Jurnal Tekstil: Jurnal Keilmuan dan Aplikasi Bidang Tekstil dan Manajemen lndustri | ISSN 3024-9295 (print), 2797-9229 (online) | Vol. 9, No. 2, 2026, Hal. 120-133

From Linear to Circular: A System Dynamics Approach to Sustainable Garment Production at PT XYZ Garment

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Received July 27, 2026/Revised August 18, 2026/Accepted October 28, 2026/Published November 11, 2026

ABSTRAK

PT XYZ Garment merupakan perusahaan manufaktur garmen dengan sistem produksi *make-to-order* yang masih dijalankan secara tradisional dan manual, sehingga pemantauan, pencatatan, pelaporan, dan pengukuran efisiensi produksi menjadi terbatas. Perusahaan juga masih menerapkan model ekonomi linier, di mana limbah kain dibuang tanpa dimanfaatkan kembali. Penelitian ini bertujuan mengevaluasi kinerja sistem produksi yang sedang berjalan dan memprediksi kinerjanya pada model ekonomi sirkular menggunakan pendekatan *system dynamics*. Tahapan penelitian meliputi observasi, wawancara, studi literatur, identifikasi sistem, penyusunan *causal loop diagram*, pemodelan *stock and flow diagram*, serta simulasi selama 208 minggu berdasarkan data historis produksi. Dua skenario dibandingkan, yaitu model linier yang sedang berjalan dan model sirkular yang memanfaatkan kembali limbah kain melalui perantara dan pengrajin. Hasil simulasi menunjukkan bahwa skenario sirkular menghasilkan indikator kinerja yang lebih tinggi dibandingkan model linier: total permintaan meningkat sekitar 98% (dari 8.122 menjadi 16.095 unit), total penjualan meningkat sekitar 98% (dari 8.123 menjadi 16.096 unit), rata-rata kepuasan pelanggan meningkat 10,77% (dari 4,14 menjadi 4,58 pada skala 5 poin), dan tingkat sirkularitas mencapai 16.575 unit dibandingkan 0% pada model linier. Rata-rata *Green Image Factor* pada skenario sirkular sebesar 0,069, yang menunjukkan kontribusi daur ulang sekitar 6,9% terhadap penjualan. Temuan ini menunjukkan bahwa pendekatan *system dynamics* mampu menggambarkan hubungan dinamis antarvariabel produksi dan dapat menjadi dasar untuk mengevaluasi kebijakan berorientasi keberlanjutan. Hasil ini merupakan temuan berbasis simulasi dan masih memerlukan validasi empiris pada parameter utama sebelum diterapkan secara nyata. Penelitian ini menyediakan kerangka kerja berbasis simulasi untuk menilai kelayakan transisi perusahaan garmen menuju ekonomi sirkular.

Kata Kunci: ekonomi sirkular, garmen, limbah kain, simulasi, dinamika sistem.

ABSTRACT

PT XYZ Garment is a garment manufacturer operating a make-to-order system that still relies on traditional, manual processes, which limits monitoring, tracking, reporting, and efficiency measurement of the overall production system. The company also applies a linear economy model in which fabric waste is disposed of without reuse. This study evaluates current production performance and predicts performance under a circular economy model using a system dynamics approach. The research stages include observation, interviews, literature review, system identification, causal loop diagram development, stock and flow diagram modeling, and a 208-week simulation using historical production data. Two scenarios were compared: the existing linear model and a circular model that reuses fabric waste through an intermediary-and-craftsmen mechanism. The simulation results show that the circular scenario produced higher values across key indicators: total demand increased by approximately 98% (from 8,122 to 16,095 units), total sales by approximately 98% (from 8,123 to 16,096 units), and average customer satisfaction by 10.77% (from 4.14 to 4.58 on a 5-point scale). The circularity rate reached 16,575 units compared to 0% under the linear model, and the mean Green Image Factor was 0.069, indicating that recycling contributed approximately 6.9% relative to sales. These findings indicate that system dynamics can capture the dynamic interrelationships among production variables and support the evaluation of sustainability-oriented policy changes. However, they are simulation-based and require empirical validation of key parameters before real-world implementation. This study provides a simulation-based framework for assessing the feasibility of circular economy transition in garment companies.

Keywords: *circular economy, fabric waste, garment production, simulation, system dynamics.*

1. Introduction

The fashion and garment industry is one of the largest contributors to environmental pollution, generating significant waste throughout the production process. The conventional linear economy model, characterized by a "take-make-dispose" approach, has led to the depletion of natural resources and increased landfill waste. In particular, the garment production unit at PT XYZ Garment currently still follows this linear model, where waste generated during production ends up in landfills, contributing to environmental degradation and resource inefficiency.

According to data from UNEP, Global Fashion Agenda, Ellen MacArthur Foundation, and Science Advances as processed by TheRoundup.org, up to 100 billion new garments are produced each year, and 87% of the materials used to make clothing end up in landfills; equivalent to one truckload every second, with only 1% of clothes recycled into new garments (Ruiz Suárez, 2023). This highlights the urgent need for the textile and garment industries to prioritize product flow and waste management in order to mitigate their environmental impact.

