SUSTAINABLE FASHION DESIGN BASED ON THE LIFE CYCLE ASSESSMENT (LCA) FRAMEWORK

HA TU VAN [1], LUONG HOANG TUYET VAN [2*], TRAN THI KIM PHUONG [3], NGUYEN THI PHUONG ANH [4], BUI THI NHA NHA [5]

[1,2,3,] *Faculty of Garment Technology - Fashion Design, Industrial University of Ho Chi Minh City, Ho Chi Minh City, Vietnam,*

[4] *Smart Shirts Garments Manufacturing Bao Minh Company Limited, Ninh Binh Province, Vietnam.*

[5] *Undergraduate Student, Faculty of Garment Technology and Fashion, Industrial University of Ho Chi Minh City, Ho Chi Minh City, Vietnam.*

** Corresponding author: luonghoangtuyetvan9126@gmail.com.vn*

Abstract. This study focuses on integrating a simplified life cycle assessment (screening LCA) into the digital fashion design process to provide environmental information during the product development stage. Using Optitex 2D/3D software, a case study compares three dress designs with distinct structural characteristics to evaluate material efficiency and environmental indicators. The product selected for the empirical analysis is a women's casual dress (size M, 130 cm in length) made from 90 g/m² polyester crepe georgette fabric with a width of 1.37 m.

The results show that Design A achieved a marker efficiency of 81.71% and consumed 1.38 m of fabric; Design C achieved 75.22% and 1.45 m; and Design B achieved 66.51% and 2.18 m. Using Design B as a baseline, Design A and Design C utilized 36.70% and 33.49% less fabric, respectively. Based on screening factors for virgin polyester fiber, the estimated indicators for climate change, fossil resource depletion, and freshwater consumption for Design A, Design C, and Design B were 0.77, 0.81, and 1.22 kg CO_2e; 13.73, 14.43, and 21.69 MJ; and 3.35, 3.52, and 5.30 L, respectively.

Since the environmental indicators were estimated based on fabric mass using a consistent set of factors, the differences between the designs primarily reflect variations in fabric consumption. Consequently, these indicators serve as a basis for preliminary comparisons between design options rather than for an independent, comprehensive assessment of the product's total environmental performance. The results are limited to three designs and one material type. The results demonstrate the potential of combining Optitex data with screening LCA to support early-stage comparison of design alternatives.

Keywords. Sustainable fashion design; Life Cycle Assessment (LCA); Digital fashion design; 3D apparel design; Design-oriented LCA; Virtual prototyping.

1 INTRODUCTION

1.1 Research Context

The fashion industry is often characterized as a creative sector; however, a closer look reveals it to be one of the most resource-intensive industries. This is not merely a subjective opinion but is clearly evidenced by data. According to the United Nations Environment Program, the textile industry accounts for approximately 8-10% of global greenhouse gas emissions and consumes around 93 billion cubic meters of water annually [1]. Meanwhile, the Ellen MacArthur Foundation estimates that 92 million tons of textile waste are generated each year, with the vast majority ending up in landfills or being incinerated [2].

These figures indicate that the fashion industry's challenges are not confined to a single stage but are systemic, spanning the entire product lifecycle. From raw material extraction, manufacturing, and distribution to usage and disposal, every phase leaves a significant environmental footprint [3].

In the initial stage, fiber production-whether natural or synthetic-consumes vast amounts of water and energy and contributes to biodiversity loss and soil degradation [4]. Moving to the manufacturing phase, fabric dyeing and finishing processes are major sources of water pollution, accounting for approximately 20% of global industrial wastewater [1]. Furthermore, these processes generate significant air and soil pollutants [5].

Regarding synthetic fibers, the widespread use of polyester is linked to the release of microplastics into aquatic environments. Research by Browne et al. demonstrates that plastic microfibers can be released

© 2026 Ho Chi Minh City University of Industry

during washing and accumulate in the oceans, causing long-term impacts on marine ecosystems [6]. This highlights how the environmental impact of fashion extends into the product usage phase.

At the end-of-life stage, the issue becomes even more pronounced as the "fast fashion" model drives short-term consumption. As products are constantly replaced, the volume of textile waste rises rapidly, with the majority not being effectively reused [3]. This raises a direct question: is the pace of fashion development exceeding the environment's carrying capacity?

