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Feasibility Evaluation of the ECO-C3DP Machine Production Business for Plastic Waste Recycling under Stochastic Market Conditions

Heppy Riani Indrajati [1*], Alva Edy Tontowi [1], Novi Anny Indrawati [2]
[1] Universitas Gadjah Mada Yogyakarta
Bulaksumur, Caturtunggal, Kec. Depok, Kabupaten Sleman, Daerah Istimewa Yogyakarta 55281, Indonesia
[2] Universitas Teknologi Sumbawa
Jl. Raya Olat Maras Batu Alang, Pernek, Kec. Moyo Hulu, Kabupaten Sumbawa, Nusa Tenggara Bar. 84371, Indonesia

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ABSTRACT

This study evaluates the commercial feasibility of an integrated shredder and 3D printer (ECO-C3DP) machine for the MSME segment through the integration of eco-modular architecture and Techno-Economic Analysis (TEA) based on stochastic Monte Carlo simulation. The technical evaluation results indicate that the machine architecture is divided into four functional modules with a Modularity for End-of-Life (MEOL) score of 0.6269, placing the product in the ideal Region A quadrant characterized by ease of disassembly and maintenance efficiency. Deterministically, an initial investment of IDR 800,759,131 with a recommended selling price of IDR 65,818,471/unit is proven to be highly feasible, generating an NPV of IDR 908,669,032, an IRR of 45.76%, a PBP of 2.61 years, and a BCR of 1.40. Under stochastic market conditions across 1,000 iterations, the capital return certainty (NPV≥0) reaches 76.9% under the triangular distribution and 66.6% under the uniform distribution, with a minimum sales tipping point of ≥13"-" 14" units/year" . Based on Government Regulation (PP) No. 7 of 2021, this business unit operates in the Micro Enterprise category with a 27.2%–32.2% transition probability of upgrading to a Small Enterprise. The commercialization strategy is directed through a Business-to-Government-to-Community (B2G2C) partnership using an Estate Model scheme based on the LKPP E-Catalog listing and TKDN certification.

Corresponding Author:

Heppy Riani Indrajati
Universitas Gadjah Mada Yogyakarta
Email: heppyrianiindrajati@mail.ugm.ac.id

INTRODUCTION

The issue of plastic waste has become one of the environmental problems receiving increasing global attention. Plastics are widely used across various industrial and household sectors because they are lightweight, durable, and relatively inexpensive. However, their resistance to natural decomposition has led to the continuous accumulation of plastic waste over time. Global plastic production is reported to have reached approximately 430 million metric tons per year and continues to increase in line with the growing consumption of plastics across various industrial sectors (United Nations Environment Programme, 2023). In Indonesia, plastic waste is one of the main components of national waste generation with an estimated amount of around

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7.8 million tons per year (World Bank, 2021). This condition shows that plastic waste management is not only an environmental challenge, but also encourages the need to develop technology that is able to increase the added value of waste so as to support the sustainability of resource utilization.

One of the most widely applied approaches in plastic waste management is mechanical recycling technology (Jeswani et al., 2021). Compared to chemical recycling and energy recovery, this approach is simpler and has been widely applied to various scales of plastic waste treatment (Harasymchuk et al., 2024). In this process, plastic waste is processed through the stages of chopping, melting, and forming pellets before being reused as raw materials in the manufacturing process, such as injection molding, filament extrusion, and extrusion-based additive manufacturing. Although mechanical recycling has been widely implemented, the system still faces a number of limitations in practice. The processing process flow which consists of several separate stages causes the system to be relatively long and requires different types of machines with different functions. In addition, plastic materials undergo repeated processing cycles from solid to liquid and back to solid, which has the potential to increase energy consumption as well as decrease process efficiency (Vanaraj et al., 2025). The flow of the mechanical recycling processing stages is shown in sequence in the flow diagram of figure 1 and figure 2.

Figure 1. Stages of the Mechanical Recycling Process Based on Pelletization and Injection Molding

Figure 2. Mechanical Recycling Process Stages for Extrusion-Based Additive Manufacturing Applications

This condition also has an impact on the increasing need for technology investment and the complexity of the production system. As a result, some business actors are only able to produce products in the form of shredded or plastic pellets with relatively low added value (Ogwu & Kosoe, 2025). This condition shows the need for technological innovation that is able to simplify the recycling process chain while increasing the added value of the products produced. One of the approaches that has begun to be developed is distributed direct recycling so that the plastic waste processing process and manufacturing process can be carried out in one more integrated flow. This approach is expected to reduce process complexity while increasing the efficiency and economic value of recycled products.

Along with the development of manufacturing technology, the application of additive manufacturing in the treatment of plastic waste offers an alternative to increase the added value of recycled products (Habiba et al., 2024). This technology allows products to be created directly from digital models through a layer-by-layer printing process, making it more flexible than conventional methods that require special molds (Ngo et al., 2018; Santoso et al., 2025; Hassan et al., 2024). This flexibility opens up opportunities for the use of plastic waste as raw materials to produce products with higher economic value (Mikula et al., 2021). This development then led to the birth of the C3DP machine concept, which is the integration of the plastic waste shredding process with 3D printing technology in one system. Through this integration, the production stages become simpler, the processing process is more efficient, and plastic waste can be processed directly into the final product without going through many stages like in conventional mechanical recycling systems . The integrated processing flow of the ECO-C3DP machine concept can be seen in figure 3.

Figure 3. Mechanical Recycling Process Stages of ECO-C3DP Machine

Various previous studies have proven the potential of using plastic waste in additive manufacturing systems. However, most of the research still focuses on technical aspects, such as the characteristics of recycled materials, the mechanical properties of the product, and the optimization of the parameters of the printing process (Dong et al., 2025; Jayawardane et al., 2023). Other research on Direct Recycle 3D Printing, FPF and FPG also emphasizes the development of a system that allows recycled plastics to be used directly in the printing process without going through the stages of making pellets or filaments (Little et al., 2020). However, these studies have not studied the feasibility of implementing a system that integrates the process of enumerating plastic waste with the 3D printing process from an economic and investment perspective, especially at the MSME scale. In reality, information about financial feasibility and investment risks is an important aspect to assess the potential implementation of the technology in the industry. Therefore, this study focuses on evaluating the feasibility of the ECO-C3DP machine production business through a techno-economic approach by considering the uncertainty of market conditions using Monte Carlo simulation.

Although the ECO-C3DP machine offers a more integrated approach to the plastic recycling process, the success of a technological innovation is not only determined by its technical advantages. Various technologies have shown good performance at the laboratory stage, but many of them have not been successfully implemented and commercialized widely so that they have not had a real impact on reducing plastic waste (Mahmoud, 2026). This phenomenon is known as the Valley of Death, which is a condition when a technology fails to make the transition from the laboratory prototype stage to commercial market adoption (P. Jiang & Zhang, 2025). One of the main causes of this condition is the lack of a comprehensive evaluation of the feasibility of technology implementation before entering the commercialization stage. As a result, even though a technology offers technical advantages, its adoption rate by business actors remains low due to uncertainty about economic aspects and investment risks. Therefore, the ECO-C3DP machine needs to be evaluated both from the technical aspect of eco-modular design and the economic feasibility and risk aspects of its implementation in order to have a greater opportunity to be adopted and commercialized. The Valley of Death curve on this engine project can be seen in figure 4 below:

Figure 4. Valley of Death Curve on the ECO-C3DP Engine Design Project

The application of circular economy principles in the ECO-C3DP machine is not only reviewed from the machine's ability to process plastic waste, but also from the design architecture of the machine itself. The machine design that is environmentally friendly (eco-modular architecture) and supports ease of disassembly allows certain components to be dismantled, repaired, replaced, reused or developed without having to replace the entire product. These characteristics are the basis for evaluating the eco-circular aspects of the ECO-C3DP machine through an eco-modular architecture approach (Omair et al., 2025). This approach prevents recycling machines from becoming the generation of new metal waste in the future. In contrast to the linear economy that follows a take-make-dispose pattern, the circular economy emphasizes the return of waste into the production cycle so that materials that were previously considered residues can be reused as secondary raw materials (Selvam et al., 2024). This system forms a closed-loop supply chain, where the flow of materials not only moves from producers to consumers but also returns to the production process through reverse flow (Rumasukun, 2026). Thus, the circular economy not only plays a role as a sustainability concept, but also as an operational framework that bridges the gap between the development of technology and its implementation in real production systems. In this context, the ECO-C3DP machine has the potential to support the implementation of circular economy principles through an eco-modular architecture and mechanical process that can reprocess plastic waste into products with selling value.

