteristics similar to natural sand, making it as valuable as a typical foundry waste [4]. The latter creates then a potential for its reuse in sustainable and waste management initiatives.

Life cycle assessment (LCA) constitutes an ISO-standardized methodology employed to systematically quantify the environmental impacts associated with all stages of a product system, from raw material acquisition through production, use, and end-of-life treatment. While LCA does not inherently function as a prescriptive decision-making apparatus, it serves as a critical decision-support framework for environmental management, enabling evidence-based identification of inefficiencies and environmental trade-offs [5].

Within the domain of additive manufacturing (AM), the application of LCA has gained substantial momentum, as documented in the recent comprehensive review by Kokare et al. (2023). The authors synthesized findings from 77 LCA studies and highlighted the integration of LCA across a range of AM technologies, including powder bed fusion, directed energy deposition, material extrusion, and binder jetting. The study emphasizes that LCA facilitates the identification of environmental hotspots such as energy-intensive processing stages, high feedstock consumption, and the environmental burden associated with support material generation and post-processing operations. Furthermore, the LCA framework enables comparative analyses between AM and conventional subtractive manufacturing, illuminating the conditions under which AM may confer environmental advantages such as reduced material waste, design optimization, and distributed production potential [6].

In parallel, the systematic literature review conducted by Faheem et al. (2024) extends the discourse by examining the alignment of AM practices with the United Nations Sustainable Development Goals (SDGs). Their findings underscore the relevance of LCA as a strategic enabler for operationalizing sustainability principles within AM workflows. Specifically, LCA contributes to SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) by guiding the adoption of circular economy principles, evaluating the use of bio-based and recycled materials, and supporting energy efficiency initiatives. The study also highlights the current underutilization of LCA in integrating social and economic dimensions, suggesting a need for more holistic sustainability assessments [7].

With increasing global emphasis on sustainable manufacturing, industries must consider not only the economic but also the environmental and social impacts of their operations. The LCA framework offers a systematic approach to quantifying these impacts and identifying areas for improvement such as for renewable energy adoption, material reclamation, and landfill reduction. ISO 14040 and 14044 standards supports LCA methodologies by establishing a healthy and systematic framework for quantifying environmental impacts across the life cycle of a product. As outlined by Walter (2024), the standards define four essential phases; goal and scope definition, inventory analysis, impact assessment, and interpretation, each designed to ensure methodological accuracy, data coherence, and system boundary clarity. This structured approach enables identification of environmental hotspots and supports scientifically justified comparisons between products or processes [8].

Key principles embedded in these standards include transparency, consistency, completeness, and reproducibility, which together uphold the credibility of LCA studies across diverse sectors [8]. ISO 14040 introduces the foundational concepts and framework, while ISO 14044 provides operational criteria for conducting LCA, including allocation methods, data quality requirements, and provisions for critical review [8]. This dual-standard model has become integral to environmental decision-making, enabling researchers and practitioners to evaluate sustainability trade-offs in complex systems with precision and accountability [8]. In this study, the methodology adopted follows ISO 14040 standard, which ensures a comprehensive and reliable assessment of the 3D sand printing process.

The use LCA in managing waste sand from 3D printing processes, such as those using the Voxeljet VX1000 printer, provides significant benefits by offering a comprehensive evaluation of environmental impacts associated with sand waste. This study focuses on managing substantial volume of waste sand generated during printing of sand cores using Voxeljet VX1000 printer. While about 40% of the sand can be recycled, this percentage drops when strength of mould or core printed from recycled sand falls below required standards [9]. LCA helps identify and evaluate potential environmental impacts across all stages, from production of the raw material to its disposal, highlighting areas for improvement in waste management [10].

By applying LCA to waste sand management, it is possible to assess both the feasibility and effectiveness of recycling methods, ensuring that only the most environmentally efficient processes are adopted [11]. As noted in LCA: Best Practices of ISO 14040 Series (2004), LCA offers decision-makers valuable data that supports more sustainable practices and continuous improvement, stating that "LCA provides decision-makers with systematic and objective data that can guide sustainable practices and improvements in environmental performance" [9]. This is particularly relevant in the 3D printing industry, where optimizing sand reuse not only reduces waste but also enhances sustainability, ensuring the long-term viability of the process.

