Integrating BPMN with LCA for Cradle-to-Gate Sustainability Assessment of Pharmaceutical 3D Printing

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Abstract: - Pharmaceutical additive manufacturing enables patient-specific solid dosage forms and supports distributed, on-demand production, yet its environmental performance remains insufficiently characterized. This research proposes a structured framework that couples Business Process Model and Notation (BPMN) with an ISO-aligned Life Cycle Assessment (LCA), mapping the cradle-to-gate operations of 3D-printed drug production and informing sustainability impact assessments. Drawing on the 3D-SustainDrugs project, the study models the end-to-end workflow for hot-melt extrusion (HME) filament preparation and Fused Deposition Modeling (FDM) printing, and uses the process map to define system boundaries, responsibilities, and data-collection points across material suppliers, primary manufacturing, secondary manufacturing, and distribution/healthcare services provision. The resulting life cycle inventory captures key inputs (e.g., materials, electricity, water), operational parameters (e.g., printing time, productivity, nozzle/bed temperature), and outputs (e.g., dosage forms, scrap/misprints, packaging mass), which are mapped to impact indicators, including Global Warming Potential and Cumulative Energy Demand, complemented by water footprint, resource depletion, human toxicity, and ecotoxicity. Even prior to full numerical reporting, the BPMN–LCA linkage enables systematic identification of environmental hotspots, indicating that energy-intensive thermal steps (HME/FDM), time-driven electricity use during printing, and material losses due to misprints or reprinting are likely the dominant contributors. Finally, the developed framework supports transparent "what-if" scenarios and sensitivity analyses (e.g., reject-rate reduction, productivity improvements, temperature and cycle-time adjustments, packaging and end-of-life alternatives), providing decision support to reduce sustainability impacts without compromising quality or operational performance.

Key-Words: - Additive Manufacturing, Pharmaceutical Production, Sustainable Manufacturing, Life Cycle Assessment (LCA), Process Modeling, Business Process Model and Notation (BPMN)

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1 Introduction

Three-dimensional (3D) printing, also known as additive manufacturing, is increasingly being adopted in pharmaceutical manufacturing to enable patient-specific solid dosage forms and flexible, small-batch manufacturing, enabling the production of personalized dosage forms and complex drug delivery systems with precise control over geometry and release profiles [1]. While conventional pharmaceutical manufacturing relies on large-scale

batch processes that consume significant energy, require substantial material use, and generate substantial waste, additive manufacturing offers opportunities for on-demand, decentralized production, with potential reductions in material waste and logistical impacts [1].

Despite its promise, published evidence on the cradle-to-gate environmental profile of pharmaceutical 3D printing is still limited, particularly at the unit-operation level. ISO 14040/44 Life Cycle Assessment (LCA) enables systematic, standardized, and consistent quantification of environmental burdens by structuring the goal/scope, inventory, and impact assessment stages. In additive manufacturing research, LCA has been used to assess the environmental footprint of 3D printing processes across various sectors, revealing environmental hotspots such as electricity-intensive thermal process steps, time-driven energy use, and yield-related material losses in the modelled system [2].

Specific to pharmaceutical 3D printing, initial studies indicate that energy consumption and carbon emissions for producing solid dosage forms can be comparable to those of traditional tableting under certain conditions, with printer settings and process parameters significantly influencing outcomes [3].

Understanding the environmental implications of pharmaceutical 3D printing is critical for aligning this innovative manufacturing route with sustainability goals. Frameworks that integrate detailed process mapping with LCA data support systematic identification of environmental "hotspots," enabling researchers and practitioners to target critical stages for improvement. Furthermore, hybrid approaches that combine experimental optimization with machine learning have been proposed to reduce energy consumption and emissions in pharmaceutical 3D printing, pointing toward digital strategies that enhance both efficiency and sustainability [4]. However, comprehensive assessments that link operational process models to environmental impacts across the entire life cycle remain scarce, particularly in personalized drug manufacturing.