The garment industry produces ready-to-wear clothing and related apparel items and has become the fourth-largest contributor to Indonesia's foreign exchange earnings after oil and gas. According to Indonesia's Central Bureau of Statistics, the clothing production index showed a consistent annual increase from 2016 to 2019, declined during 2020–2021 due to the COVID-19 pandemic, and has risen again from 2022 to the present (Badan Pusat Statistik, 2024). The export market for the garment industry also extends beyond domestic consumers to international clients. According to the Indonesian Ministry of Industry, in 2024 the export value of the textile industry, including garments, ranked fourth among national export commodities, amounting to USD 3.38 billion or approximately IDR 53.73 trillion (Kementerian Perindustrian, 2024). However, the production process generates significant amounts of textile waste and wastewater, which can contribute to environmental pollution if not managed properly. The global textile industry generates approximately 92 million tons of waste annually, with projections indicating this figure could rise to 134 million tons per year by 2030 if current trends persist (Earth.org, 2023). This waste contributes to environmental pollution, as a significant portion ends up in landfills or is incinerated, making textile and garment manufacturers collectively responsible for about 10% of global carbon emissions, underscoring the need for sustainable practices within the sector.

A circular economy model offers a promising alternative to the challenges posed by the linear economy model. This approach emphasizes the reduction, reuse, and recycling of waste materials to create closed-loop systems that minimize resource consumption and environmental harm. Circular economy principles have been shown to transform waste into valuable resources, reduce environmental footprints, and create sustainable economic opportunities (Ellen MacArthur Foundations, 2013). However, transitioning from a linear to a circular economy requires systemic changes in production practices and waste management. These changes are inherently complex and involve numerous interdependent factors, such as material flows, waste processing, and stakeholder coordination. System dynamics is a methodology that facilitates the modeling and analysis of such complex systems. By capturing the interactions between various components within a system, system dynamics allows researchers to simulate, analyze, and optimize system behavior over time (Forrester, 1961). This approach is particularly useful in the context of garment production, as it can provide valuable insights into the transition toward circular economy practices. System dynamics can model waste generation, recycling processes, and resource flows, enabling stakeholders to evaluate the impact of policy changes, production adjustments, and resource allocation strategies (Sterman, 2000).

Beyond modeling approaches, the broader adoption of information technology within the textile and garment manufacturing sector remains uneven. A systematic literature review covering technologies such as Enterprise Resource Planning (ERP), Internet of Things (IoT), Artificial Intelligence (AI), and Big Data Analytics found that, while digitalization has increased production efficiency, optimized supply chains, and supported data-based decision-making in several companies, many other technological innovations within the textile and garment industry have not yet been widely adopted, leaving considerable room for further development (Imran, 2025). This gap reinforces the relevance of applying a structured, data-driven approach such as system dynamics modeling within garment production units like PT XYZ Garment that have yet to adopt such technologies, in order to evaluate current production performance and to support an evidence-based transition toward more sustainable and efficient practices.

The current garment production system at PT XYZ Garment operates under this linear economy framework, generating substantial waste throughout the production process, all of which is disposed of in landfills. This practice not only exacerbates environmental challenges but also highlights inefficiencies within the production system. Based on interviews conducted within the garment production unit, the efficiency of raw material usage in production is approximately 85%, meaning that around 15% of the material becomes

fabric waste. If this condition persists over a long period, it will result in a substantial accumulation of material loss and a corresponding negative environmental impact. This leftover fabric, however, can still be reused as craft material or repurposed into items of added value by artisans. The current fabric waste management practice involves only two main actors: the garment production unit, which generates the fabric waste, and artisans, who reuse it. Field findings show that both parties face difficulties in determining where to distribute the remaining fabric waste and to whom it should be given. This suggests the need for an intermediary capable of receiving, managing, and distributing residual fabric waste to parties who can utilize it, so that production waste no longer ends up in landfills.

A similar challenge has been observed in other manufacturing contexts, where the absence of a structured, technology-supported system leads to recurring operational inefficiencies. For instance, a manual material-fulfillment process in a vehicle production line was found to cause production delays of approximately 12 hours and an extension of the production cycle from 3–4 days to 5–6 days, largely due to the absence of a standard operating procedure and a structured fulfillment system (Gunawan et al., 2024). Following the design and implementation of a structured, system-based approach, delivery delays were reduced to only 1–2 working hours, demonstrating that the transition from a manual, ad hoc process to a structured, monitorable system can substantially improve production reliability. This finding reinforces the relevance of adopting a structured, system-based approach such as system dynamics to address the monitoring, tracking, and waste-management inefficiencies currently faced in the manual production process at PT XYZ Garment.

Despite growing awareness of sustainable practices, PT XYZ Garment has not yet implemented a structured approach to evaluate and manage the transition from its current linear production model toward a more sustainable, circular one. A circular economy approach which emphasizing reduction, reuse, and recycling, could effectively address this issue, but such a transition requires systemic changes that are complex and involve multiple interdependent variables, including material flow, waste generation rate, and resource utilization over time. Evaluating these dynamic interactions through direct trial in the actual production environment would be costly and risky; therefore, a simulation-based approach is required to assess the potential impact of a circular economy model before its implementation.

System dynamics provides an appropriate method to model and simulate these interdependent variables, enabling the prediction of system performance under both the existing linear model and a proposed circular economy scenario. By comparing these two scenarios, PT XYZ Garment can quantify the potential improvement in material efficiency and the reduction in disposed fabric waste resulting from a shift toward circular economy practices, providing a reliable basis for sustainability-oriented decision-making.

Based on the issues described above, this research is conducted to answer the following research question: How does the transition from a linear to a circular economy model affect the performance of the garment production system at PT XYZ Garment, as evaluated through a system dynamics simulation? Accordingly, this research aims to evaluate the current performance of the garment production system and to predict its performance under a circular economy model using a system dynamics approach.