2 Methodology

This study applies a partial LCA (process impact assessment), aligned with ISO 14040 principles, to quantify material and energy use, waste generation, and related CO_2 emissions for a 3D sand printing process using the Voxeljet VX1000 system. The assessment does not include upstream raw material extraction or downstream end-of-life phases, and therefore is not a complete life cycle assessment. The Vaal University of Technology, Sebokeng Campus, which hosts a Voxeljet VX1000 3D sand printer, was selected as the focal point for this study.

The assessment was based on direct shadowing and observation of a specific Voxeljet VX1000 print job, allowing the collection of empirical, real-time operational data rather than relying solely on generic machine specifications or literature values. Figure 1 illustrates sequential phases involved in conducting a partial LCA as per ISO 14040 standards. The assessment is structured to examine the environmental performance of producing furan-based silica sand cores, with a focus on material flows and energy consumption.

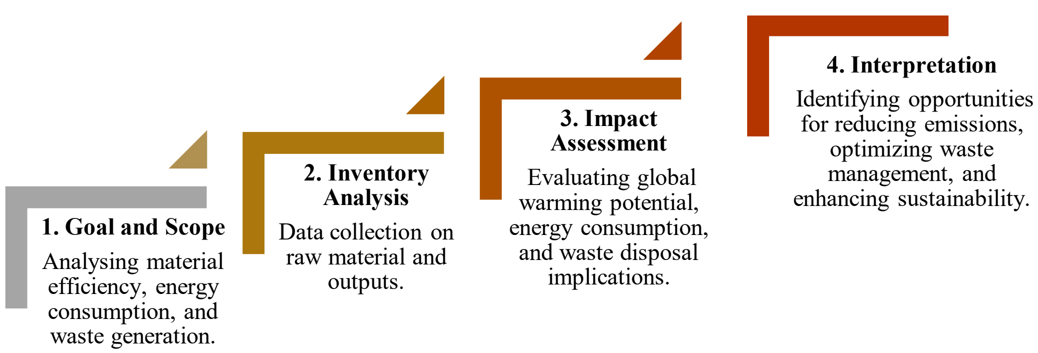

Fig. 1. Flowchart illustrating the process of conducting the partial Life Cycle Assessment (LCA) in accordance with ISO 14040 standard [4].

Goal and scope: The partial LCA was conducted in accordance with ISO 14040 standards, focusing on the 3D sand printing process utilizing the Voxeljet VX1000 system.

- **Functional unit:** 15 printed furan-based silica sand cores, each weighing approximately 2.5 kg, produced in a single build cycle of 6.83 hours.
- **System boundary:** Cradle-to-gate (excluding raw material extraction and downstream disposal/reuse).
- **Impact categories considered:** Material utilisation efficiency and Scope 2 CO_2 emissions from electricity consumption.

Inventory Analysis: The life cycle inventory (LCI) phase involved quantifying all material and energy inputs and outputs associated with the 3D sand printing process. To facilitate a comprehensive analysis, the data acquisition strategy was separated into primary and secondary sources, as outlined in table 1. This approach ensured the collection of both empirical process data and contextual background information necessary for a healthy Life Cycle Assessment (LCA).

Table 1. Data collection methods for LCA.

Category	Data Source	Purpose
Primary Data	On-site Measurements	Direct quantification of process performance
	Interviews	Gaining contextual insights from operators, and technicians
	Process Documentation	Understanding operational steps, parameters, and control mechanisms
Secondary Data	Supplier and Vendor Information	Understanding specifications, material properties, and sourcing details
	Material Sampling	Collection of waste sand generated, and printed sand parts.
	Database Searches	Accessing existing life cycle inventories, emission factors, or standardized datasets

Primary data collection involved on-site measurements and direct observations within the operational environment to quantify key parameters such as energy consumption, material throughput, and process efficiencies. Additionally, structured interviews with plant personnel were conducted to capture operational notes and maintenance protocols. Supplementary documentation such as process flow diagrams, operating manuals, and production logs were analysed to portray the sequence of unit operations. Secondary data encompassed peer-reviewed literature, technical reports, and supplier specifications related to sand, binders, and additive inputs, as well as utility records and transportation data. These sources provided critical insights into upstream and downstream impacts, enabling the estimation of environmental burdens across the system boundary.