Against this backdrop, the shift toward sustainable fashion is no longer merely a trend but an imperative. European Commission policies have emphasized the role of design in minimizing environmental impact through a circular economy approach [7]. Notably, research suggests that approximately 80% of a product's environmental impact is determined at the design stage [8].

Consequently, design is not solely a matter of aesthetics; it is a pivotal stage for a product's Sustainability. In practice, however, design decisions remain driven primarily by trends, costs, and aesthetic appeal. Quantitative tools such as Life Cycle Assessment (LCA)-despite their long-standing presence-have yet to be effectively integrated into the design process, particularly within digital design environments. A distinct gap thus remains between "creative design" and "quantitative environmental assessment".

1.2 Research Problem

Although the role of design in determining environmental impact is widely acknowledged, the integration of sustainability factors into fashion design practice remains limited. In reality, design decisions often prioritize aesthetics and cost, while environmental considerations are addressed only at later stages of the value chain [5].

A primary reason for this is the lack of decision-support tools that can quantify environmental impact in a way that is both intuitive and compatible with the design workflow. While Life Cycle Assessment (LCA) is recognized as an effective method for evaluating product life cycles [9], its application in the fashion industry faces significant barriers, including complex data requirements, lengthy analysis times, and difficulties integrating it into creative design environments [9].

Concurrently, the development of digital design tools (2D/3D) has created new opportunities. These systems enable rapid prototyping, reduce the need for physical samples, and allow for design optimization before production. However, they largely focus on form and technical aspects, failing to integrate environmental metrics into the decision-making process [10].

Consequently, a research gap exists: an integrated approach that combines digital design and LCA, particularly during the early design stages. In other words, the question is not merely about "assessing environmental impact", but rather: Is it possible to embed this assessment directly into the design process itself?

This is precisely the focus of the present study.

1.3 Research Objectives and Questions

RESEARCH OBJECTIVES. This study aims to evaluate the feasibility of integrating digital design data with screening Life Cycle Assessment (LCA) to support comparisons of design options during the product development stage.

Specific objectives include:

- Comparing marker efficiency, fabric consumption, and waste rates across three design options under identical conditions
- Defining the scope and calculation method for a simplified LCA suitable for the design stage
- Comparing the three design options within the Optitex 2D/3D environment
- Assessing the applicability and limitations of screening LCA as a design support tool.

RESEARCH QUESTIONS. Based on the aforementioned objectives, the study addresses the following key research questions:

- RQ1: How do the three options differ in terms of marker efficiency, fabric consumption, and material waste?
- RQ2: How can material data from Optitex be converted into screening LCA indicators?

- RQ3: To what extent can screening results support design decision-making?
- RQ4: What limitations must be considered when interpreting environmental indicators calculated using fixed secondary coefficients?

RESEARCH CONTRIBUTIONS. In addition to addressing the research questions, the paper aims to make the following contributions:

- Academic: Providing quantitative case-study evidence regarding design, material usage, and screening environmental indicators.
- Methodological: Presenting a workflow for integrating digital design data with screening LCA.
- Practical: Supporting data-driven decision-making for designers.

2 THEORETICAL FRAMEWORK & LITERATURE REVIEW

2.1 Sustainable Fashion

CONCEPTS AND OBJECTIVES. Sustainable fashion is generally understood as an approach aimed at minimizing the fashion industry's negative environmental and social impacts throughout the product lifecycle [11]. This concept extends beyond merely "reducing impact" to imply systemic change-spanning everything from production methods to consumption patterns [12].

Sustainable fashion encompasses not only environmental considerations but also labor conditions, business models, and consumer behavior. Consequently, it is a multidimensional concept requiring appropriate supporting tools for implementation [12].

Furthermore, numerous studies have linked sustainable fashion to the Sustainable Development Goals (SDGs)-specifically SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action)-demonstrating that this is no longer solely an industry-specific issue but part of a global development strategy [13].

APPROACHES TO SUSTAINABLE FASHION.

Eco-Design.

Eco-design is considered the most direct approach to integrating environmental considerations into the design process. Rather than addressing consequences after the fact, eco-design aims to mitigate impact from the outset through the selection of materials, structural choices, and production processes [8].

In the context of fashion, eco-design involves not only material selection but also pattern layout and the optimization of material usage during the initial design phase.

Circular Calendar.

Circular fashion aims to replace the linear "take-make-dispose" model by extending the product lifecycle through reuse, recycling, and remanufacturing [2].

However, a closer look reveals that circular fashion does not begin with recycling; rather, it starts at the design stage, where the product's recyclability is determined.