At the supply chain level, pharmaceutical additive manufacturing shifts production from centralized batch plants toward distributed, on-demand (make-to-order) nodes, changing inventory positioning and distribution patterns and enabling postponement strategies. The latter supply chain strategies can redistribute environmental impacts among upstream and downstream stakeholders, making sustainability outcomes highly dependent on process design, routing decisions, and operational settings at each operational echelon. As a result, environmental assessment approaches that do not incorporate explicit process and supply chain details may overlook vital trade-offs among flexibility, quality assurance, and sustainability.

In this context, evaluating sustainability in pharmaceutical additive manufacturing involves more than examining machine or process efficiency. It depends on interactions among production technologies, quality-control systems, and supply chain configurations, such as decentralization levels, batch sizes, and postponement strategies. Choices intended to enhance responsiveness or personalization can also increase energy use, raise rejection rates, or increase reprocessing, resulting in complex sustainability trade-offs. Understanding these interactions requires analytical methods that explicitly link operational process logic with environmental impact assessments, rather than treating production steps as isolated elements.

Current LCA studies on pharmaceuticals and additive manufacturing primarily rely on static process descriptions or simplified assumptions about production flows and rejection rates. Although useful, these methods often fail to capture how decisions focused on quality, rework processes, and operational fluctuations influence environmental impacts across manufacturing processes and the supply chain. Therefore, there is a need for frameworks that integrate standardized process modeling with LCA, enabling clear attribution of environmental burdens to specific processes, operational choices, and supply chain stakeholders.

To tackle this methodological challenge, this study integrates BPMN-based process modelling with an LCA structure, ensuring that system boundaries and inventory variables follow the workflow's actual decision logic to evaluate the environmental performance of 3D-printed pharmaceutical production. By coupling Business Process Model and Notation (BPMN) with LCA data, this study aims to provide a holistic view of environmental impacts, identify key process inefficiencies, and support informed decisions toward more sustainable pharmaceutical manufacturing.

2 Methodological Approach

The 3D-SustainDrugs project [5] addresses the aforementioned challenges by exploring how 3D printing technologies can reshape pharmaceutical supply chains through a distributed, make-to-order production paradigm. The project targets medicines suitable for solid-dosage formulation via 3D printing, including the development of 3D-printed,

personalized drug-delivery systems for Non-Steroidal Anti-Inflammatory Drugs (NSAIDs).

By integrating additive manufacturing with digital process control, 3D-SustainDrugs demonstrates how late-customization strategies can postpone final product differentiation until the last possible operations echelon—closer to the point of care and real demand. This increases flexibility and agility, reduces inventory and waste, and enables faster, localized responses to public health needs while preserving regulatory compliance and quality assurance requirements. By bridging digital transformation and sustainable manufacturing, 3D-SustainDrugs advances an intelligent, resilient pharmaceutical supply chain model aligned with Industry 5.0 and smart specialization principles.

Operationally, the project formalizes the end-to-end workflow using BPMN [6], [7] to create a shared, standardized representation of the 3D printed dosage supply chain and to anchor environmental data collection at clearly defined measurement points. The BPMN model structures responsibilities across the raw-material supplier, primary manufacturing, and secondary manufacturing (where relevant, also storage/distribution), capturing flows of materials, information, and quality documentation (e.g., specifications and certificates). Gateways in the model explicitly represent quality-driven decisions that route products to either secondary finishing/packaging or rework/reprint, thereby linking conformance outcomes to additional energy, material, and waste use.

BPMN is used to make decision gateways and rework loops explicit, assign data ownership to each actor, and define the exact measurement points needed to populate the inventory. The methodology ensures that environmental inventory flows are consistently assigned to specific stakeholders, decision points, and quality control loops throughout the pharmaceutical supply chain. This is especially crucial in regulated, quality-focused production settings, where non-conforming outputs result in rework, reprinting, or disposal, each with different environmental impacts.