The implementation of the implementation of the circular economy is not only carried out in large-scale industries, but can also take place through a distributed approach based on local communities, where the process of collecting, processing, and utilizing waste is carried out closer to the material source (Kassab et al., 2023). This approach is known in the literature as distributed recycling or distributed circular manufacturing, which utilizes small-scale production technologies such as 3D printing to process materials directly near the source (Caceres-mendoza et al., 2023). The decentralized production system opens up opportunities for micro, small, and medium enterprises (MSMEs) to play a role in plastic waste recycling activities (Sharma et al., 2025). MSMEs tend to have flexibility in resource management and adaptability to operational changes, which

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can support the transformation process (Kahveci, 2025), also have geographical proximity to the local environment which has the potential to support more efficient use of resources (Gennari, 2022). In addition, MSMEs face limited resources and capital, a simpler operational structure allows for more affordable technology investment needs compared to large-scale industries (H. Jiang et al., 2023). These characteristics support the involvement of MSMEs in a locally-based production system that supports efficiency in resource utilization and has the potential to reduce distribution costs. With these characteristics, MSMEs are relevant users in the application of the ECO-C3DP machine-based distributed recycling system in a local-scale plastic recycling system.

Although the ECO-C3DP machine has the potential to be applied to MSME-scale plastic recycling businesses, its implementation does not only depend on the user's operational capabilities, but also on the availability and access to the machine. Limited capital and technical capabilities are often an obstacle for MSMEs in adopting new technologies (Okunola, 2026). This condition shows that the use of machines at the user level is conditional, that is, it can only occur if the machine is available and accessible. Without such availability, analysis at the user level risks producing conclusions that cannot be realized. Investment costs and limited access to financing are major obstacles in the adoption of technology by MSMEs (Ramos-Vecino et al., 2026). Therefore, it is necessary to have a machine provider that acts as the main enabler that ensures the availability of affordable and reliable technology. This condition shows that business opportunities do not only lie in recycling activities, but also in the provision of ECO-C3DP machines.

The success of technology implementation is influenced by two main aspects, namely the technical aspect and the economic aspect (Rachman & Nur, 2025). However, the two aspects are not always in line, so technology that can technically function is not necessarily economically feasible (Nazir et al., 2026). The ECO-C3DP machine is one of the alternatives that has the potential to support the application of circular economy principles. Therefore, a feasibility evaluation is required before it is adopted by the industry to assess investments in real operations. This evaluation is carried out through two dimensions, namely the technical aspect of eco-modular architecture and the economic aspect. The eco-modular architecture dimension is used to evaluate the design characteristics of the ECO-C3DP machine product by analyzing the relationship between components, the level of modularity and the ease of disassembly and management of components. Meanwhile, the economic dimension is used to evaluate the feasibility of commercialization of machines through Techno-Economic Analysis (Danial et al., 2021). The technical aspects in TEA are based on the design specifications, design capacity, material requirements and technical parameters of the available prototypes while the economic aspects are carried out using the indicators of Net Present Value, Internal Rate of Return, Return on Investment, Benefit-Cost Ratio, and Payback Period (Ferdiawan et al., 2025). Analysis can still be carried out at the stage before commercial operation because the technical aspects used come from the design and data of the machine's development. Without a feasibility evaluation, businesses risk not breaking even or even incurring losses. Thus, financial feasibility analysis is important in evaluating the production business of ECO-C3DP machines on the MSME scale.

However, the MSME-based business environment that adopts technology is inseparable from the characteristics of a dynamic and uncertain system (Su et al., 2023; Putritamara et al., 2023; Mawardi et al., 2025). The use of a deterministic feasibility evaluation approach has limitations in representing system uncertainty because it is not able to adequately capture variability, thus potentially producing biased estimates and increasing risk in investment decision-making (Khodabakhshian et al., 2023). The mismatch between deterministic approaches and stochastic system characteristics suggests the need for an approach that comprehensively accommodates uncertainty. Therefore, a probabilistic approach is needed so that the evaluation of business feasibility can reflect various possible conditions in the system. Economic feasibility is then analyzed by considering uncertain market conditions. The demand and selling price variables are modeled as stochastic variables using Monte Carlo simulations which produce various possible market conditions so that the probability of a business being in a decent or unsuitable condition can be known. In addition, the results of the Monte Carlo simulation can provide information about the limits of feasible and unsuitable conditions based on various combinations of demand and selling prices. Thus, the results of the evaluation are not only in the form of deterministic feasibility values, but also the probability of investment success in various market scenarios.

Although the probabilistic approach is widely used to accommodate uncertainty in various fields, its application to technology-based business feasibility analysis, especially in the context of distributed recycling and ECO-C3DP machines is still relatively limited (Pirbalouti & Askari-nasab, 2024; Tan & Zhao, 2026). On the other hand, research on the circular economy generally focuses more on environmental and technical aspects, while techno-economic research focuses more on financial aspects. Until now, there is still little research that integrates the evaluation of the eco-circular characteristics of product design with the evaluation of economic feasibility and market uncertainty in one comprehensive analytical framework. This condition shows that there is a research gap that there is no integrated techno-economic evaluation that combines eco-modular technical analysis, determination of safe limits of sales demand and selling prices, measurement of the certainty of investment capital return based on the stochastic market, and mapping the scale of MSME businesses based on Government Regulation No. 7 of 2021 on the ECO-C3DP machine.

To bridge this gap, this study developed an integrated techno-economic evaluation framework to test the feasibility of commercialization of ECO-C3DP machines. This framework integrates two main assessment pillars, namely the technical dimension of sustainability based on the Eco-Modular Design Assessment to measure the modularity and ease of disassembly index and the economic dimension through Techno-Economic Analysis combined with the Monte Carlo stochastic simulation of two distributions to establish the safe limit of commercialization, measure the certainty of return on investment capital (), and map the potential for scale transition MSME efforts. This integration is expected to be a comprehensive and objective decision-making instrument for technology developers, potential investors, and regulators in overseeing the downstream of sustainable plastic waste recycling technology$NPV \geq 0$.

METHOD

The study employed a quantitative integrated-system modeling approach combining technical eco-modular design evaluation with techno-economic analysis (TEA). The technical evaluation assessed the circularity of the ECO-C3DP machine using module independence, disassembly module index, material similarity, lifespan similarity, and modularity for end-of-life, followed by mapping the design into a two-dimensional eco-modular matrix. The economic evaluation included production costs, CAPEX, OPEX, cost of goods sold, pricing, cash flow, NPV, IRR, ROI, BCR, and payback period. Market potential was estimated using TAM, SAM, SOM, and demand based on the availability of plastic waste, the number of manufacturing micro and small enterprises, machine processing capacity, target-market share, and adoption rate. Financial uncertainty was evaluated through 1,000-iteration Monte Carlo simulations using uniform and triangular distributions, incorporating variations in target-market share, adoption rate, and profit margin. The analysis also examined the investment tipping point, investment resilience, business-scale classification, and commercialization strategies using Business Model Canvas and SWOT analysis.

RESULTS AND DISCUSSION

ECO-Modular Design Evaluation of the C3DP

The product architecture evaluation was carried out to test the extent to which the ECO-C3DP machine structure meets the principles of eco-modular architecture and the principle of ease of disassembly. Machine structures are grouped in functional units of product architecture which are then mapped based on their materials. Mapping the hierarchy and material allocation of the ECO-C3DP engine is presented in figure 5:

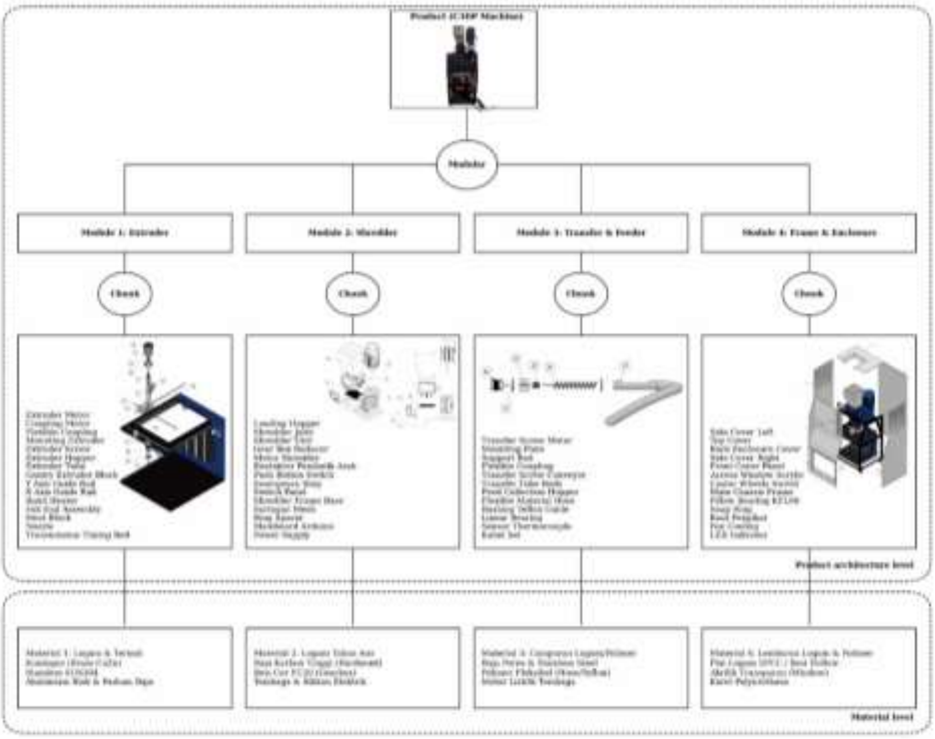

Figure 5. Modular Architecture Diagram and Material Mapping of ECO-C3DP Machinery