Impact Analysis: Approximate residual coated sand versus printed sand was derived from analysing input-output data collected during life cycle inventory (LCI) phase of the study. This involved quantifying the total mass of coated sand loaded into the Voxeljet VX1000 printer for a complete print cycle and comparing it to the mass of the final printed sand cores. The difference was quantified and expressed as a percentage to determine the proportion of waste or spent sand generated during a print cycle.

In addition, the printing process duration (6.8 hours) was recorded, and the corresponding electricity consumption was estimated based on operational power requirements of the printer. Scope 2 CO_2 emissions were quantified using the emission factor of 0.931 tCO_2/MWh [11]. Hourly emissions were derived by multiplying the estimated energy demand (in MWh) by the emission factor and the carbon dioxide (CO_2) global warming potential of 21 [12]. Figure 2 below demonstrates formula extracted from the NCPC-RECP end-user manual.

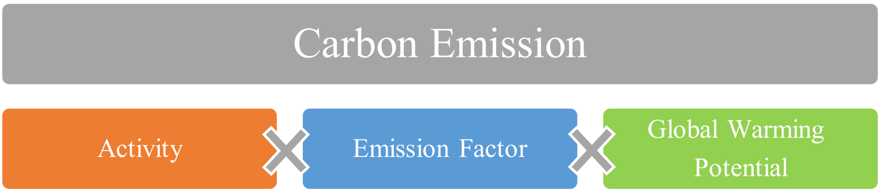

Fig. 2. Determination of carbon emissions [12].

Interpretation: The interpretation phase involved evaluating the significance of the inventory and impact assessment results in relation to the study objectives. Key performance indicators such as material utilization efficiency and CO_2 emissions were assessed. The findings were cross-referenced with circular economy principles to determine improvement opportunities. Conclusions and recommendations were drawn to guide decision-making for sustainable waste sand management.

By clearly defining the functional unit, system boundaries, and data collection methods, this section establishes a solid foundation for a thorough life cycle assessment of the 3D sand-printing process. The well-defined scope ensures alignment with ISO standards and promotes consistency across the inventory analysis, impact evaluation, and interpretation stages. This systematic approach is critical for pinpointing environmental impact areas, improving material and energy efficiency, and supporting the adoption of circular economy strategies within additive manufacturing operations.

3 Results

The assessment considered the following input and output parameters depicted in Figure 3 below. These parameters helped quantify resource consumption and waste generation, forming the basis for impact assessment. The key findings are illustrated in Table 3 below.

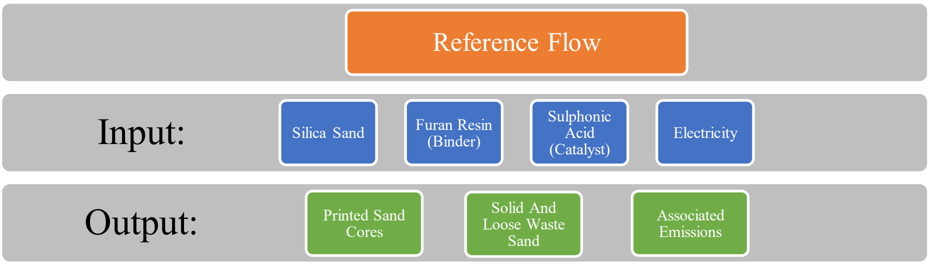

Fig. 3. Reference flow framework for the partial life cycle assessment (LCA) study.

Table 2. Compiled data on resource usage and emissions produced throughout the process.