From a supply chain perspective, the BPMN model serves as a coordination layer that links physical flows, such as materials and energy, with informational and decision flows, including quality checks, approvals, and routing. This is especially important in pharmaceutical manufacturing, where compliance requirements create critical decision points that affect throughput, rework rates, and waste. Explicitly including these decision gates in the process model enables environmental impacts to be linked to governance and quality management decisions rather than seen solely as a result of technological performance.

Building on this process map, the environmental assessment follows an ISO-aligned LCA logic and compiles an inventory that combines primary measurements (e.g., laboratory monitoring of energy use, material consumption, rejects, and emissions during Hot-Melt Extrusion (HME) and Fused Deposition Modeling (FDM) of NSAIDs) with secondary sources (literature and sectoral inputs). The study also specifies a practical indicator set, including Global Warming Potential and Cumulative Energy Demand, complemented by water footprint, resource depletion, human toxicity, and ecotoxicity.

This BPMN-LCA linkage supports environmental hotspot identification and scenario testing at the unit-operation level and across the broader supply chain, enabling evidence-based decisions that reduce impacts without compromising product performance. Specifically, the framework evaluates improvement levers by tightening process and quality control decision rules, lowering energy intensity by adjusting operating conditions and cycle times, minimizing material losses, and optimizing packaging and end-of-life routes (e.g., recycling, incineration, or landfill, where applicable). In this way, the 3D-SustainDrugs project moves beyond one-off accounting toward a decision-support approach for sustainable redesign of distributed pharmaceutical manufacturing and supply chain configurations.

This methodological approach enables systematic scenario analyses. Adjustments to operating conditions, quality thresholds, or supply chain configurations can be made at specific points in the BPMN model and consistently reflected in the life cycle inventory and impact indicators. Consequently, the developed framework facilitates comparative assessments of different production and supply chain configurations under the same regulatory and quality constraints, extending parameter sensitivity analyses.

3 Results and Discussion

This research provides a structured BPMN-to-inventory mapping that assigns measurement points and data ownership across actors and exposes hotspot mechanisms, particularly those driven by quality-control routing and reprint loops, within a cradle-to-gate assessment boundary. The structured BPMN-LCA linkage provides valuable insight by pinpointing where and why environmental pressures accumulate across the workflow, and by making the unit-operation impacts of gateways, rework, and reprinting explicit. This research's contribution extends beyond impact quantification, clarifying and

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making sustainability-related decision points traceable throughout the production and supply chain workflow.

A key output of the 3D-SustainDrugs project is the BPMN-based representation of the supply chain and production workflow for FDM 3D-printed pharmaceutical dosage forms (Figure 1). The BPMN model structures the process into four main stakeholders, specifically: (i) raw-material supplier, (ii) primary producer, (iii) secondary producer, and (iv) healthcare services providers. Moreover, the model clarifies responsibilities and data exchanges across the supply chain. Importantly, the model explicitly embeds quality-driven decision gateways that determine whether a printed dosage form proceeds to downstream steps (e.g., finishing or packaging) or returns to rework/re-print, in the effort to make the environmental implications of rejects and re-printing traceable at the process level.