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Based on the product hierarchy in figure 5.1, the ECO-C3DP machine is divided into four functional modules. The first module is an extruder assembly that functions to melt plastic materials and then mold them layer by layer using materials with high thermal conductivity and corrosion resistance such as aluminum. The second module is a shredder assembly that functions to reduce the size of plastic waste with high mechanical strength and wear-resistant materials such as high carbon steel and FC20 cast iron in the gearbox. The third module is the transfer & feeder assembly which functions as a material conveying system using a special motor and hose to flow the plastic pieces automatically and smoothly. The fourth module is the frame & enclosure, which is the frame and outer cover that functions to support the machine structure and protect the operational system using SPCC plates, hollow iron and transparent acrylic windows. After the hierarchical structure and relationships between components were identified, the level of physical interconnectedness and ease of disassembly was measured using four sustainable modular drivers, namely module independence, disassembly module index, material similarity and lifespan similarity. The quantitative computational results of the four parameters are summarized in table 1:

Table 1. Calculation Results of ECO-Modular Architecture and Total MeoL

Evaluation Parameter	**Value**	**Threshold / Description**
Module Independence (MI)	0.8172	Passed
Disassembly Module Index (DMI)	0.5729	Passed
Material Similarity (MSmat)	0.4917	Nearly Passed
Lifespan Similarity (MSlife)	0.6259	Passed
X-Axis = (MI + DMI) / 2	0.6950	Passed
Y-Axis = (MSmat + MSlife) / 2	0.5588	Passed
Total MEoL Index	0.6269	Eligible as ECO-Modular

Based on Table 1, the ECO-C3DP machine demonstrates a very good modular design and supports recyclability. The Module Independence (MI) value reaches 0.8172, or 81.72%, indicating that the components can operate independently within their respective modules. The ease of disassembly between modules is reflected by a Disassembly Module Index (DMI) value of 0.5729, indicating that the connections between modules can use standard bolts that are easy to remove without damaging the components. The average of these two values forms a horizontal-axis coordinate of 0.6950, exceeding the minimum feasibility threshold of 0.50. In the assessment of physical similarity, the consistency of component lifespans (Lifespan Similarity / MSlife) has a value of 0.6259, while the similarity of material types (Material Similarity / MSmat) has a value of 0.4917. The material similarity value is approximately 0.49 because the heating module and electrical control system still combine various types of materials. The combination of these physical similarity values produces a vertical-axis coordinate of 0.5588. Overall, the total value of the machine's recyclability and end-of-life maintenance performance reaches a score of 0.6269. This value indicates that the ECO-C3DP machine meets the feasibility criteria for an ECO-modular design. The resulting assessment is subsequently presented in the following figure:

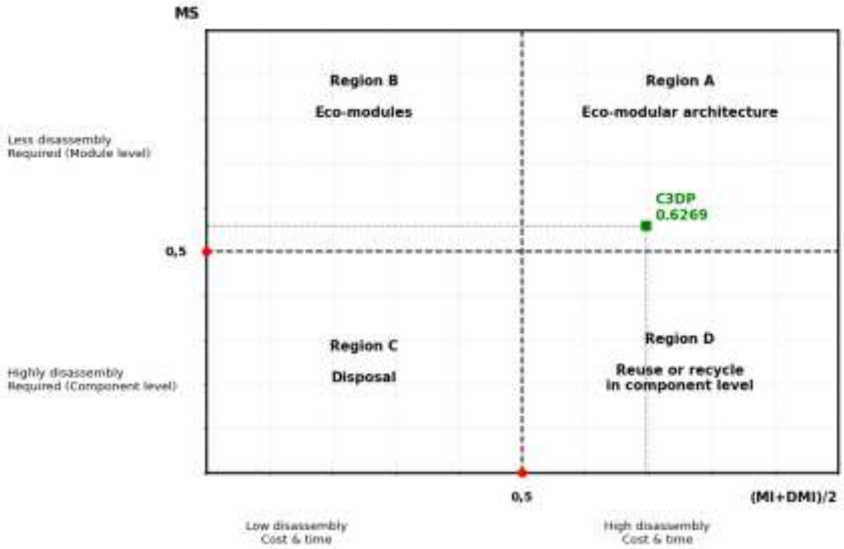

Figure 6. ECO-C3DP Machine End-of-Life Modularization Evaluation Matrix

Based on the illustration in Figure 6, the intersection of the horizontal-axis coordinate of 0.6950 and the vertical-axis coordinate of 0.5588 results in a total MEoL score of 0.6269, placing the ECO-C3DP machine in Region A. This position demonstrates that the machine is easy to maintain and assemble/disassemble, while also reducing the time and costs required for repairs. Therefore, the ECO-C3DP machine is less likely to become electronic waste at the end of its service life, as its materials can be readily recovered and recycled.

Evaluasi Tipping Point

Determining the Safe Sales Threshold and Financial Feasibility

The safe sales threshold and financial feasibility of the commercialization of the ECO-C3DP machine were evaluated in two stages. The first stage involved a deterministic feasibility evaluation to measure the performance of the operational plan under static conditions. The second stage involved a stochastic feasibility evaluation using the Monte Carlo method to assess the resilience of the investment to real-market fluctuations.

a. Deterministic Approach

The potential market absorption of the ECO-C3DP machine was estimated progressively based on waste supply (waste supply-driven), with the detailed data presented in Table 2 below.

Table 2. Estimated Market Potential for ECO-C3DP Machines Based on Waste Supply

Year	SAM	SOM	Demand
2026	79,994	800	20
2027	100,002	1,000	25
2028	120,004	1,200	30
2029	103,991	1,040	26
2030	88,011	880	22

Based on Table 2, the sales targets for the ECO-C3DP machine were determined progressively according to the availability of plastic waste. The potential Serviceable Available Market (SAM) corresponds to a requirement of 79,994 to 120,004 machines per year. By considering a relevant market share (Serviceable Obtainable Market / SOM) of 1%, the target market ranges from 800 to 1,200 units per year. Furthermore, assuming an initial adoption rate of 2.5% of the target market, the resulting realistic actual demand target ranges from 20 to 30 units per year. In 2026, the target is 20 units, increasing to 25 units in 2027 and reaching a peak of 30 units in 2028 in line with the peak in waste supply, before declining to 26 units in 2029 and 22 units in 2030. To meet the estimated market demand, a production budget was developed based on the technical requirements for each machine unit. Based on the Bill of Materials (BOM), the total variable manufacturing cost per unit is Rp 33,729,606. Material costs are predominantly allocated to the shredder module at Rp 12,915,000, followed by the extruder module at Rp 9,103,500, the 3D printer subsystem at Rp 7,991,106, and the mechanical-electronic integration module at Rp 3,720,000. In addition to raw materials and component costs, the annual fixed operating cost is Rp 115,221,008 per year, while the cost of goods manufactured (COGM) is Rp 39,491,083 per unit. By applying a reasonable gross profit margin target of 40%, the recommended commercial selling price is set at Rp 65,818,471 per unit.

To initiate business operations at this production scale, the total initial capital investment required is Rp 800,759,131. This capital consists of capital expenditure (CAPEX) for equipment procurement and first-year operating working capital (OPEX-1). The entire capital requirement is planned to be financed through a non-KUR entrepreneurial bank loan with an annual interest rate of 11.5% and a repayment period of five years, resulting in annual installment payments of Rp 219,393,406 or Rp 18,282,784 per month. Based on the selling price structure, market absorption volume, and financing burden, the ECO-C3DP machine production business is projected to generate profits and maintain stable and healthy cash flow. The initial investment is projected to be fully recovered within a payback period of 2.61 years, with the projected cash flow presented in Figure 7.