Slow Calendar.

Slow fashion can be viewed as a response to fast fashion. Rather than prioritizing speed, it emphasizes quality, durability, and conscious consumption [14].

Under this approach, Sustainability depends not only on technology but also on how products are designed and used.

THE ROLE OF THE DESIGN PHASE. Numerous studies have demonstrated that the design phase plays a pivotal role in determining environmental impact, as choices regarding materials, structure, and manufacturing processes are established at the outset [12], [8].

Factors such as:

- Pattern layout
- Design complexity
- Material selection

This has a direct impact on the efficiency of material use and the level of waste generated.

However, despite the acknowledged importance of design, most research remains at a conceptual level. Quantitative tools to assist designers in making sustainable decisions in practice are still limited.

Therefore, a key consideration is the feasibility of integrating environmental assessment directly into the design process.

2.2 Product Life Cycle Assessment (LCA) Model

CONCEPT. Life Cycle Assessment (LCA) is a method for evaluating the environmental impact of a product throughout its entire life cycle, from raw material extraction to end-of-life disposal [9].

According to ISO 14040, LCA enables analysis of system inputs and outputs to identify potential environmental impacts [9]. A key strength of LCA is that it provides a comprehensive perspective, helping to avoid "impact shifting" between stages [15].

LCA STAGES.

A typical LCA study comprises four main stages:

- Raw material extraction
- Manufacture
- Use
- End of life cycle

Notably, many studies indicate that the raw material and production stages often account for a significant proportion of the total environmental impact of fashion products [16], [17].

ASSESSMENT INDICATORS.

Common indicators used in LCA include:

- Climate change (carbon footprint)
- Fossil resource use
- Freshwater consumption

These indicators help quantify environmental impacts and identify "hotspots" within the product life cycle [18].

LCA AS A DESIGN SUPPORT TOOL It is worth noting that LCA is not merely an assessment tool; it can also support design decision-making [15], [18].

However, in practice, the application of LCA during the design phase remains limited due to:

- Complex data requirements
- Time-consuming analysis processes
- Difficulty in integrating it into creative design environments.

2.3 LCA Applications in Fashion and Research Gaps.

Although Life Cycle Assessment (LCA) has been widely adopted in the fashion industry, its practical implementation faces numerous obstacles.

Recent studies indicate challenges, including a lack of reliable data, difficulties in standardizing results, and hurdles in integrating the process into design workflows [19], [20].

Furthermore, traditional LCA methods are often too complex for use in fast-paced product development environments [21].

In many instances, LCA is applied only after the product has already been defined, whereas direct integration into the design phase remains limited.

Additionally, existing research has yet to clearly analyze the relationships between pattern layout, design complexity, material usage, and environmental impact-factors that designers can directly control.

This paper aims to address this research gap.

2.4 Research Model (Conceptual Framework)

BASIS FOR MODEL CONSTRUCTION. The research model is developed based on the principles of eco-design and LCA, wherein design is regarded as the central intervention point for reducing environmental impact [8], [9].

The core of the model lies in the analysis sequence: design characteristics → pattern layout results → material mass → screening environmental indicators.

MODEL STRUCTURE. The model is structured according to the Input-Process-Output logic.

- Input (Design variables): pattern layout, design complexity, material selection
- Process: digital design (2D/3D) + screening LCA
- Output: material consumption, material waste, screening environmental indicators

SIGNIFICANCE OF THE MODEL.

The model enables:

- Linking design data with screening environmental indicators
- Quantifying design decisions
- Supporting the evaluation of design alternatives within a digital environment.

3 RESEARCH METHODS

3.1 Experimental Design

This study employed a comparative case study method in a digital design environment to assess material utilization efficiency and environmental screening indicators under controlled conditions.

Three casual dress designs with distinct structural characteristics were selected. At the same time, material type, body size, product length, fabric width, and marker-making conditions were kept constant to ensure a valid internal comparison.

- Design A: A basic dress with a simple structure and minimal components.
- Design B: A ruffled dress featuring a complex design with numerous components and cut lines.
- Design C: A square-neck dress with a waist tie, included as an additional structural variant to broaden the comparison across designs.

This approach allows for a focus on the observed differences between design structure and material utilization efficiency across the three case studies [22]. The inclusion of Design C enhances the diversity of the comparison and enables an assessment of whether the number of pattern pieces is the sole factor influencing marker efficiency. The results are not intended to establish causal relationships or to be generalized across the entire garment industry.