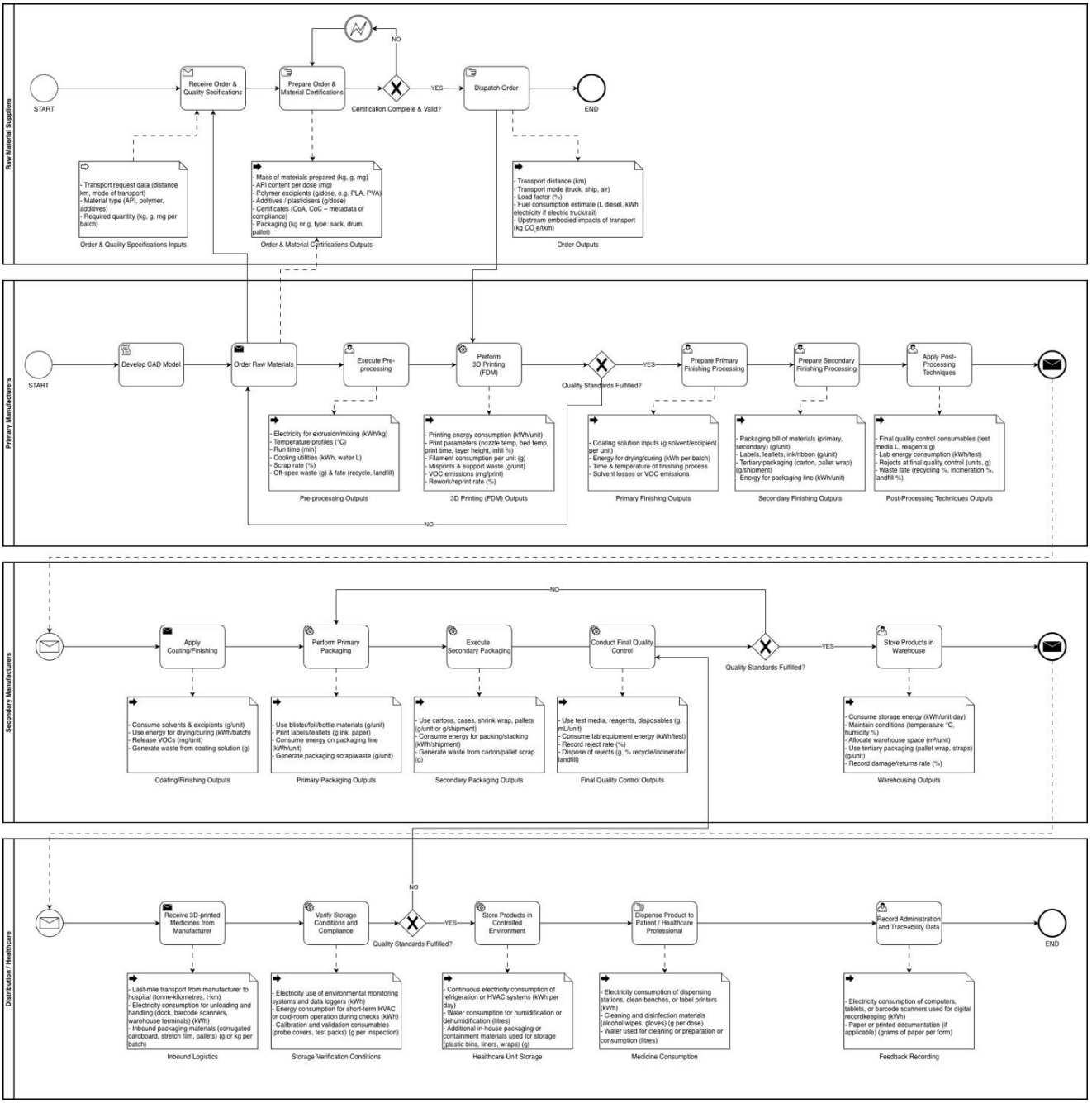

Fig. 1: BPMN model of the cradle-to-gate workflow for pharmaceutical additive manufacturing, covering material supply, primary manufacturing, quality-control gateways, rework loops, secondary packaging, and distribution.

3.1 BPMN structural analysis and interpretation for sustainability accounting

The end-to-end workflow and stakeholder interactions are summarized in Figure 1. The diagram does not solely provide a descriptive process map, but also a structured analytical object that makes sustainability-relevant decisions and feedback loops explicit. The BPMN representation organizes the end-to-end workflow into stakeholder "swimlanes" and separates physical transformation activities (e.g., HME and FDM), information exchanges (e.g., specifications, certificates, quality documentation), and decision gateways that control routing under regulatory constraints. This structure is particularly important in pharmaceutical additive manufacturing, as conformity assessment is not considered a peripheral activity. On the contrary, it determines whether production proceeds downstream or returns upstream via rework loops, which can substantially increase energy demand, material use, and waste.