2. Research Method

This study employs a quantitative simulation-based research design, using system dynamics as the primary analytical method to model and evaluate the garment production system at PT XYZ Garment under both a linear and a circular economy scenario. While the initial phase of the study draws on qualitative data collection to identify system variables and parameters, the core analytical work is quantitative in nature, involving the construction, calibration, and simulation of a stock-and-flow model over a defined time horizon. The research therefore adopts a pragmatic methodological stance, integrating qualitative data collection for system identification with quantitative modeling for scenario analysis and performance evaluation. This combination is consistent with established system dynamics research practice, in which model structure is informed by stakeholder knowledge and empirical data, while model behavior is evaluated through quantitative simulation (Sterman, 2000).

The research strategy is a single-site case study of PT XYZ Garment's production system, which is appropriate given the exploratory nature of the research questions and the need to capture contextual detail about the system's feedback structure (Saunders et al., 2023). The time horizon is cross-sectional: data were collected at a single point in time to represent the current ("as-is") system, while the simulation projects system behavior forward over a 208-week (four-year) period under two defined scenarios.

Research Procedure

The research was conducted in six sequential stages: (1) data collection and system identification; (2) dynamic hypothesis formulation and causal loop diagram (CLD) development; (3) stock and flow diagram (SFD) construction and parameterization; (4) model testing and validation; (5) baseline (linear) simulation; and (6) alternative (circular economy) scenario simulation and comparison.

Stage 1: Data Collection and System Identification

Primary Data Collection

Primary data were collected through semi-structured interviews with four categories of key stakeholders, as detailed in Table 1. The semi-structured format was selected to allow in-depth exploration of each stakeholder's perspective while maintaining thematic consistency across interviews (Saunders et al., 2023). Each interview was conducted individually, lasted approximately 30-90 minutes, and was recorded and transcribed for analysis.

Table 1. Respondent of semi-structured interview

No	Respondent	Description	Role in System	Number of Respondent
1	Head of Garment Production	Head of Garment Production which have a control and responsible of Garment Production Department	Decision-maker; oversees entire production process	1 Respondent
2	Garment Production Staff	Staff that work in Garment Production Department to support it operations.	Operational-level; executes daily production activities	2 Respondent
3	Garment Expert	An expert in Garmen which have a experience in garment for above 15 years	External advisor; 15+ years of industry experience	1 Respondent
4	Fabric Waste Utilizator/Craftmen	Individual or SME's that utilize the fabric waste to become a new products.	End-user of fabric waste; converts waste into craft products	2 Respondent

The interview protocol was structured around five thematic areas: (a) current production workflow and business processes; (b) current fabric waste generation, handling, and disposal practices; (c) awareness and prior experience with circular economy principles; (d) perceived challenges and benefits of CE adoption; and (e) expectations for a future CE-integrated production system. Responses from each stakeholder category were cross-referenced to triangulate findings and ensure data consistency before use in model parameterization.

Secondary Data Collection

Secondary data were collected from internal company records (historical production volumes, sales figures, demand data) and three external reference documents: ISO 9001:2015, which informed the customer satisfaction measurement framework; ISO 14001:2015, which informed the Green Image Factor (GIF) formulation; and the Ellen MacArthur Foundation (2013) report, which provided the theoretical basis for circular economy variable definitions and expected CE performance benchmarks.

Stage 2: Dynamic Hypothesis Formulation and CLD Development

Key variables identified from the interview data and literature review were organized into a Causal Loop Diagram (CLD) representing the feedback structure of the garment production system. The CLD was developed iteratively: an initial structure was derived from the literature, then refined through stakeholder validation to ensure it accurately reflected real-world system behavior. The system boundary was defined to include the following processes: raw material procurement, production, finished goods inventory, sales, demand management, customer satisfaction, fabric waste generation, fabric waste processing, craft production, and circularity rate. Variables external to the boundary, such as macroeconomic demand drivers and upstream supplier behavior, were treated as exogenous inputs or constants.

The CLD identifies three balancing loops and four reinforcing loops. The balancing loops govern demand backlog management, customer satisfaction, and fabric waste recycling. The reinforcing loops connect procurement, production, and sales to customer satisfaction, and connect the circularity rate to the Green Image Factor and production demand, capturing how improved sustainability performance positively feeds back into business growth.

Stage 3: SFD Construction and Parameterization

The CLD was translated into a quantitative Stock and Flow Diagram (SFD) using Vensim simulation software. Four stock variables were defined: Raw Material Inventory (initial value: 180 units), Finished Goods

(initial value: 75 units), Demand Backlog (initial value: 0), and Craft inventory (initial value: 0). Key flow and auxiliary variables, their equations, and data sources are summarized in Table 2.

Table 2. Key model parameters and data sources

Variable	Value / Equation	Source
Production Efficiency	0.85 (85%)	Garment Production Staff (Interview)
Production Capacity	100 units/week	Head of Garment Production (Interview)
Production Time	1 week	Garment Production Staff (Interview)
Distribution Time	1 week	Garment Production Staff (Interview)
Recycling Efficiency	0.70 (70%)	Literature review
Crafting Efficiency	0.98 (98%)	Fabric Waste Utilizer (Interview)
Demand	RANDOM NORMAL (60, 90, 75, 5, 42) × (1 + CS Effect + GIF Effect)	Historical production data (Interview)
Customer Satisfaction	IF-THEN-ELSE function of Demand Backlog % (scale 1–5)	ISO 9001:2015
Green Image Factor	Circularity Rate / (Sales + Craft Sales)	ISO 14001:2015
GIF Effect	Delay Information of GIF × 1.5	Expert Interview
CS Effect on Demand	(Delayed CS − 2) / 30	Expert Interview

To capture real-world demand variability, the Demand variable was modeled using a random normal distribution with a mean of 75 units/week and a standard deviation of 5. A Simple Moving Average (SMA) of the three preceding periods was used as the basis for procurement and production order decisions, reflecting a realistic short-term forecasting approach. Unit consistency throughout the model was maintained using four conversion unit (CU) auxiliary variables. The simulation period was set to 208 weeks (four years) with a weekly timestep, representing a sufficiently long horizon to observe the dynamic feedback effects of the circular economy transition on system-level performance indicators.