Figure 1. 3D garment simulation of Design A, Design B and Design C

3.2 Controlled Variables and LCA Scope

To ensure comparability, key design variables were held constant. The functional unit was defined as a woman's casual dress (Size M, 130 cm length) made from 90 g/m² polyester crepe georgette fabric (1.37 m width), using a one-way marker layout.

The scope of the screening LCA was limited to the stage from fossil raw material extraction to the production of virgin polyester fiber (cradle-to-gate, up to the fiber production stage). Fabric weaving, dyeing, and finishing, sewing, packaging, transportation, use, and end-of-life stages were excluded [23], [24].

Key assumptions: the fabric was treated as 100% polyester; fabric mass served as a proxy for fiber mass; and average coefficients were used as screening data in the absence of specific supply-chain data. Consequently, the results do not constitute a full LCA of the dress.

Design software: Optitex version 23.

- Optitex 2D (pattern development and marker making)
- Optitex 3D (garment simulation)

Fabric Material.

- Polyester Crepe Georgette
- Quantity: 90 g/m²
- Type: lightweight woven
- Drape length: medium-high

Fabric Width: 1.37m

Body Measurements.

- Size M
- Height: 160 cm
- Bust: 88 cm
- Waist: 64 cm
- Hips: 90 cm

Product Length: 130 cm (for all three models)

Marker Conditions. Markers were set up with:

- One-way layout
- No pattern piece rotation
- Grain direction maintained.

The markers used a single fabric layer 137 cm wide, and the results were based on the "Current Nesting" output within the Marker Area and Efficiency Evaluation window. Key settings include Opposite Piece: Up/Down; Orientation: Undefined; Rotation: 1-Way; Enable Folding: None; Piece Tilt, CCW Tilt, and CW Tilt = 0°; Shrink, X Shrink, and Y Shrink = 0%. The study does not compare different nesting algorithms.

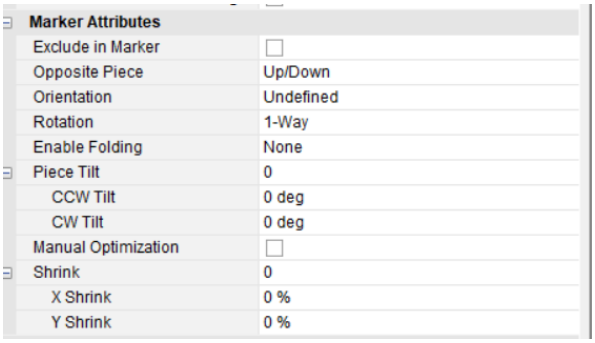


Figure 2. Marker condition settings interface

3.3 Pattern and Marker Design

Three designs were drafted using Optitex 2D and marker-laid to evaluate material utilization efficiency.

Design A - Basic dress.

- 12 items
- Marker efficiency: 81.71%
- Fabric consumption: 1.38 m

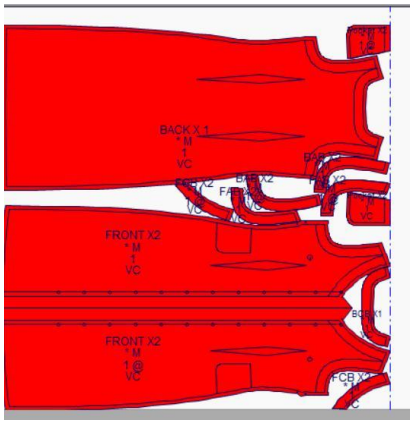


Figure 3. Marker layout - Design A

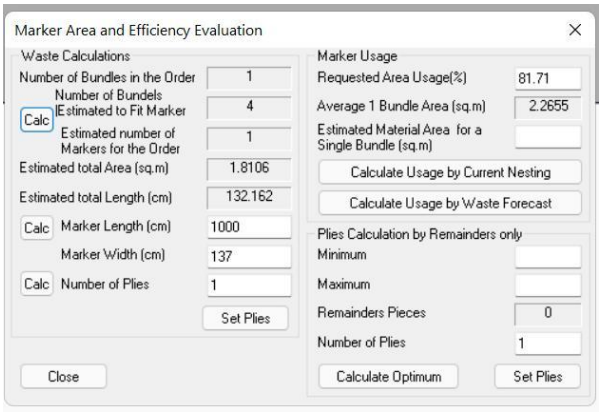


Figure 4. Marker evaluation - Design A

Design B - Ruffled dress.