In the sub-chapters that follow, a robust interpretation of BPMN highlights three features directly linked to environmental performance. Overall, BPMN provides a transparent basis for sustainability accounting by converting a complex, regulated workflow into a traceable network of activities, gateways, and measurement points that can be consistently mapped to the life cycle inventory.

3.1.1 Gateway-driven routing and rework amplification

Quality-control gateways introduce conditional execution paths. When a dosage form (or intermediate such as a filament batch) fails a specification, the BPMN routes the flow to rework, reprint, or disposal. From an environmental standpoint, these are not "exceptions"; they are structurally embedded in the logic. The environmental burden of the overall system, therefore, depends strongly on the reject/reprint rate and the point in the process where the non-conformance is detected. For instance, early detection reduces downstream packaging/handling burdens, while late detection increases cumulative burdens.

3.1.2 Multi-actor handoffs and data responsibility boundaries

The BPMN clarifies where responsibility for measurement and reporting sits. For example, suppliers typically own certificates, batch metadata, and upstream transport data. Primary manufacturing owns machine parameters, energy metering, yield/reprint logs, and in-process quality control. Secondary packaging owns packaging bills, labelling, and rejects, while healthcare and distributors own storage conditions, cold-chain energy, handling losses, and end-use traceability. This matters for a cradle-to-gate assessment in distributed production because the inventory cannot be assembled reliably without explicit ownership of data streams (e.g., material certificates, batch traceability, electricity metering, and waste records). In this context, BPMN functions as a governance layer that reduces the risk of "missing inventory items" and improves auditability.

3.1.3 Hotspot localization through unit-operation granularity

The BPMN decomposes the system into unit operations that are known, from both engineering reasoning and LCA experience, to be potential hotspots, such as energy-intensive thermal steps (HME heating and FDM printing), time-driven electricity consumption (print time per dose), and yield losses due to misprinting or reprinting. By making these steps explicit and linking them to decision gates, the BPMN supports a structured environmental hotspot hypothesis before full numerical reporting. If a process step has a high specific energy intensity and is located upstream of a rework loop, small improvements in yield and stability may translate into disproportionately large reductions in cumulative impacts.

3.2 Computational complexity of BPMN-based evaluation and scenario analysis

BPMN can be viewed as a structured process network whose size and logic influence how difficult it is to evaluate and compare scenarios. Two notions of complexity are relevant for BPMN-driven sustainability assessment.

First, there is structural processing complexity. More specifically, converting the BPMN to an LCA-ready representation requires extracting all activities, identifying stakeholders, and attaching inventory fields to each task, including inputs, outputs, energy, emissions, waste, and data sources. This effort proportionately increases with the number of tasks and flows in the diagram, since each element is processed once to build the inventory template.

Second, there is routing complexity driven by gateways and feedback loops. When the BPMN contains multiple conditional branches, the number of possible execution routes can grow rapidly if one tries to list every route explicitly. This becomes more evident when quality-control gateways trigger rework or re-print loops, as repeated cycles multiply

the number of potential process traces and amplify resource use.

For environmental evaluation, a robust approach is therefore to avoid enumerating every possible route and instead work with expected routing behavior. In practice, this means representing gateway outcomes using acceptance and rejection rates, while treating rework and re-printing as expected multipliers on upstream activities. The latter preserves the process logic while keeping evaluation tractable and directly linking uncertainty in quality outcomes to changes in cumulative impacts.

Finally, scenario and sensitivity analysis add a further layer of computational effort, as the BPMN-based evaluation is repeated under alternative assumptions (e.g., reject rates, production rates, printer settings, energy mixes, packaging intensity, or storage conditions). The overall effort is therefore driven less by the diagram alone and mostly by how many scenarios are explored or whether uncertainty is assessed through repeated simulation runs.

3.3 Detailed FDM printing in primary manufacturing and measurement variables for the LCI

Figure 1 positions FDM printing as a core transformation step in primary manufacturing and a likely environmental hotspot. This is attributed to the fact that FDM printing is time- and temperature-driven, electricity-intensive, and sensitive to quality deviations that trigger re-printing. To strengthen the analysis, FDM should be described as a sequence of operational sub-steps, with clearly defined parameters that can be measured and mapped consistently into the life cycle inventory.