Stage 4: Model Testing and Validation

Both the linear and circular models were tested prior to simulation using eight structural validity criteria adapted from (Burns & Musa, 2001) : (1) clarity of implied causality; (2) existence and appropriate definition of all quantities and units; (3) existence of causal relationships; (4) causal sufficiency; (5) uniqueness of cause-effect assertions; (6) directionality of causal links; (7) identification of predicted side effects; and (8) absence of tautological definitions. In addition, Vensim's built-in unit consistency check and structural error check were applied. Both models passed all eight structural criteria and all Vensim error checks with no errors detected, confirming that the models are structurally valid and dimensionally consistent. All causal relationships were verified to be grounded in either empirical interview data or established literature, with no variables producing redundant or conflicting effects.

Stage 5 & 6: Baseline and Scenario Simulation

Two simulations were conducted on identical model structures, differing only in the inclusion of fabric waste recycling variables:

Linear Model (Scenario 1 as Baseline)*:* The model represents the existing production system in which all fabric waste is disposed of as landfill waste. This model does not include a recycling process, circularity rate, or Green Image Factor calculation.

Circular Economy Model (Scenario 2 as Alternative)*:* The model extends the linear structure by adding a fabric waste processing flow, a craft production stock, a circularity rate flow, and a Green Image Factor auxiliary variable. Fabric waste is redirected through an intermediary to craftsmen, who convert it into craft products at a crafting efficiency of 98%. The resulting circularity rate feeds back positively into the Green Image Factor, which in turn influences demand and expected production orders through the GIF Effect auxiliary variable.

Performance comparison between the two scenarios was conducted on five key indicators: total demand, total sales, average demand backlog, average customer satisfaction, and cumulative circularity rate over the 208-week simulation period.

3. Result and Discussion

This section presents the findings derived from the system dynamics modeling used to represent the current linear garment production system at PT XYZ Garment and to simulate a proposed circular garment production system. After both models were developed and simulated, a comparative analysis was conducted to evaluate the improvement achieved through the transition toward a circular economy approach.

System Dynamics Modeling

System dynamics is a methodology for understanding and addressing complex systems characterized by interdependent feedback loops and dynamic behaviors over time (Sterman, 2000). This approach is particularly relevant to the garment production system at PT XYZ Garment, where resource flows, fabric waste management, and production efficiency are deeply interconnected.

Dynamic Hypothesis Formulation and Causal Loop Diagram

Prior to constructing the Causal Loop Diagram (CLD), the system boundary was defined to delineate the scope of variables included in the model and those treated as exogenous. The system boundary encompasses the following core subsystems: raw material procurement, production process, finished goods management, demand and sales, customer satisfaction, fabric waste generation, fabric waste processing, craft production, and circularity performance. Variables outside the boundary, such as upstream supplier pricing, macroeconomic consumer behavior, and government regulatory changes, are treated as exogenous constants or random inputs, as their internal dynamics are beyond the scope of this study.

The dynamic hypothesis was formulated by constructing a CLD based on an extensive literature review, followed by semi-structured interviews with key stakeholders, such production staff, fabric waste managers, and circular economy practitioners, (to refine and validate the model structure. Several key insights from the interviews were incorporated to ensure the CLD reflects real-world system dynamics: embracing sustainability can improve brand reputation and subsequently drive higher revenue; recycling requires an upfront investment but generates substantial cost savings over time; eco-friendly practices attract loyal customers and strengthen competitive advantage; and implementing recycling initiatives is expected to increase business-to-business demand by approximately 40–75%, with direct consumer demand increasing by approximately 0–25%.

The resulting CLD, presented in Figure 1, captures the causal structure of the system through three balancing loops (B) and four reinforcing loops (R), each representing a distinct feedback mechanism within the production and waste management system.