- 17 details
- Marker efficiency: 66.51%
- Fabric consumption: 2.18 m

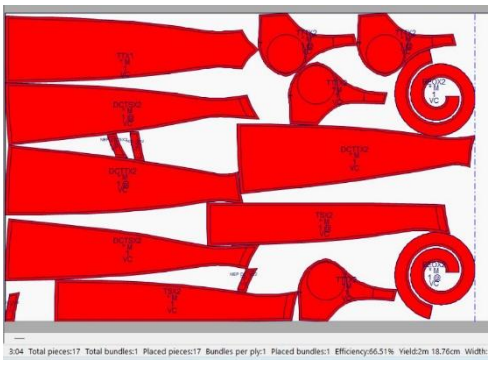


Figure 5. Marker layout - Design B

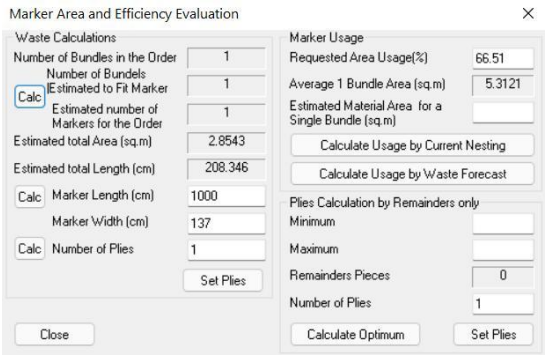


Figure 6. Marker evaluation - Design B

Design C - Square-neck dress with a waist tie.

- 11 pattern pieces
- Marker efficiency: 75.22%
- Fabric consumption: 1.45 m.

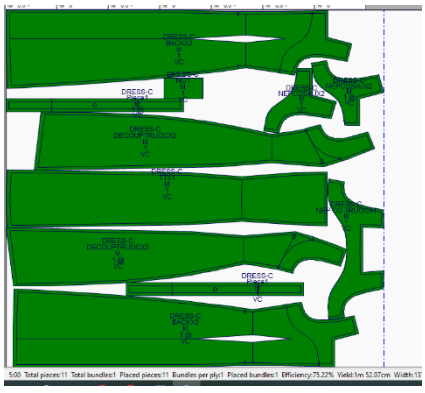


Figure 7. Marker layout - Design C

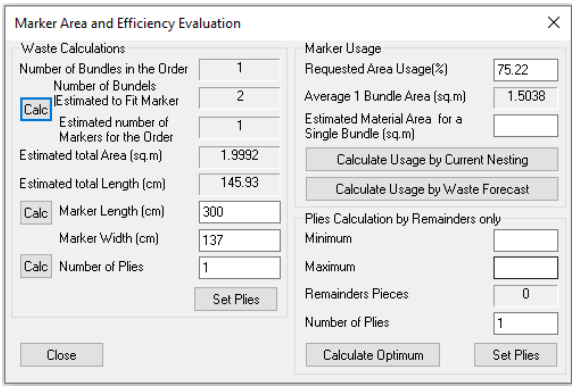


Figure 8. Marker evaluation - Design C

Among the three cases examined, Design A achieved the highest marker efficiency (81.71%), followed by Design C (75.22%) and Design B (66.51%). Notably, Design C consists of only 11 pattern pieces-fewer

than Design A (12 pieces) yet its marker efficiency remains lower than that of Design A. These results indicate that the number of pattern pieces is not the sole factor influencing marker efficiency; the shapes of the pieces, their dimensional proportions, and their nesting capabilities on the fabric width must also be considered. Given the three-case study design, the results are interpreted as observed differences rather than evidence of a causal relationship or statistical significance.

3.4 3D Simulation

Three designs were simulated in Optitex 3D to:

- Evaluate the fit
- Assess the drape
- Confirm feasibility

The use of 3D simulation facilitates the early-stage evaluation of fit, relative drape, and assembly feasibility [10]. All three designs used the same M-size avatar and material profile in Optitex 23; the 3D simulation results were not directly incorporated into the screening LCA calculations.