A robust process description distinguishes six FDM operational sub-steps, namely: (i) slicing and job preparation, (ii) printer warm-up and stabilization, (iii) active printing and extrusion deposition, (iv) cooling and part removal, (v) in-process and post-process inspection, and (vi) disposition decisions (accept, reprint, or discard). In regulated settings, inspection is inseparable from documentation. Batch identifiers, parameter logs, and test results need to be recorded and linked to the quality pathway defined by the BPMN gateways.

For sustainability accounting, FDM should be parameterized using variables that explain both direct consumption and quality-driven amplification effects. Those may refer to time and throughput (e.g., print duration per unit, warm-up duration, handling/cooling time, items per job, accepted units per hour), machine power by operating state (e.g., electricity demand during warm-up, steady printing, idle/standby, and between-job transitions), process settings (e.g., nozzle and bed temperatures, print speed, layer height, infill strategy, and any constraints required for dose uniformity and mechanical integrity), material flows (e.g., filament consumed per accepted unit, start-up waste, scrap due to misprints), quality performance (e.g., misprint/reject rate, typical failure modes, triggers for reprint decisions), and waste and emissions (e.g., waste classification, routing for rejected prints and contaminated polymers).

The BPMN is valuable as it shows exactly where printing outcomes are evaluated and what happens when they fail. Reprint loops mean that quality performance is not only a compliance issue, but also a sustainability driver. Higher reject rates multiply upstream printing energy and material use and may also increase downstream packaging and handling burdens when failures are detected late. By documenting which parameters are recorded at each step and how those relate to acceptance decisions, the study can transparently connect printing conditions, process stability, and cumulative environmental impacts.

This structure supports targeted “what-if” experiments. Indicatively, alternatives such as improving yield through tighter parameter control, reducing warm-up and idle losses through scheduling and batching, increasing throughput without compromising quality, and shifting detection earlier to prevent avoidable downstream burdens, may be assessed.

3.4 From BPMN workflow to LCA-ready inventory structure

In this light, the BPMN model is used not only to define inventory variables, but also to quantify how gateway-driven routing and reprint loops scale the expected environmental burdens of primary manufacturing. On that basis, building on the BPMN workflow, the work realized formalizes the LCA data structure by defining the critical inventory variables required to quantify impacts for pharmaceutical FDM. These variables cover several inputs (e.g., materials, electricity, water), operational conditions (e.g., printing duration, productivity, nozzle and bed temperatures), and outputs (CO_2-eq emissions, VOC emissions, scrap/misprints, packaging mass, liquid waste from tests). Those are mapped to a consistent set of impact categories: Global Warming Potential, Cumulative Energy Demand, water footprint, resource depletion, human toxicity, and ecotoxicity. This framework is essential to ensure that each unit operation (HME filament preparation, FDM printing, quality control, packaging) can be linked to

measurable flows and compared across different scenarios.

Even before full-scale numerical reporting, the BPMN-LCA structure already indicates the most likely environmental "pressure points" in pharmaceutical 3D printing, namely: (i) energy-intensive thermal steps (HME and FDM), (ii) time-driven electricity consumption during printing (minutes per dose, items per hour), and (iii) material losses via scrap, filament residues, misprints, and reprints, which amplify both energy and waste footprints. These hotspots are consistent with findings from recent pharmaceutical 3D printing sustainability research, showing that process settings, print time, and failed prints can dominate energy and carbon intensity [3], [4], and that planning centralized versus decentralized production benefits from an LCA-based decision framework [8].