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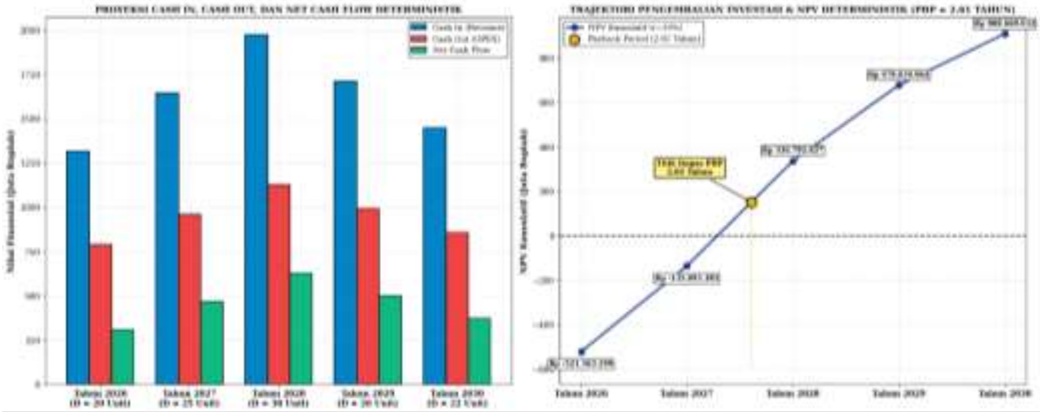

Figure 7. Deterministic Financial Feasibility Evaluation of the ECO-C3DP Machine

The projected operational cash flow graph illustrates the movement of cash inflows, cash outflows, and net cash flow over the five-year business period from 2026 to 2030. Throughout the period, revenue from machine sales consistently exceeds annual operating expenditures. In 2026, with sales of 20 units, cash inflows amount to Rp 1,316,272,054, while operating expenditures total Rp 789,763,232, resulting in a net cash flow of approximately Rp 307,115,416. In 2027, with sales increasing to 25 units, cash inflows rise to Rp 1,645,500,676, while operating expenditures reach Rp 958,481,094, generating a net cash flow of Rp 467,626,175. Cash flow reaches its peak in 2028, with a sales target of 30 units, generating the highest cash inflow of Rp 1,974,619,102 and operating expenditures of Rp 1,127,142,485, resulting in a net cash flow of Rp 628,083,211. In 2029, with sales declining to 26 units, cash inflows of Rp 1,711,124,069 and operating expenditures of Rp 992,110,730 still generate a net cash flow of Rp 499,619,933. Subsequently, in 2030, with sales declining to 22 units, cash inflows amount to Rp 1,448,190,562 and operating expenditures total Rp 857,366,737, while the business continues to generate a positive net cash flow of Rp 371,430,419. These results demonstrate that the business operation consistently generates a positive and stable cash balance each year.

The investment recovery trajectory and cumulative net present value illustrate the recovery of the business's initial capital investment. During the first two years, cumulative net cash flow remains negative due to the allocation of initial capital and investment costs, reaching -Rp 521,563,299 in 2026 and -Rp 135,095,385 in 2027. The break-even point is reached in the 2.61st year, or in less than three years, when the curve crosses the zero line and enters the profit zone. After passing this break-even point, cumulative net profit increases to Rp 336,792,827 in 2028, rises to Rp 678,039,964 in 2029, and reaches a total cumulative net profit of Rp 908,669,032 at the end of 2030. These results confirm that the ECO-C3DP machine manufacturing business has strong financial feasibility, a rapid payback period of less than three years, and promising long-term profit prospects. To provide a comprehensive overview of the business's financial performance, the results of the deterministic investment feasibility evaluation are summarized through several key indicators in Table 3.

Table 3. Deterministic Financial Feasibility Results of the ECO-C3DP Machine

Parameter	Feasibility Indicator	Calculation Result	Description
NPV	Net Present Value	Rp 908,669,032	Feasible
IRR	Internal Rate of Return	45.76%	Feasible
PBP	Payback Period	2.61 years	Feasible
BCR	Benefit-Cost Ratio	1.40	Feasible
ROI	Return on Investment	38.4%	Feasible

Therefore, under the deterministic projection conditions, the commercialization plan for the ECO-C3DP machine is 100% financially feasible and highly prospective.

b. Stochastic Monte Carlo Approach Using Triangular and Uniform Distributions

Considering the dynamics of the MSME-scale manufacturing market and its inherent uncertainty, the deterministic evaluation results were further tested using the Monte Carlo method with 1,000 iterations. This analysis modeled simultaneous fluctuations in the demand and selling price of the machine using two probability distributions: the triangular distribution, which represents realistic market conditions based on the most likely value, and the uniform distribution, which represents highly volatile market conditions without a preference for a central value. The stochastic distributions of demand and selling prices for both approaches, compared with the deterministic reference values, are presented in Figures 8 and 9.

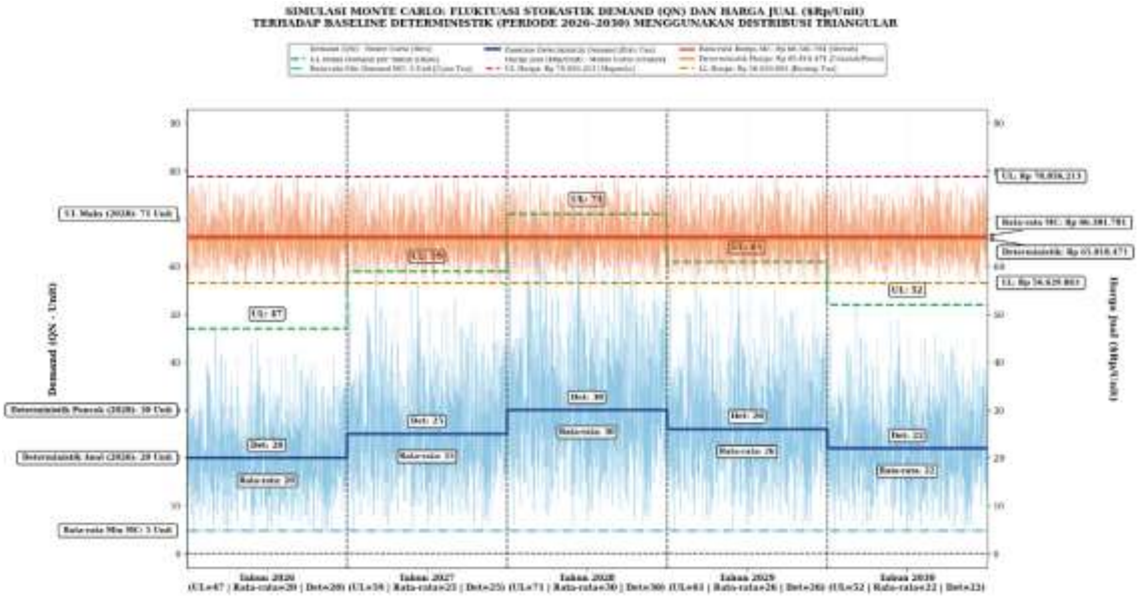

Figure 8. Stochastic Fluctuations in Demand and Selling Price Using the Triangular Distribution

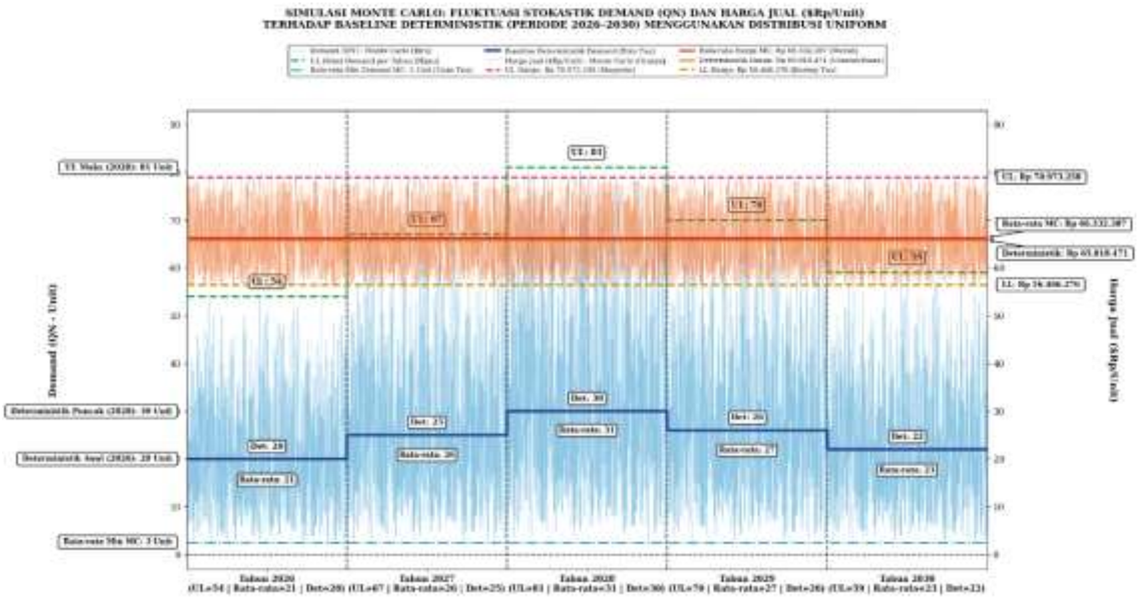

Figure 9. Stochastic Fluctuations in Demand and Selling Price Using the Uniform Distribution

Based on the results of the 1,000 iterations, the data were filtered based on financial feasibility indicators. The descriptive statistics for the feasible and infeasible groups under each distribution are presented in Tables 4 and 5.