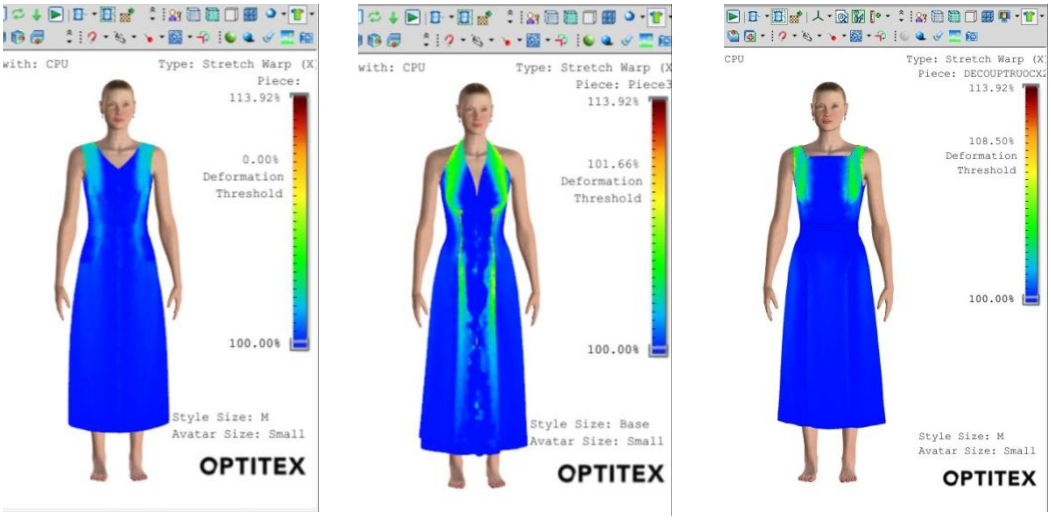


Figure 9. Simulation - Design A, Design B, and Design C

3.5 Evaluation Metrics

(1) Material Utilization Efficiency

- Marker efficiency (%)
- Fabric consumption (m)

The data was extracted directly from the Optitex software.

(2) Material Waste.

$$\text{Waste} = 100\% - \text{Efficiency}$$

- Design A: 18.29%
- Design B: 33.49%
- Design C: 24.78%

(3) Environmental Impact (Screening LCA). Due to limitations in supply chain data, the study employs a screening LCA based on material Mass and secondary data. This approach is intended for internal comparison during the early design stage and does not replace a full LCA study [21].

Fabric mass calculation formula:

$$\text{Mass} = L \times W \times GSM$$

In there:

- Mass (kg): The mass of fabric used for one product.
- L (m): Fabric consumption length, taken from marker results.

  - W (m): Fabric width
  - GSM (kg/m²): Fabric weight (grams per square meter), converted from g/m² to kg/m².
- Design A: 1.38 × 1.37 × 0.09 = 0.170 kg
- Design B: 2.18 × 1.37 × 0.09 = 0.269 kg
- Design C: 1.45 × 1.37 × 0.09 = 0.179 kg

(4) Screening LCA Factors for Virgin Polyester Fiber.

- Climate change: 4.55 kg CO_2e/kg
- Fossil resource depletion: 80.7 MJ/kg
- Freshwater consumption: 19.7 L/kg
- The factors represent average values for 1 kg of virgin polyester staple fiber, sourced from the LCA technical report by Textile Exchange and SCS Consulting Services [24]. The report employs a cradle-to-gate boundary, spanning from raw material extraction to yarn production. As the material under study is finished georgette crepe fabric, the yarn-stage coefficients are used as proxy data for screening purposes.
- Result:

Table 1. Screening LCA results based on average virgin polyester staple-fiber factors

Index	Design A	Design B	Design C
Climate change (kg CO_2e)	0.77	1.22	0.81
Depletion of fossil resources (MJ)	13.73	21.69	14.43
Freshwater consumption (L)	3.35	5.30	3.52

Since the same coefficient is applied to all three designs, the relative differences among the three environmental indicators correspond to the relative differences in fabric mass. Consequently, these indicators are calculation results dependent on the material, rather than three independent verifications of environmental performance.

4 FINDINGS

4.1 Comparing Material Usage Efficiency

The marker layout results reveal distinct differences in material utilization efficiency among the three design options.

Specifically, Design A (a basic-style dress) achieved the highest marker efficiency at 81.71%, followed by Design C (a square-neck dress with a waist tie) at 75.22%, while Design B (a ruffled dress) achieved 66.51%. Compared to Design B, Design A showed a 15.20 percentage-point advantage, and Design C showed an 8.71 percentage-point advantage. The results indicate that Design C falls between Design A and Design B in terms of marker efficiency under controlled conditions.