The work's contribution is also practical, since it defines the parameter set needed for "what-if" scenarios and sensitivity analysis to support eco-design and operational improvement. Typical scenarios enabled by the framework indicatively include reducing misprints/reprints through tighter quality control gating, evaluating the effect of printing duration and productivity on environmental indicators (e.g., Global Warming Potential), testing alternative operating temperatures and cycle times as proxies for energy intensity, comparing packaging intensities and downstream handling options, as well as checking sensitivity to assumptions such as recyclability and end-of-life handling for solid wastes. Since the BPMN model specifies where each measurement belongs, scenario changes can be propagated transparently through the LCA and then to impact indicators.

3.5 Simulation and initial scenario results

Although full primary measurements are not yet reported in this work, the BPMN–LCA linkage is used to run transparent "what-if" simulations. This section presents an illustrative scenario exploration that demonstrates the magnitude of variability in printing energy for pharmaceutical 3D printing and the amplification effect created by reprint loops, which are explicitly represented in the BPMN model.

Pharmaceutical 3D-printing evidence shows that electricity demand can vary substantially across printer technologies and operating conditions. For example, the measured energy required to fabricate 10 printlets ranges from 0.06 to 3.08 kWh, with higher-temperature systems generally consuming more electricity and non-negligible standby consumption also reported [3]. This wide range motivates scenario testing rather than relying on a single deterministic value at early stages of model development.

Moreover, the BPMN gateway that routes non-conforming outputs to reprint/rework creates a direct scaling effect. As the probability of print failure (or quality rejection) increases, the expected number of print attempts per accepted unit also increases, thereby amplifying upstream electricity and material use. Desktop FDM failure rates can be high in open operational settings, highlighting the importance of controlled operation, monitoring, and quality management for both compliance and sustainability performance [9]. In a regulated pharmaceutical context, the failure rate is expected to be lower. Nevertheless, the BPMN representation enables systematic stress-testing of both conservative and adverse cases to quantify the potential penalty of reprinting.

Table 1 summarizes the scenario set and the corresponding normalized electricity multipliers for the printing step induced solely by re-printing. Multiplier expresses the increase in printing electricity demand per accepted output due to reprints only (i.e., reflecting repeated print attempts). The results indicate that even modest increases in rejection can meaningfully increase electricity demand, while higher rejection rates can rapidly become dominant drivers of cradle-to-gate impacts due to repeated thermal cycles. Importantly, these scenario outcomes can be implemented consistently in the LCI since the BPMN model specifies exactly where acceptance is determined and where reprint loops are executed.

3.6 Future challenges

While the present study focuses on BPMN-driven workflow structuring and the corresponding life cycle inventory requirements, it does not yet report inferential statistics because a sufficiently large set of repeated observations across comparable conditions is not currently available within the scope of this work. As future work, a structured data-collection campaign aligned with the BPMN measurement points is scheduled. This will enable formal statistical validation of differences across settings and sites using hypothesis testing, including statistical tests for comparisons of mean energy use, print time, or material consumption, and categorical outcomes such as accept/reject frequencies and reprint incidence. Such statistical testing will complement the scenario and sensitivity analyses by quantifying the significance and robustness of observed differences and by supporting evidence-based prioritization of process improvements.

Moreover, as a next step, simulation and initial scenarios will be populated with primary measurements at the BPMN measurement points, enabling statistical comparisons across conditions. Indicatively, mean electricity per unit across printer settings and accept/reject frequencies across regimes will be assessed, followed by formal uncertainty analysis.

Table 1: Illustrative scenario set derived from BPMN gateways and literature-reported ranges to demonstrate printing-stage sensitivity (energy variability and reprint-loop amplification) within the BPMN–LCI mapping.