Category	Item	Quantity	Unit
Inputs			
Raw Materials	Silica Sand	500.00	kg
	Furan Resin	10.00*	Kg
	Additives/Catalysts	1.50	kg
Energy	Electricity	8.20	kWh
Process			
Lean	Print job cycle time	6.83	Hr
Outputs			
Final Product	Average weight of printed cores	2.52	kg
	Number of printed cores	15	Per cycle
	Total silica sand utilized	37.80	kg
	Total resin utilized	0.76	kg
	Total catalyst utilized	0.11	Kg
Waste	Unused coated sand	462.50	kg
	Unused catalyst	1.39	kg
Electricity Consumption	VX1000 Printer	56.10	kW
CO2 Emissions	CO2 from Electricity	0.16	t CO2 per hr

* The printer automatically discharges the exact amount needed for the print job, storing any excess back in the machine compartment.

This inventory analysis highlighted significant inefficiencies, particularly in material usage and energy consumption, which require optimization. A comprehensive process flow chart has been created to support the LCI phase, as shown in Fig.4 below, the flow chart provides a visual representation of the entire sand printing process.

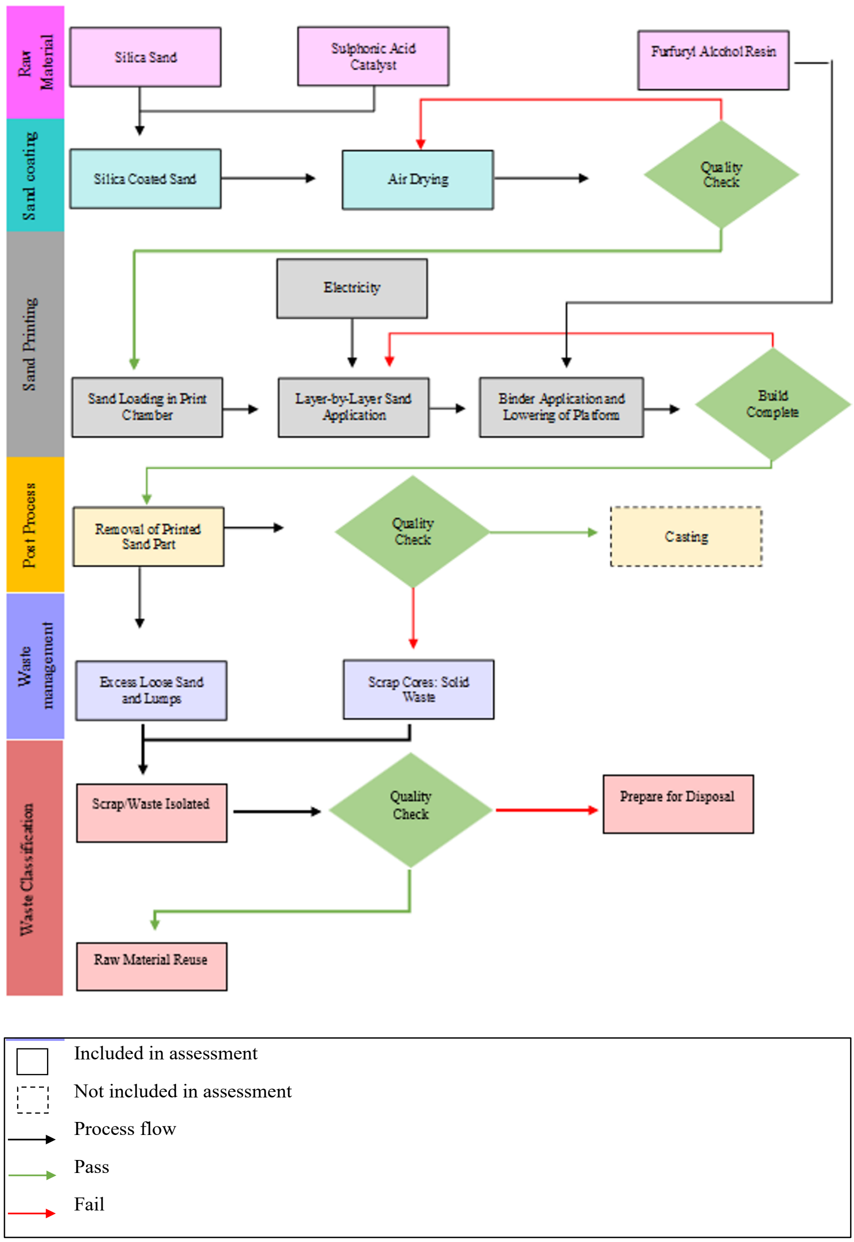

Fig. 4. System boundary of assessment for the 3D sand printing process.