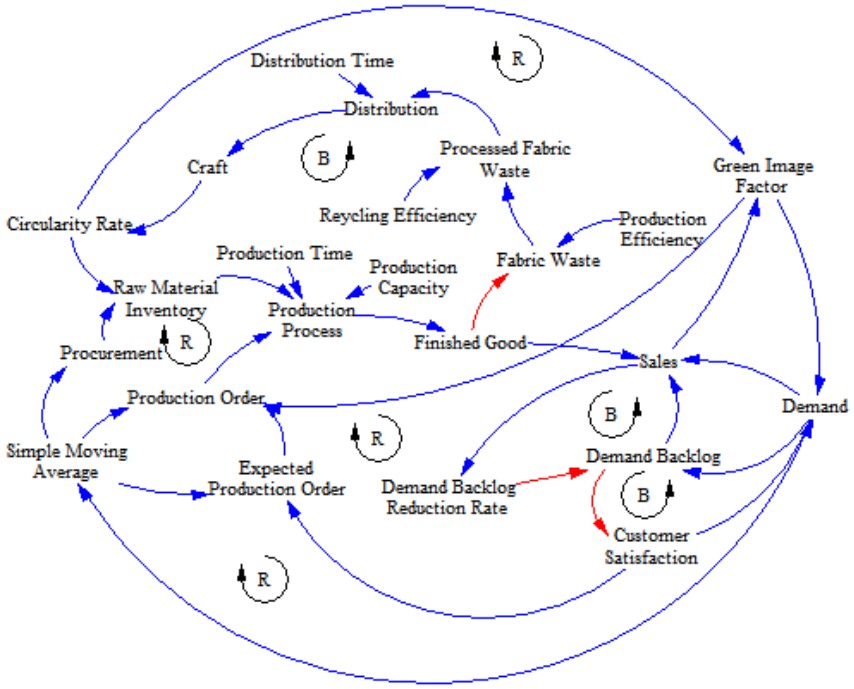


Figure 1. Causal loop diagram

The resulting CLD identifies three balancing loops and four reinforcing loops that govern system behavior. The balancing loops relate sales to demand backlog reduction, customer satisfaction to demand and backlog, and fabric waste processing to circularity rate and raw material inventory. The reinforcing loops connect procurement, production, and sales to customer satisfaction and demand, as well as circularity rate to the Green Image Factor and production order, illustrating how sustainability performance feeds back positively into production demand. Blue arrows indicate positive causal relationships (+), in which an increase (or decrease) in the origin variable produces a corresponding increase (or decrease) in the destination variable. Red arrows indicate negative causal relationships (−), in which an increase in the origin variable produces a decrease in the destination variable, and vice versa.

Model Development

The CLD was translated into a formal system dynamics model using Vensim, in which stocks, flows, and auxiliary variables were defined along with their causal relationships. Parameter values were derived from expert interviews and the literature review to ensure the model is both research-based and grounded in practical industry expertise.

Two models were developed for comparison: the Linear Garment Production model and the Circular Garment Production model. This comparison is intended to evaluate customer satisfaction in accordance with ISO 9001:2015 principles and to assess the Green Image Factor (GIF) in accordance with ISO 14001:2015 principles, allowing for a comprehensive assessment of operational strategy and sustainability performance (Alfani, 2023). Customer satisfaction is defined as a function of the demand backlog percentage, ranging from a rating of 5 (demand backlog below 10%) to a rating of 1 (demand backlog of 75–100%). The Green Image Factor, which reflects the market's perception of a manufacturer's ecological responsibility (Handfield et al., 2002), is calculated as a function of the circularity rate relative to sales.

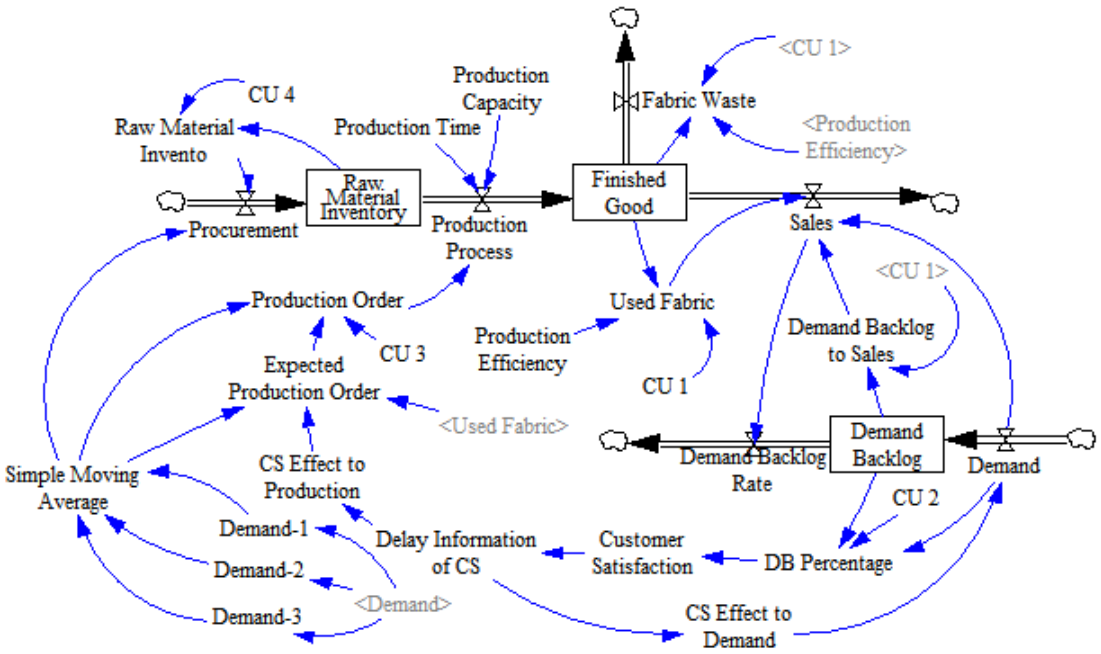


Figure 2. Linear garment production model

The Linear Garment Production model (Figure 2) represents the existing production process, from procurement to sales, with an emphasis on operational efficiency and demand fulfillment. This model does not incorporate a Green Image Factor calculation, reflecting the absence of recycling activity in the current system. Within this model, the demand backlog serves as a key indicator of customer satisfaction: a higher backlog corresponds to lower satisfaction, which subsequently reduces demand, while higher satisfaction reinforces customer loyalty and repeat demand.