Table 4. Feasibility Statistics for the Triangular Distribution

Parameter	Feasible	Infeasible
Number of Iterations	769 (76.9%)	231 (23.1%)
Average Selling Price	Rp 66,898,021	Rp 64,663,216
Selling Price Range	Rp 56,753,775 – Rp 78,856,213	Rp 56,629,863 – Rp 76,634,806
Demand 2026 (min–max)	11–47 units	4–18 units
Demand 2027 (min–max)	14–59 units	5–23 units
Demand 2028 (min–max)	16–71 units	6–28 units
Demand 2029 (min–max)	14–61 units	5–24 units
Demand 2030 (min–max)	12–52 units	4–20 units
Five-Year Average Range	14–58 units	5–22 units
Overall Average Demand	29 units/year	13 units/year

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Table 5. Feasibility Statistics for the Uniform Distribution

Parameter	Feasible	Infeasible
Number of Iterations	666 (66.6%)	334 (33.4%)
Average Selling Price	Rp 67,445,910	Rp 64,112,007
Selling Price Range	Rp 56,466,276 – Rp 78,973,258	Rp 56,490,074 – Rp 78,558,555
Demand 2026 (min–max)	10–54 units	2–18 units
Demand 2027 (min–max)	13–67 units	3–23 units
Demand 2028 (min–max)	15–81 units	3–28 units
Demand 2029 (min–max)	13–70 units	3–24 units
Demand 2030 (min–max)	11–59 units	2–20 units
Five-Year Average Range	13–66 units	2–22 units
Overall Average Demand	33 units/year	12 units/year

Referring to the overall results of the stochastic data analysis presented in Tables 4 and 5, the safe sales thresholds for the two market scenarios are described as follows:

1. Tipping Point Boundaries

The Monte Carlo method successfully identified the critical threshold boundaries separating the success and failure of ECO-C3DP machine commercialization.

a. Feasible Scenario

The business is categorized as feasible and profitable when the company is able to sell an average of at least 13–14 machines per year over the five-year operating period. In particular, during the first year, 2026, when the product is newly introduced to the market, the company must sell at least 10–11 machines as a safe threshold to prevent a cash-flow deficit. If this initial safe threshold is achieved, the market is expected to absorb sales smoothly at an average level of approximately 29–33 units per year, allowing the initial investment to be recovered on schedule while generating stable profits.

b. Infeasible Scenario

An infeasible condition occurs when sales in the first year, 2026, decline sharply to a range of 2–18 units, followed by low average machine sales over the five-year period of only approximately 12–14 units per year. The Monte Carlo iterations indicate that when average annual sales fall below 13 units per year, the resulting revenue is insufficient to cover production costs, routine operating expenses, and bank loan repayment obligations. Consequently, the business is expected to incur financial losses.

2. Price Fluctuation Sensitivity

The financial feasibility of the business is highly sensitive to the selling price formed in the market, as described below.

a. Lower-Limit Price Scenario: Rp 56,466,276–Rp 56,629,863

When competitive pressure forces the selling price downward toward the cost of goods sold (COGM), resulting in a gross profit margin of approximately 30%, the break-even burden increases significantly. Under this condition, the manufacturer must implement a volume-driven strategy by selling at least 18 units in the first year and maintaining average five-year sales above 22 units per year. If annual sales fall below 22 units at the lower-limit price, the business is expected to experience overall financial losses.

b. Upper-Limit Price Scenario: Rp 78,856,213–Rp 78,973,258

When the machine can be sold at a higher price, corresponding to a gross profit margin of up to 50%, the business remains financially secure and is less vulnerable to losses when sales decline. The manufacturer only needs to sell 10–11 units in the first year or maintain an average of 13–14 units per year to ensure that the business remains feasible and profitable.

c. Evaluation of the Recommended Selling Price

Setting the recommended selling price at Rp 65,818,471 per unit, based on a COGM of Rp 39,491,083 and a 40% margin, proves to be an ideal choice because it is very close to the average market price generated by the simulation, which ranges from Rp 66,329,503 to Rp 66,381,729 per unit. At this price level, the manufacturer only needs to sell approximately 20–30 units per year to maintain positive cash flow, cover operating expenses, and provide optimal protection against the risk of market losses.

Investment Resilience Evaluation

The investment resilience evaluation was conducted to measure the degree of certainty regarding the recovery of the initial investment and to identify the risk of business failure in the commercialization of the ECO-C3DP machine under dynamic real-market conditions. The investment resilience test was conducted to assess the certainty of recovering the initial investment of Rp 800,759,131 under two different market-dynamics scenarios.

a. Realistic Market Scenario (Triangular Distribution)

Under normal market conditions, where sales and prices fluctuate around their most likely values, the business has a 76.9% probability of recovering its initial investment. This indicates that, out of 1,000 simulated possible market conditions, 769 iterations resulted in a feasible status, with a median profit (P50) of Rp 851,048,708 and an average net present value of Rp 1,444,731,915. This result is further supported by an internal rate of return (IRR) of 61.88% and a benefit-cost ratio (BCR) of 1.45. The potential risk of failure to recover the initial investment under this market condition is relatively low, at 23.1%.

b. Extreme Market Volatility Scenario (Uniform Distribution)

When the market was tested under conditions of high uncertainty without a clear trend, in which all possible movements in market prices and demand were assigned equal probabilities, the business still demonstrated strong financial resilience, with a feasibility probability of 66.6%. This indicates that, out of 1,000 simulated possible market conditions, 666 iterations resulted in a feasible status, with a median profit (P50) of Rp 775,780,282 and an average net present value of Rp 1,983,956,528. This result is further supported by an internal rate of return (IRR) of 78.28% and a benefit-cost ratio (BCR) of 1.50. The potential risk of failure to recover the initial investment under this scenario is 33.4%. Overall, a comparison of the two probability distributions demonstrates that the ECO-C3DP machine manufacturing business has strong financial resilience against market dynamics. The probability of investment success consistently ranges from 66.6% to 76.9%, confirming that the initial investment of Rp 800,759,131 has a strong likelihood of being recovered. This framework also successfully quantifies market risk reserves within a measurable range of 23.1% to 33.4%, thereby providing a transparent basis for management, investors, and banking institutions to formulate operational risk mitigation strategies from the early stage of commercialization.

Evaluation of MSME Business Scale Classification Based on Government Regulation No. 7 of 2021

The business-scale evaluation was conducted to determine the business classification of the ECO-C3DP machine manufacturer and to map the probability of upward business-class mobility based on the criteria of initial capital and annual revenue in accordance with Government Regulation No. 7 of 2021. The evaluation is described as follows:

Waste-Supply-Based Business Scale Classification in Central Java

The market potential analysis (SAM) in this section focuses on the availability of plastic waste in Central Java Province. The data were obtained from the National Waste Management Information System (SIPSN) of the Ministry of Environment and Forestry (KLHK). Central Java was selected because it has consistently been recorded as one of the largest waste-generating provinces in Indonesia, particularly in 2021, 2022, and 2025, with waste generation exceeding 5.75 million tons per year. The abundant supply of raw materials makes Central Java an ideal location for assessing the feasibility of this waste-recycling machine business. The mapping of the ECO-C3DP machine business classification is presented in Figures 10 and 11 below.

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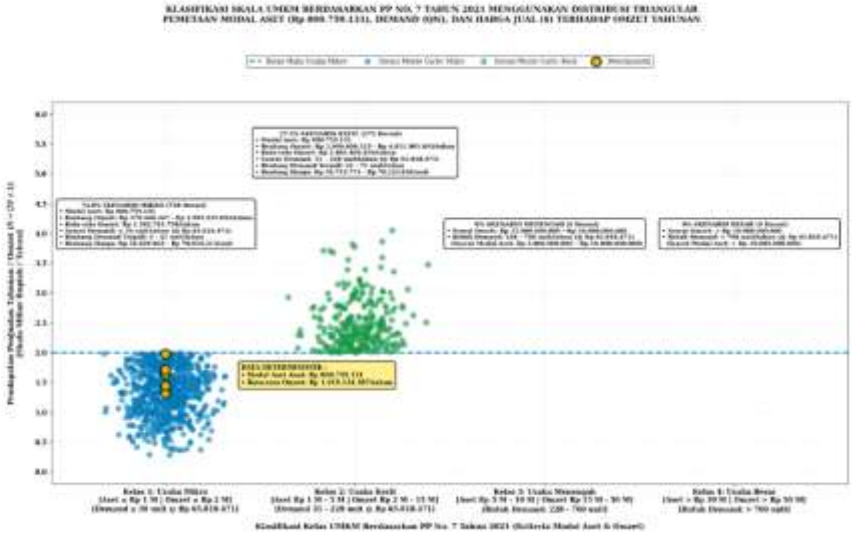