Impact Assessment: From the collected life cycle inventory data, it was determined that approximately 92.50% of the coated sand remained unused after the studied print cycle. This high percentage of residual material highlights a significant inefficiency in the material utilization of the 3D sand printing process. The large volume of unused sand not only presents a substantial waste management challenge but also has implications for environmental impact, resource depletion, and overall process sustainability. Given an emission factor of 0.931 tCO_2/MWh and a CO_2 global warming potential of 21, the printing process in this study emitted 1.090 t CO_2 (Scope 2 emissions), highlighting the environmental impact of electricity usage.

While the generated waste sand may be reused in subsequent cycles, excessive reuse may compromise print quality and cause machine malfunctions. Eventually, the waste is landfilled, leading to soil and water contamination risks. Strategies such as enhanced recycling alternative, reuse applications (circular economy), or coating recovery technologies can improve sustainability. In addition, the integration of low-carbon energy sources such as solar, wind, and hydroelectric systems can markedly reduce Scope 2 emissions by displacing carbon-intensive electricity generation. Concurrently, implementing energy-efficient technologies and process optimization strategies enhances system performance, reducing overall energy demand and associated greenhouse gas emissions.

The outcomes of this ISO-aligned LCA study reveal notable inefficiencies in material utilization and energy consumption. These insights emphasize the need for systemic improvements, including circular material strategies, enhanced reuse pathways, and the integration of low-carbon energy sources. By addressing these areas, organizations can significantly improve the environmental performance of 3D sand printing processes while fostering innovation in sustainable manufacturing practices.

4 Conclusion

This study employed a partial LCA to evaluate the environmental impacts of the 3D sand printing process, concentrating on material waste and energy consumption. The assessment facilitated a detailed analysis of resource usage, revealing significant inefficiencies such as the substantial amount of unused coated sand (approximately 92.50% left after the studied print cycle) and notable CO_2 emissions (1.090 t CO_2) resulting from electricity consumption over 6.8 hours.

By pinpointing these inefficiencies, the study underscored the potential for implementing circular economy principles to alleviate these impacts. Strategies suggested included material reclamation, energy efficiency improvements, and the adoption of renewable energy sources. These measures aim to reduce the environmental footprint by decreasing material waste, lowering energy demand, and mitigating greenhouse gas emissions. Additionally, integrating low-carbon energy sources like solar, wind, and hydroelectric systems could significantly reduce Scope 2 emissions.

Ultimately, the study highlighted the crucial role of LCA in guiding sustainable manufacturing practices and aiding the transition to more resource-efficient, low-carbon production systems. While this study focused on a process impact assessment of the Voxeljet VX1000 3D sand printing process, future research will extend the scope to a complete life cycle assessment (LCA) in line with ISO 14040/14044 standards. This expanded approach will:

- Include upstream stages such as silica sand extraction and resin production.
- Assess downstream stages including core use, potential reuse/recycling routes, and end-of-life disposal impacts.
- Integrate additional impact categories, such as water consumption and particulate emissions indicators.
- Compare alternative scenarios (e.g., different geometries, packing densities, and binder systems) to identify design-stage strategies for reducing environmental impact.

By encompassing the entire life cycle, the next phase will provide a more comprehensive understanding of sustainability trade-offs and enable more robust recommendations for resource efficiency and waste management projects such as circular economy integration in 3D sand printing.

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Data availability: Data supporting the findings of this study can be made available by the corresponding authors upon reasonable request.

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