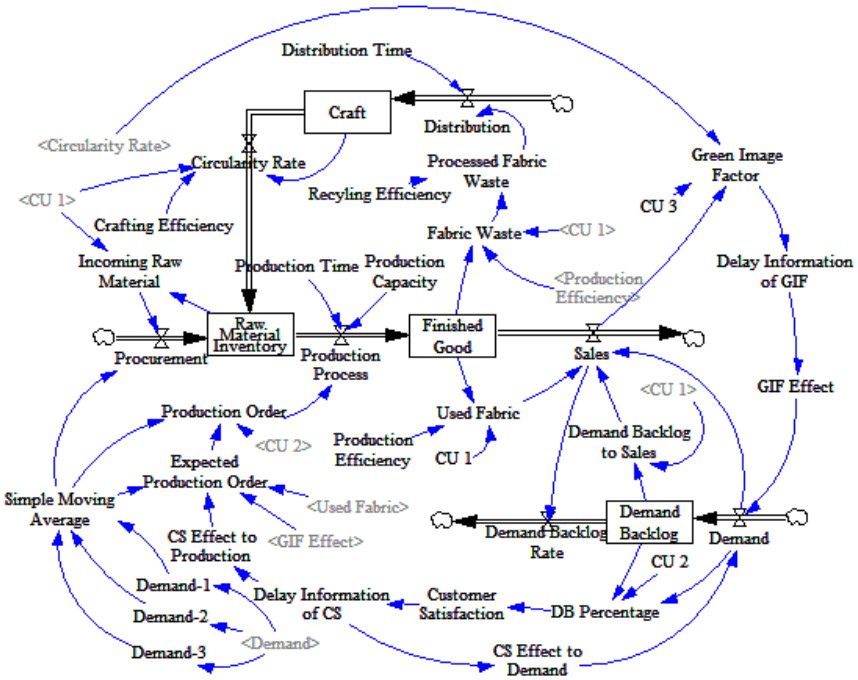


Figure 3. Circular garment production model

The Circular Garment Production model (Figure 3) builds upon the linear model by integrating a fabric waste management process, in which unused material is processed and distributed to craftsmen to be converted into new products. This model introduces the Green Image Factor (GIF) as an additional performance indicator, reflecting the system's dual focus on operational efficiency and environmental sustainability. Within this model, the recycling process positively influences the GIF, which in turn increases product demand and expected production orders, illustrating a reinforcing relationship between sustainability performance and business growth.

To ensure model transparency and replicability, the mathematical structure of the Circular Garment Production model is presented in full below. All stock variables are defined by integral equations representing their accumulation over time, while flow and auxiliary variables are defined by algebraic equations governing their rates and relationships. The unit of measurement for all production-related variables is **pieces (units)**, with time measured in **weeks**.

Stock Variables

The four stock variables, their integral equations, initial values, and units are presented in Table 3.

Table 3. Stock variable equations and initial values

Stock Variable	Equation	Initial Value	Unit
Raw Material Inventory	INTEG (Procurement + Circularity Rate − Production Process)	180	Pieces
Finished Goods	INTEG (Production Process − Fabric Waste − Sales)	75	Pieces
Demand Backlog	INTEG (Demand − Demand Backlog Reduction Rate)	0	Pieces
Craft	INTEG (Distribution − Circularity Rate)	0	Pieces
Stock Variable	Equation	Initial Value	Unit

The initial values of Raw Material Inventory (180 units) and Finished Goods (75 units) were derived from historical production records at PT XYZ Garment. Demand Backlog and Craft are initialized at zero, reflecting the absence of accumulated backlog and craft inventory at the start of the simulation period

Both models share the same core structure and parameter values, differing only in the variables associated with the recycling process, in order to allow for a direct and consistent comparison. The simulations were conducted over a 208-week period (equivalent to four years), using a weekly timestep. To capture real-world uncertainty, the Demand variable was modeled using a random normal distribution, while a conversion unit (CU) variable was applied throughout the model to maintain consistency of measurement units.

Flow Variables

The flow variables governing material and product movement through the system are defined in Table 4.

Table 4. Flow variable equations and units

Flow Variable	Equation	Unit
Demand	RANDOM NORMAL (60, 90, 75, 5, 42) × (1 + CS Effect to Demand + GIF Effect)	Pieces/week
Demand Backlog Reduction Rate	Sales	Pieces/week
Procurement	IF THEN ELSE (Incoming Raw Material ≤ (2 × IF THEN ELSE (SMA = 0, 75, SMA)), 5 × IF THEN ELSE (SMA = 0, 75, SMA), 0)	Pieces/week
Production Process	DELAY MATERIAL (IF THEN ELSE ((MIN (Production Capacity, Production Order)) ≤ 0, 90, MIN (Production Capacity, Production Order)), Production Time, 90, 0)	Pieces/week
Sales	MIN (Finished Goods − Used Fabric, (Demand Backlog to Sales + Demand))	Pieces/week
Fabric Waste	Finished Goods × (1 − Production Efficiency)	Pieces/week
Distribution	DELAY1 (Processed Fabric Waste, Distribution Time)	Pieces/week
Circularity Rate	Craft × Crafting Efficiency	Pieces/week

The Demand variable is modeled using a random normal distribution with a minimum of 60 units/week, a maximum of 90 units/week, a mean of 75 units/week, and a standard deviation of 5, reflecting empirically observed weekly demand variability at PT XYZ Garment. The Procurement equation implements a reorder policy based on the Simple Moving Average (SMA) of the three preceding demand periods: if current raw material inventory falls below twice the SMA, procurement is triggered at five times the SMA to replenish stock. The Production Process flow incorporates a one-week material delay (DELAY MATERIAL), reflecting the actual production lead time observed at PT XYZ Garment

Model Testing

Model testing was conducted using eight structural testing criteria, namely clarity, quantity existence and units, causality existence, cause insufficiency, additional cause, cause-effect reversal, predicted effect existence, and tautology (Burns & Musa, 2001), supplemented by Vensim's built-in unit and structural error checks.