Scenario	BPMN element stressed	Parameter setting	Literature basis	Normalized multiplier on printing electricity due to reprints	Expected implication for cradle-to-gate impacts
S0	Printing energy baseline variability	Electricity per 10 printlets spans 0.06-3.08 kWh	[3]	-	Confirms high sensitivity to printer choice and operating conditions; motivates scenario modelling rather than single-point assumptions
S1	QC gateway → reprint loop	Low rejection (5%)	Scenario stress-test; reprint mechanism represented in BPMN	1.05	Small but non-trivial amplification of electricity and material use
S2	QC gateway → reprint loop	Moderate rejection (10%)	Scenario stress-test	1.11	Reprinting begins to materially increase energy/time-driven burdens
S3	QC gateway → reprint loop	High rejection (25%)	Scenario stress-test	1.33	Reprinting becomes a dominant driver; upstream thermal steps amplified
S4	QC gateway → reprint loop	Adverse rejection (41.1%)	Observed desktop FDM failure rate in open settings	1.70	Substantial amplification; emphasizes value of monitoring, operator practices, and robust quality control
S5	Printer operating states (idle/printing transitions)	Reduce idle losses via higher batching and reduced “non-productive” time	Empirical evidence that 3D-printer power differs by operating state [10]	-	Reduces energy per accepted unit by lowering non-productive electricity share; complements reject-rate reduction
S6	Location / electricity mix	Evaluate printing under lower vs higher carbon-intensity grids	Electricity GHG intensity varies by country and over time [11]	-	Same kWh can lead to materially different GWP; supports location-sensitive supply-chain scenarios

4 Conclusions

This study presents a structured BPMN-LCA framework for assessing the environmental performance of pharmaceutical solid-dosage production via HME filament preparation and FDM printing. The BPMN process map organizes the end-to-end workflow into clear roles (supplier, primary producer, secondary producer, distribution/ healthcare services providers) and makes quality-driven routing explicit through decision gateways, distinguishing compliant batches from those requiring rework or re-print. This structured representation improves transparency and, most importantly, defines consistent measurement points for LCA inventory compilation (inputs/outputs, emissions, and wastes), supporting robust hotspot identification across the supply chain.

Beyond documentation, the approach establishes a practical basis for continuous improvement by linking unit operations to an explicit set of environmental variables and impact categories, enabling systematic scenario comparison. The work further highlights that the BPMN representation can serve as the backbone for a future digital twin, allowing optimization experiments across printing

parameters, alternative materials, and waste-management scenarios, while preserving traceability and quality constraints.

Future work will focus on populating the framework with high-resolution operational data, including real-time electricity demand metering, time-at-temperature profiles for HME/FDM, and continuous VOC emissions monitoring, so that variability across batches, machine states (start-up/standby), and quality-driven rework loops can be quantified and incorporated into the life cycle inventory with reduced uncertainty. Such data would also enable the BPMN model to evolve toward a digital twin backbone, supporting near-real-time key performance indicators (KPIs) and their respective dashboards, as well as systematic optimization of process settings under explicit quality constraints.

Overall, the proposed BPMN-LCA framework offers a replicable, decision-oriented basis for designing and scaling environmentally improved, quality-assured 3D printed pharmaceutical manufacturing within distributed supply chain settings. By combining process transparency with unit-operation level environmental accounting, the framework identifies hotspots and supports evidence-based prioritization of improvement actions and more credible sustainability reporting as pharmaceutical additive manufacturing moves toward broader adoption. In this way, it provides a practical bridge between operational process design, regulatory-quality requirements, and measurable sustainability outcomes for next-generation, patient-centric drug production.

For policymakers, the framework provides a clear foundation for assessing when decentralized pharmaceutical manufacturing truly promotes sustainability and when it might merely shift environmental impacts upstream or into rework cycles. This supports more trustworthy sustainability reporting and informed decisions to shape the policy landscape and foster the adoption of new manufacturing technologies.

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Contribution of individual authors to the creation of a scientific article (ghostwriting policy)

Naoum Tsolakis, Charisios Achillas, and Dimitrios Aidonis conducted the analysis of the transformation of the pharmaceutical supply chain driven by 3D printing production.

Naoum Tsolakis and Dimitrios Aristotelis Koumpakis conducted the LCA.

Charisios Achillas and Christos Vlachokostas critically discussed the findings from the LCA study.

Naoum Tsolakis and Alexandra Michailidou prepared the draft paper and incorporated all comments from authors.

Charisios Achillas and Naoum Tsolakis revised the paper in response to the comments from the anonymous Reviewers.

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