Figure 10. MSME Business Classification Mapping Graph Based on Government Regulation No. 7 of 2021 Using the Triangular Distribution

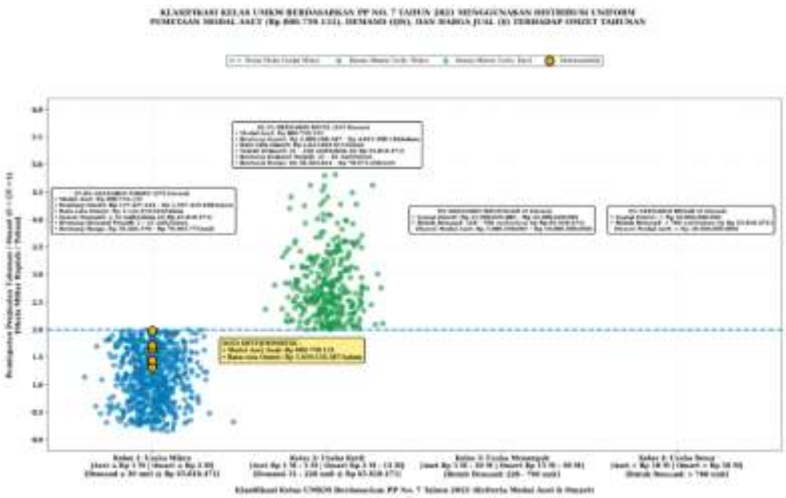

Figure 11. MSME Business Classification Mapping Graph Based on Government Regulation No. 7 of 2021 Using the Uniform Distribution

In terms of initial capital requirements, the total investment required to establish an ECO-C3DP machine production unit amounts to Rp 800,759,131. In accordance with the provisions of Government Regulation (PP) No. 7 of 2021, this asset value is below the maximum threshold of Rp 1,000,000,000. Therefore, the business unit is legally classified as Class 1 Micro Enterprise. Under the static market scenario, with planned sales of 20 to 30 units per year at the recommended price of Rp 65,818,471 per unit, annual revenue ranges from Rp 1,316,272,054 to Rp 1,974,619,102, with an average annual revenue of Rp 1,619,141,293. Since the maximum annual revenue does not exceed Rp 2,000,000,000, the business unit operates stably at the Micro Enterprise scale under normal operating conditions. Although its initial capital base places it within the Micro Enterprise category, the results of 1,000 Monte Carlo iterations indicate a significant potential for business growth under dynamic market conditions. Under the triangular distribution model, 72.8% of the scenarios, or 728 iterations, remained within the Micro Enterprise scale. Annual revenue ranged from Rp 278,446,447 to Rp 1,995,925,094, with an average of Rp 1,342,741,758, generated from sales of 4 to 41 machines per year at selling prices ranging from Rp 56,629,863 to Rp 78,856,213 per unit. On the other hand, there was a 27.2% probability, or 272 iterations, of the business upgrading to Class 2 Small Enterprise. This upward classification occurred when market demand increased to a range of 22 to 71 units per year at selling prices ranging from Rp 56,753,775 to Rp 78,223,658 per unit, directly increasing annual revenue to a range of Rp 2,000,408,225 to Rp 4,051,985,493, with an average annual revenue of Rp 2,482,406,450.

Under the uniform distribution model, which represents market conditions characterized by high volatility without a tendency toward a central value, 67.8% of the scenarios, or 678 iterations, remained at the Micro Enterprise scale. Annual revenue ranged from Rp 157,427,624 to Rp 1,997,429,498, with an average annual revenue of Rp 1,144,874,949, generated from sales of 2 to 42 machines per year at selling prices ranging from Rp 56,466,276 to Rp 78,903,775 per unit. Meanwhile, there was a 32.2% probability that the business would move up to the Small Enterprise scale. This upward classification could occur when market demand increased to 21–81 units per year at selling prices ranging from Rp 56,482,824 to Rp 78,973,258 per unit, resulting in annual revenue ranging from Rp 2,000,280,347 to Rp 4,819,398,310, with an average annual revenue of Rp 2,823,603,015. The simulation results also demonstrate that there is a 0% probability of the business directly developing into a Medium Enterprise or Large Enterprise. This condition is attributable to two factors:

a. Based on Government Regulation No. 7 of 2021, entry into the Medium Enterprise category requires annual revenue between Rp 15,000,000,000 and Rp 50,000,000,000. At the benchmark selling price, this corresponds to the requirement to sell approximately 228 to 760 machines per year. Meanwhile, the Large Enterprise category requires annual revenue exceeding Rp 50,000,000,000, which would require sales of more than 760 machines per year.
b. The minimum sales target of 228 units per year is not realistic if the business relies solely on the supply of plastic waste in Central Java at the current market absorption level. In addition, producing machines on such a large scale would require substantially larger factory facilities and asset capital than the initial investment of Rp 800,759,131.

Overall, the Central Java-based modeling demonstrates that the ECO-C3DP machine manufacturing business is established on an affordable capital base at the Micro Enterprise level, while offering a 27.2% to 32.2% probability of upgrading to the Small Enterprise category. These findings provide assurance to banking institutions and investors that this waste-recycling machinery downstreaming business has manageable capital risk while offering promising business growth potential.

National Waste-Supply-Based Business Scale Classification

To assess the scalability potential of the industry without geographical limitations, the business-scale evaluation was further simulated using the potential supply of plastic waste at the national level. The increase in the production target requires a larger initial investment allocation, amounting to Rp 3,641,101,751. Based on the criteria stipulated in Government Regulation (PP) No. 7 of 2021, ownership of assets valued between Rp 1,000,000,000 and Rp 5,000,000,000 places the ECO-C3DP machine production business in Class 2 Small Enterprise from the outset. The national-level business-scale mapping is presented in Figures 12 and 13 below.

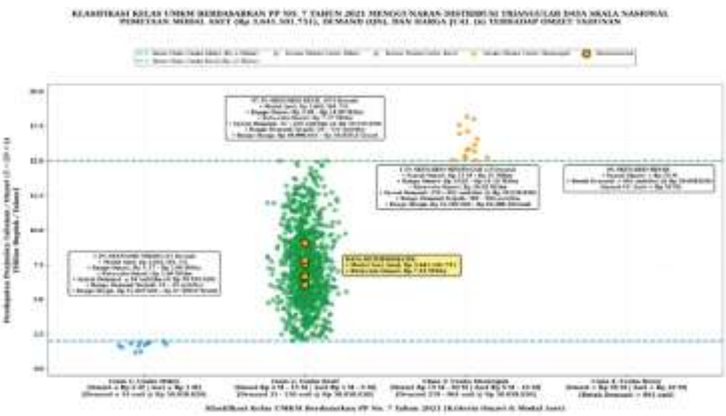

Figure 12. MSME Business Classification Mapping Graph Based on Government Regulation No. 7 of 2021 Using National Data and the Triangular Distribution

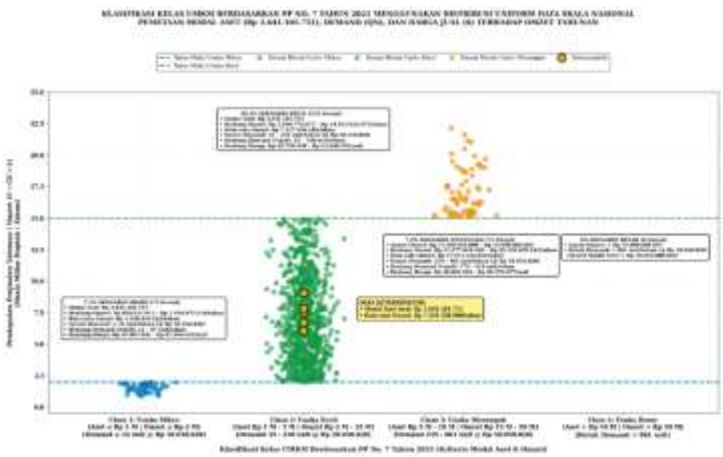

Figure 13. MSME Business Classification Mapping Graph Based on Government Regulation No. 7 of 2021 Using National Data and the Uniform Distribution

Referring to Figures 12 and 13, the operational dynamics and potential for business-scale upgrading of the ECO-C3DP machine business are described as follows:

Under the triangular distribution model using national-scale data, the business unit predominantly operates within Class 2 Small Enterprise, accounting for 97.3% of the scenarios or 973 iterations. The number of machines sold ranges from 25 to 321 units per year at selling prices between Rp 49,906,662 and Rp 68,850,372 per unit, generating annual revenue ranging from Rp 2,000,494,674 to Rp 14,988,932,735, with an average annual revenue of Rp 7,371,332,461. In contrast, only 1.2% of the scenarios or 12 iterations fall within Class 1 Micro Enterprise, with annual revenue ranging from Rp 1,171,201,002 to Rp 1,956,840,978 and an average annual revenue of Rp 1,661,960,688. This condition is attributable to relatively low market demand, ranging from 15 to 45 units per year, at selling prices between Rp 51,033,670 and Rp 67,908,079 per unit. Unlike the Central Java regional analysis, expanding the market to the national level creates a 1.5% probability for the business unit to advance to Class 3 Medium Enterprise. This upgrade can be achieved when market demand increases to between 189 and 353 units per year at selling prices ranging from Rp 55,546,949 to Rp 65,586,184 per unit, resulting in annual revenue ranging from Rp 15,019,819,411 to Rp 18,178,922,942, with an average annual revenue of Rp 16,248,808,813.