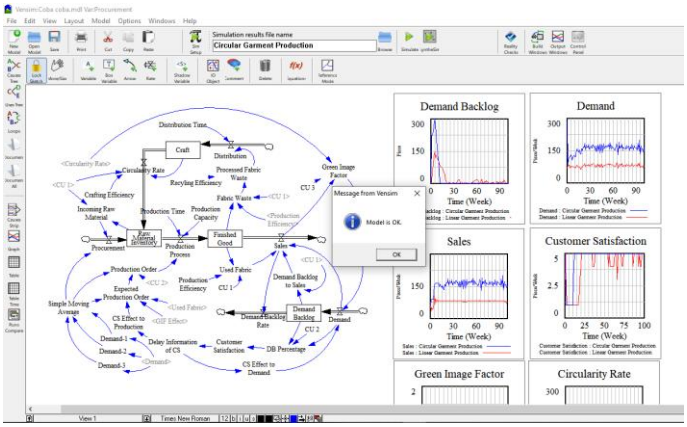


Figure 4. Model validations check in vensim

Both the Linear and Circular Garment Production models successfully passed all testing criteria with no errors detected. All variables were appropriately defined with consistent units, demonstrated clear and substantiated cause-and-effect relationships, and showed no redundant or conflicting causal links, confirming that both models are structurally valid for further simulation and analysis.

Simulation Results

Linear & Circular Garment Production Model

The simulation of both the Linear and Circular Garment Production models was conducted over a full 208 week (4 year) period, from which all cumulative performance statistics reported in the Model Comparison section (total demand, total sales, circularity rate, and average customer satisfaction) are derived. For visualization purposes, Figures 5 and 6 display the first 100 weeks of the simulation output, which is sufficient to observe the key dynamic behaviors of each model, its including the initial demand backlog peak, the stabilization phase, and the differentiation between linear and circular model performance. As the system reaches a relatively stable behavioral pattern by approximately week 40 and sustains it through week 208. The full 208-week cumulative figures are reported in Table 5.

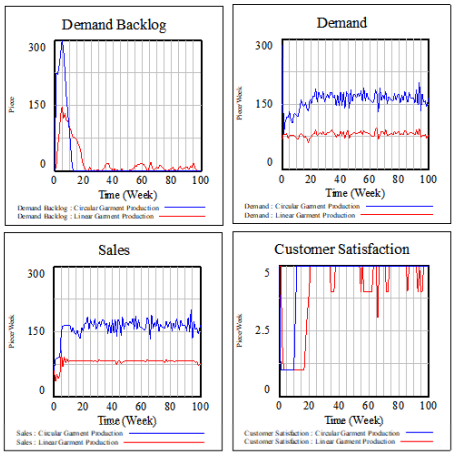


Figure 5. Linear and circular garment production result

The simulation comparing the Circular (blue line) and Linear (red line) Garment Production models over a 100-week period shows that the demand backlog in the circular model diminishes rapidly within the first 20 weeks and remains near zero for the remainder of the simulation, in contrast to the linear model, which peaks at approximately 300 pieces before stabilizing around week 20. Demand under the circular model is consistently higher, fluctuating between 150 and 300 pieces per week, compared to 50–100 pieces per week under the linear model, suggesting that enhanced production efficiency and sustainable practices help attract and retain customers. Sales mirror this demand pattern, with the circular model showing a consistent upward trajectory and sustained higher sales levels than the linear model. Customer satisfaction under the circular model remains consistently high, with an average score of approximately 5 throughout the simulation, whereas the linear model exhibits considerable volatility due to unmet demand and elevated backlogs.

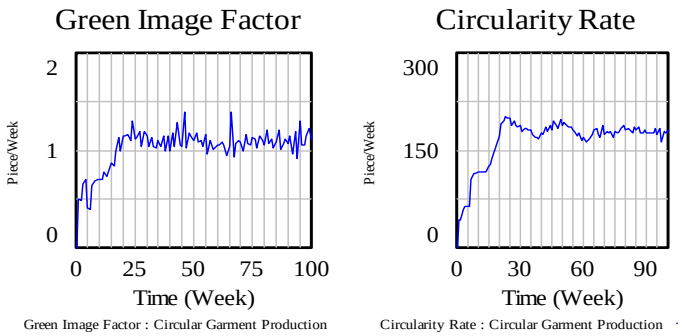


Figure 6. Circular garment production (green image factor & circularity rate result)

Figure 6 displays the Green Image Factor and Circularity Rate over the first 100 weeks of the circular economy simulation. The Green Image Factor (GIF) under the circular model exhibits considerable variability over the simulation period, with instantaneous values ranging from approximately 0.06 to 1.7. This wide range reflects the dynamic nature of the GIF equation, which defined as the ratio of the Circularity Rate to total Sales plus Craft Sales, and temporary misalignments between recycling output & sales volume during early simulation weeks can produce transient spikes in the GIF value. However, as the system stabilizes from approximately week 20 onward, the GIF converges toward lower, more stable values. The time-averaged mean GIF over the full 208-week simulation period is 0.0688, indicating that, across the entire simulation horizon, recycling efficiency accounts for approximately 6.88% of total sales on average. The apparent contrast between the peak value (1.7) and the mean (0.0688) is therefore consistent and reflects a right-skewed distribution in most weekly GIF values cluster near the lower bound of 0.06–0.07, with occasional short-lived peaks during early-period adjustment phases before the system reaches its dynamic equilibrium.