Material consumption for Design A, Design C, and Design B was 1.38 m, 1.45 m, and 2.18 m, respectively. Using Design B as the consistent baseline for this study, Design A utilized 36.70% less fabric, and Design C utilized 33.49% less. Compared to Design A, Design C required an additional 0.07 m of fabric, representing an increase of approximately 5.07%.

The results demonstrate significant differences in marker efficiency and fabric consumption among the three designs under controlled conditions. These differences serve as the basis for the screening calculations presented in subsequent sections.

4.2 Material Waste Analysis

Based on marker efficiency, the material waste rate was 18.29% for Design A, 24.78% for Design C, and 33.49% for Design B. Compared to Design B, the waste rate for Design A was 15.20 percentage points lower, and that for Design C was 8.71 percentage points lower. Notably, Design C consists of 11 pattern pieces-fewer than the 12 in Design A-yet its waste rate is 6.49 percentage points higher than Design A's.

These results reinforce the conclusion that material utilization efficiency is determined not only by the number of pattern pieces but also by their shapes, dimensional proportions, and the way they can be

arranged within the marker. However, based on these three case studies, it is not yet possible to conclude that any single factor is the independent cause of the observed waste levels.

4.3 Environmental Impact Assessment (LCA - simplified)

In this study, environmental impact was estimated using a screening LCA based on three indicators: climate change, fossil resource depletion, and freshwater consumption. Design A resulted in 0.77 kg CO_2e, 13.73 MJ, and 3.35 L; Design C resulted in 0.81 kg CO_2e, 14.43 MJ, and 3.52 L; and Design B resulted in 1.22 kg CO_2e, 21.69 MJ, and 5.30 L. Using Design B as the baseline, the values for Design A and Design C were 36.70% and 33.49% lower, respectively, across all three indicators.

The uniform reduction across the three indicators is a direct consequence of the calculation method: the fabric mass of each design was multiplied by the same coefficient per kilogram of material. Consequently, fabric mass serves as the computational variable linking design data to environmental coefficients; the results do not demonstrate a mediating role in the statistical sense, nor do they represent independent confirmation across the three indicators.

4.4 The Relationship between Design and Environmental Impact

Among the three cases examined, Design A achieved the highest marker efficiency and the lowest fabric consumption, while Design B showed the lowest efficiency and the highest consumption; Design C fell between the other two in terms of marker efficiency, fabric consumption, and screened environmental indicators. The sequence “design characteristics → marker layout results → material quantity → screened environmental indicators” served as the studys analytical framework.

As the study involved no sample replication and no statistical testing, the results merely describe the differences among the three cases under controlled conditions. The findings should not be interpreted as indicating correlations, causal relationships, or the environmental performance of the product’s entire lifecycle.

4.5 Summary of Results

Table 2. Summary comparison among Design A, Design B, and Design C.

Index	Design A	Design B	Design C
Marker efficiency (%)	81.71	66.51	75.22
Fabric consumption (m)	1.38	2.18	1.45
Material waste (%)	18.29	33.49	24.78
Climate change (kg CO_2e)	0.77	1.22	0.81
Fossil resource depletion (MJ)	13.73	21.69	14.43
Freshwater consumption (L)	3.35	5.30	3.52

The aggregated results indicate that design options can lead to differences in material efficiency across the three cases examined; within the defined scope of the screening LCA, variations in material Mass translate directly into differences in estimated environmental indicators.

Therefore, the primary value of these results lies in their ability to provide early quantitative feedback for comparing design options, rather than establishing a universal rule applicable to all apparel products.

5 DISCUSSION

5.1 The Role of Design Decisions in Reducing Environmental Impact.

The results indicate that the three design options differ in terms of marker efficiency and fabric consumption under identical controlled conditions. Design A used the least fabric, followed by Design C, while Design B used the most; since the same set of coefficients was applied, the ranking of the screened environmental indicators corresponded to material usage.

These findings align with the view that the design phase plays a crucial role in determining a product’s materials, structure, and manufacturing processes [8]. In this study, this role is illustrated by marker layout data and material consumption figures from three specific cases.

Consequently, providing quantitative feedback during the design process can facilitate the selection of more

material-efficient options before physical prototyping.