The potential for business growth becomes even more substantial under the uniform distribution model using national-scale data. The majority of the simulation results, namely 85.3% of the scenarios or 853 iterations, indicate that the business operates within Class 2 Small Enterprise. This outcome is generated by machine sales ranging from 25 to 358 units per year at selling prices between Rp 49,788,438 and Rp 69,640,202 per unit, with annual revenue ranging from Rp 2,006,772,675 to Rp 14,953,024,471 and an average annual revenue of Rp 7,127,956,248. The high market variability represented by the Uniform model also provides a 7.2% probability of upgrading to the Medium Enterprise level. This business-scale upgrade can occur when national machine sales increase from 179 to 414 units per year at selling prices ranging from Rp 49,820,203 to Rp 69,570,377 per unit, driving annual revenue to between Rp 15,077,654,940 and Rp 22,138,639,443, with an average of Rp 17,074,122,658 per year. Meanwhile, 7.5% of the scenarios remain within the Micro Enterprise scale. This condition occurs due to low machine sales ranging from 12 to 47 units per year at selling prices between Rp 49,807,946 and Rp 67,566,695 per unit, generating annual revenue of Rp 859,025,913 to Rp 1,990,973,936, with an average annual revenue of Rp 1,559,444,622. On the other hand, the probability of the business entering Class 4 Large Enterprise remains 0%, as this category requires machine sales exceeding 861 units per year to achieve annual revenue above Rp 50,000,000,000.

A comparison of the two geographical scales confirms that the absence of an opportunity to reach the Medium Enterprise category under the Central Java model is primarily attributable to the limited regional waste supply. When the market coverage is expanded nationwide, the ECO-C3DP machine manufacturing business demonstrates significant potential for business-scale growth, with 85.3%–97.3% of the scenarios successfully reaching the Small Enterprise category and a 1.5%–7.2% probability of progressing to the Medium Enterprise category.

Commercialization Business Strategy Evaluation

The main challenge in commercializing appropriate technology (AT), such as the ECO-C3DP machine, lies in the gap between the purchasing power of end-users or MSME operators and the required machine investment cost. Direct Business-to-Consumer (B2C) sales as well as purely Business-to-Business (B2B) transactions with micro-enterprises are often constrained by the limited initial capital available to MSMEs. To overcome this barrier, the company is positioned as a Technology & Ecosystem Enabler, serving as an integrated technology and ecosystem provider rather than merely a machine manufacturer. The commercialization strategy is therefore shifted toward a Business-to-Government-to-Community (B2G2C) scheme through an Estate Model approach. Under this model, local governments and corporate entities through Corporate Social Responsibility (CSR) programs act as CAPEX buyers and absorbers of the resulting outputs, while MSMEs or waste-bank groups serve as field operators.

Production is designed around a batch system of 10 units per package to optimize labor costs and manufacturing overhead efficiency. The manufacturer performs five key enabler functions:

1. Enable Technology: Providing integrated machines with a modular architecture that is easy to operate and space-efficient.
2. Enable People: Transferring technical competencies to 2–3 selected local operators at each production center.
3. Enable System: Developing end-to-end Standard Operating Procedures (SOPs), covering the entire process from waste sorting, shredding, filament extrusion, and 3D printing to final product quality control.
4. Enable Data: Providing routine data reports covering the amount of plastic waste processed, products generated, and employment created as tangible evidence of local government program achievements for reporting to relevant ministries.
5. Enable Scale: Developing standardized guidelines based on successful pilot projects, allowing the business model to be replicated and implemented directly across various regencies and cities throughout Indonesia.

To formulate a comprehensive business strategy, the evaluation employs two main instruments: the Business Model Canvas (BMC) to map the workflow and partnership scheme under the B2G2C model, and SWOT Analysis to identify the machine's competitive advantages and formulate market risk mitigation strategies. The BMC mapping is presented in Figure 14, while the SWOT analysis is presented in Figure 15 below.

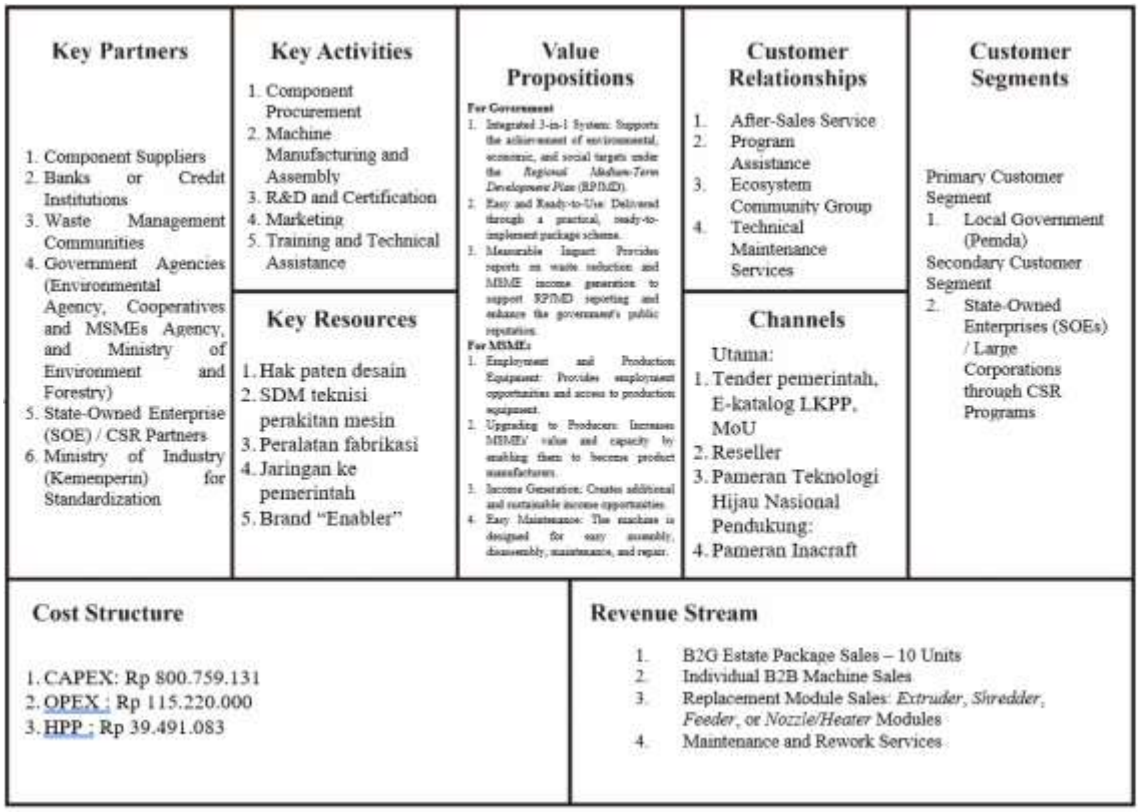

Figure 14. Business Model Canvas (BMC) of the ECO-C3DP Machine

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The upstream side (Key Partners & Key Activities) is developed in collaboration with module suppliers, banks/credit institutions, waste-management communities, and relevant ministries. Local supply-chain collaboration aims to maintain an efficient cost of goods manufactured (COGM) at Rp 39,491,083 per unit while accelerating the acquisition of Domestic Component Level (Tingkat Komponen Dalam Negeri / TKDN) certification. Key activities focus on component procurement, precision assembly, research and development (R&D), certification, integrated marketing, and operator training and mentoring. The value and resource side (Value Propositions & Key Resources) offers local governments a dual-impact solution by supporting the achievement of Regional Medium-Term Development Plan (RPJMD) waste-reduction targets while creating new employment opportunities through ready-to-use machine packages with measurable impacts. For MSMEs, this scheme provides free production facilities, skills transfer, and ease of machine maintenance. Key resources include design patent rights, assembly engineering personnel, fabrication facilities, government-network relationships, and brand reputation as an enabler.