Model Comparison

A comparative analysis between the Linear and Circular Garment Production models was conducted to evaluate the extent of improvement achieved through the transition to a circular economy approach. The comparison shows a substantial increase in total demand and total sales of approximately 98% under the circular model, an increase in average customer satisfaction of approximately 10.8% (from a rating of 4.14 to 4.58), and a circularity rate that reaches full utilization of fabric waste (100%) under the circular model, compared to 0% under the linear model. The detail of the model comparison can be seen in Table 5 below:

Table 5. Comparison table between linear and circular model

Variable	Linear Model	Circular Model	Different	Percentage (%)
Total Demand	8122	16095	7973.56	98.18
Total Sales	8123	16096	7973.56	98.16
Average Demand Bakclog	20	22	2	10%
Circularity Rate	0	16575	16575.46	100.00
Average Customer Satisfaction	4.14	4.58	0.44	10.77

It is important to note that the slightly higher average demand backlog in the circular model compared to the linear model should not be interpreted in isolation as a sign of weaker performance. The circular model generates approximately 98% higher total demand (16,095 vs. 8,122 pieces), meaning the production system is processing a substantially larger volume of orders throughout the simulation period. When the average demand backlog is expressed as a proportion of total weekly demand, the backlog-to-demand ratio is lower in the circular model, indicating that the system fulfills a larger share of its considerably higher demand. The marginally higher absolute backlog therefore reflects the scaling dynamics of a faster-growing production system rather than a deterioration in fulfillment efficiency, and is consistent with the simultaneous improvement in average customer satisfaction from 4.14 to 4.58.

The simulation results showing substantially higher total demand and sales under the circular model are consistent with theoretical arguments in previous studies indicating that circular systems have the potential not only to reduce waste but also to generate economic benefits by enabling the reuse and recycling of materials (Geissdoerfer et al., 2017). These simulation-based findings suggest that, under the modeled assumptions, circular approaches may create additional product value and open new market opportunities; the patterns that have been observed empirically in sustainable garment production contexts where repurposed waste products generate consumer interest and expand market reach. Though empirical validation in the specific context of PT XYZ Garment would be required to confirm these effects.

The full utilization of fabric waste simulated in the circular model is structurally consistent with the core circular economy principles of reuse, recycling, and waste minimization (Stahel, 2016). The model demonstrates that, under the specified parameter values, a fabric waste repurposing mechanism through an intermediary and craftsmen-based structure is theoretically capable of achieving complete waste recovery, which finding that mirrors practices reported in leading sustainable garment industries, though real world implementation outcomes would depend on factors not fully captured within the current model boundary.

The simulated improvement in average customer satisfaction under the circular model aligns with findings that contemporary consumers increasingly value sustainability and favor businesses that adopt environmentally responsible practices (Kirchherr et al., 2017). This simulation based result suggests that the adoption of circular economy principles may have the potential to enhance brand reputation and customer loyalty through an improved green image. However, the magnitude of this effect in practice would depend on actual market response, which the current model approximates through expert-estimated parameters rather than empirically observed consumer behavior data.

Overall, the system dynamics simulation results indicate that the transition from a linear to a circular economy model has the potential to substantially improve PT XYZ Garment's production performance, customer satisfaction, and sustainability outcomes, while providing a quantifiable basis, for evaluating sustainability-oriented policy decisions prior to physical implementation.

4. Conclusion

This research examines the potential transition of the garment production system at PT XYZ Garment from a linear economy model to a circular economy model through a system dynamics simulation approach. The existing production system, which operates under a linear "take-make-dispose" framework, was modeled as inefficient in terms of fabric waste utilization, with all production waste disposed of as landfill waste despite its potential to be reused. The system dynamics simulation of this current linear model produced a circularity rate of 0%, an average customer satisfaction score of 4.14, and total demand and sales of approximately 8,000 pieces over the 208-week simulation period, suggesting that the absence of a waste recovery mechanism may constrain both the sustainability performance and the overall growth potential of the production system.

The proposed circular economy model, developed by integrating a fabric waste management process within the same system dynamics structure, produced substantially improved simulation outputs across all observed indicators. The simulation results show that the circular model is able to achieve full utilization of fabric waste under the specified parameter values, with a circularity rate reaching 16,575 pieces over the simulation period, an increase in simulated average customer satisfaction to 4.58, and a rise in simulated total demand and sales to approximately 16,000 pieces, which represent a simulated improvement of nearly 98% compared to the linear model. These simulation based findings suggest that a circular economy transition has the potential to reduce the environmental impact associated with fabric waste disposal and to improve customer satisfaction and demand through enhanced sustainability performance, as approximated by the Green Image Factor mechanism in the model.

Taken together, these findings indicate that a system dynamics approach provides a useful method for representing the dynamic interrelationships between production, waste management, and customer related variables in garment production systems, and for generating scenario based projections of the potential impact of a circular economy transition prior to physical implementation. The substantial performance gap between the two simulated scenarios provides a preliminary quantitative basis for PT XYZ Garment to consider developing a structured fabric waste management mechanism, supported by collaboration with intermediaries and craftsmen, as a strategic step toward a more sustainable and resilient production system.

Limitations

This study has several limitations that should be considered when interpreting the findings. The model was developed based on data from a single garment production unit, and the parameter values were derived from interviews and historical records specific to PT XYZ Garment, which may limit the generalizability of the results to other production contexts. The demand variable was modeled using a random normal distribution calibrated to historical data, meaning that structural market shifts driven by external factors such as economic changes or competitive disruption are not captured within the model. Additionally, the Green Image Factor parameter values were estimated through expert interviews rather than empirically validated against actual market data, introducing uncertainty into the magnitude of the simulated demand uplift. Finally, the cross-sectional data collection approach means that seasonal production fluctuations and long-term structural changes in the system are not fully represented in the model.

Suggestions for Future Research

Future research is encouraged in several directions. The model should be applied to garment companies of varying scales to assess the generalizability of the framework and identify context-specific moderating factors. The system boundary could be extended to incorporate upstream supplier dynamics, financial cost-benefit flows, and carbon emission accounting for a more comprehensive sustainability assessment. The Green Image Factor parameters should be empirically validated through longitudinal market research to strengthen the demand modeling component. Finally, integrating this system dynamics framework with an enterprise resource planning (ERP) system would enable real-time data feedback from actual production operations, allowing continuous model recalibration as production conditions evolve over time.

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