The downstream side (Customer Segments, Channels, & Customer Relationships) focuses primarily on local government agencies, including the Environmental Agency (Dinas Lingkungan Hidup) and the Cooperatives and MSMEs Agency (Dinas Koperasi & UMKM), with secondary customer segments consisting of CSR programs operated by state-owned enterprises (SOEs) and private corporations. The main distribution channels are accessed through official regional budget (APBD) procurement tenders and listings on the LKPP E-Catalog, while participation in exhibitions such as the National Green Technology Exhibition and INACRAFT serves as a means of demonstrating the machine's actual results and benefits in the field. Customer relationships are maintained through routine maintenance contracts, after-sales warranties, program assistance, and the establishment of an ecosystem community forum. The cost structure and revenue streams (Cost Structure & Revenue Streams) comprise an initial capital requirement of Rp 800,759,131, annual operating expenses of Rp 115,221,008, and a COGM of Rp 39,491,083 per unit. The primary revenue stream is generated from the sale of a 10-unit B2G estate package, including installation and training, valued at Rp 660,000,000. Additional revenue is generated through individual B2B machine sales at Rp 65,818,471 per unit, module spare-parts sales, and maintenance and repair services.

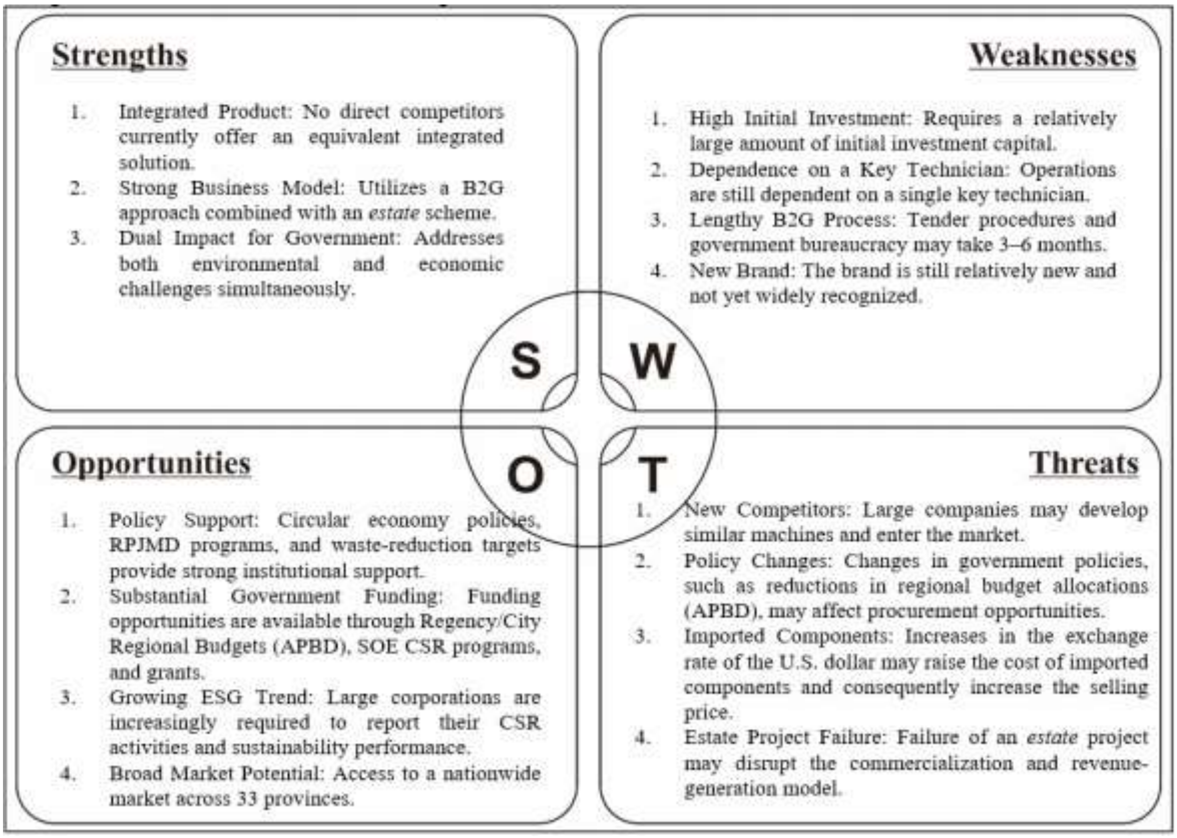

Figure 15. SWOT Analysis of the ECO-C3DP Machine

The SWOT analysis is used to formulate strategies for leveraging opportunities and addressing risks under real-world conditions. The machine has a strong competitive advantage in capturing the market due to its integrated design, which enables plastic waste to be shredded, melted, and transformed into printed products using a single system, while currently having no direct competitors. This advantage aligns well with the needs of local governments, which are required to reduce waste and create new employment opportunities in accordance with RPJMD targets. In addition, regulations requiring large companies and state-owned enterprises (SOEs) to allocate funds for environmental CSR programs provide a significant opportunity to sell machine packages without relying entirely on regional government budgets (APBD). To address the challenge of government procurement processes, which may take approximately 3–6 months, the machine will be registered in the LKPP E-Catalog to facilitate faster and more formal transactions. Meanwhile, the limited availability of technical personnel will be addressed through collaboration with local partners to assist in the production of machine modules and components. This approach can accelerate production, simplify machine assembly, and increase the use of locally sourced components to meet Domestic Component Level (TKDN) requirements. To mitigate the threat of increasing prices of imported spare parts or potential reductions in regional government budgets, the business will not rely solely on new machine sales. Recurring revenue will also be generated through the sale of replacement modules and periodic maintenance and repair services. In addition, the initial pilot project will be implemented with intensive assistance to prevent community groups from experiencing operational failures, thereby maintaining local government confidence in the product. The commercialization of the ECO-C3DP machine will be implemented through four stages:

1. Pilot Project Execution
   Establishing two pilot locations along with local operator training. This stage aims to test machine performance in the field, ensure the stability of production costs (COGM), and collect real-world data regarding the amount of plastic waste processed and the additional income generated by partner MSME groups.
2. Business Legality and E-Catalog Registration
   Establishing an official legal business entity to meet the requirements for government procurement, conducting technical feasibility testing at an accredited laboratory, completing TKDN certification through the Ministry of Industry, and registering the machine package in the LKPP E-Catalog system.
3. Regional Market Expansion and Product Exhibitions
   Presenting finished products and evidence of successful pilot projects at national-level exhibitions such as INACRAFT and green manufacturing exhibitions. These exhibitions will serve as showrooms to demonstrate the machine's capabilities and facilitate procurement partnerships with regency/city governments and corporate CSR programs.
4. National-Scale Replication and Sustainable Services
   Replicating the production-center model across local governments throughout Indonesia, supported by routine maintenance services and the availability of replacement modules and spare parts, thereby ensuring stable business operations over the long term.

CONCLUSION

Based on the eco-modular architecture assessment and stochastic techno-economic analysis, the ECO-C3DP machine was successfully classified into four main modules: extruder assembly, shredder assembly, transfer & feeder assembly, and frame & enclosure. The design met the eco-modular architecture criteria, achieving an MEoL index of 0.6269 in Region A, supported by high Module Independence (0.8172) and Disassembly Module Index (0.5729). The waste-supply-driven market analysis estimated a SAM of 79,994–120,004 units annually and a 1% SOM of approximately 800–1,200 units, resulting in a realistic deterministic demand of 20–30 machines per year for 2026–2030 at a 2.5% adoption rate.

The financial feasibility analysis, based on an initial investment of IDR 800,759,131, variable cost of IDR 33,729,606 per unit, annual fixed operating costs of IDR 115,221,008, and unit production cost of IDR 39,491,083, indicated that the recommended selling price of IDR 65,818,471 with a 40% margin was financially feasible. The project generated an NPV of IDR 908,669,032, an IRR of 45.76%, an ROI of 38.4%, a BCR of 1.40, positive cash flows, and a payback period of less than three years. Monte Carlo simulations with 1,000 iterations confirmed that the business remained feasible under market uncertainty, with a minimum first-year sales level of approximately 10–11 units and an average annual sales level of 13–14 units. The recommended price was also relatively robust to market fluctuations.

Investment resilience analysis showed a feasibility probability of 76.9% under the triangular distribution and 66.6% under the uniform distribution. Based on Government Regulation No. 7 of 2021, the business was classified as a Micro Enterprise at the Central Java regional scale, with a 27.2%–32.2% probability of progressing to the Small Enterprise category. At the national scale, with an initial investment of IDR 3,641,101,751, it was classified predominantly as a Small Enterprise (85.3%–97.3%), with a 1.5%–7.2% opportunity to progress to the Medium Enterprise category. Commercialization was therefore recommended

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through a Business-to-Government-to-Community (B2G2C) partnership using an estate model, including a 10-machine package valued at IDR 660 million, supported by e-Catalogue procurement, TKDN certification, after-sales services, and modular spare-parts provision.

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