5.2 The Relationship between Design Complexity and Material Efficiency

Among the three experimental cases, Design B comprised 17 pattern pieces and exhibited the lowest marker efficiency (66.51%), whereas Design A consisted of 12 pieces and achieved the highest efficiency (81.71%). However, Design C-despite having only 11 pieces-showed a marker efficiency of 75.22%, which was 6.49 percentage points lower than Design A's. These additional results indicate that the number of pattern pieces alone is insufficient to explain the efficiency of material utilization. Factors such as pattern shapes, the proportions between pieces, curvature, and nesting capabilities on the fabric width can simultaneously influence marker-making outcomes. Therefore, the current study design cannot be used to assert a generalized inverse relationship between "complexity" and marker efficiency.

This finding aligns with research by Subramanian Senthilkannan Muthu, which indicates that product structure and pattern design directly impact material consumption and waste generation during production [16].

Furthermore, studies on garment manufacturing suggest that complex designs often reduce the efficiency of the cutting and sewing processes due to the difficulty of optimizing piece layouts and the increased technical operations involved [5].

It should be noted that material efficiency must be balanced against aesthetic, functional, and manufacturability requirements. The screening results do not imply that a simpler-structured design is inherently superior.

5.3 Relate This to The LCA Model and Previous Studies.

Environmental indicators vary in direct proportion to material Mass because they are calculated using fixed coefficients. Consequently, this result does not serve as independent confirmation of LCA trends but rather as a quantitative illustration of the impact of material quantity within the defined screening boundaries [19].

According to research by Salik Ahmed et al., resource consumption and emissions in the fashion industry are concentrated primarily in the material production and textile processing stages [19].

The study's main contribution lies in using pattern data, marker layouts, and numerical simulations to generate screening-level environmental feedback during the design phase itself, rather than proposing a new LCA methodology.

This approach is a shift from post-design assessment to design-integrated screening assessment.

5.4 Research Contributions and Practical Implications

This study presents a process that integrates 2D pattern data, 3D simulation, marker-making results, and screening-level Life Cycle Assessment (LCA) within the product development workflow. The value of this method lies in clearly defining the functional unit, control conditions, system boundaries, data sources, and interpretation limits to facilitate internal comparisons between design alternatives.

Empirical results demonstrate that three different dress constructions yield varying levels of material consumption. The inclusion of "Design C" further reveals that the number of pattern pieces is not the sole indicator of marker efficiency, thereby highlighting the importance of geometry and the spatial arrangement of pieces on the marker. Additionally, the study shows that digital design tools can support sustainable decision-making when material data is transparently linked to screening metrics [20].

In practical terms, this process enables designers, businesses, and educational institutions to compare design variations rapidly before physical prototyping. However, screening results must be balanced against functionality, aesthetics, and manufacturability, and should not be used as the basis for commercial environmental claims [8].

5.5 Limitations and Future Research

The study has several limitations. First, only three designs and one material type were investigated, limiting generalizability. Second, the screening LCA relied on secondary data for the virgin polyester fiber stage and excluded the weaving, dyeing, and finishing, garment assembly, transportation, usage, and end-of-life phases. Third, the study lacked sample replication or statistical testing. Furthermore, certain detailed

parameters of the 3D simulation solver were not fully documented; consequently, the 3D simulation was used solely to verify form and assembly feasibility rather than for LCA calculations.
Future research should expand the range of designs, materials, sizes, and fabric widths; fully document software parameters and pattern-making algorithms; utilize primary data from suppliers; validate findings through actual cutting and sewing; and conduct sensitivity analyses on environmental coefficients. These steps will help determine whether the observed trends hold under different production conditions.

6 CONCLUSIONS

This study conducted a comparative case analysis of three dress designs using Optitex data and screening-level Life Cycle Assessment (LCA). Based on identical material, size, product length, fabric width, and marker-making parameters, Design A achieved a marker efficiency of 81.71% and consumed 1.38 m of fabric; Design C achieved 75.22% and consumed 1.45 m; and Design B achieved 66.51% and consumed 2.18 m.
Using Design B as the baseline, Designs A and C consumed 36.70% and 33.49% less fabric, respectively; material waste rates were 18.29%, 24.78%, and 33.49% for Designs A, C, and B, respectively. Notably, although Design C comprised fewer pattern pieces than Design A, it exhibited lower marker efficiency, indicating that the number of pattern pieces is not the sole determinant of marker-making efficiency.
Based on cradle-to-gate coefficients for virgin polyester fiber, the estimated values for Designs A, C, and B were 0.77, 0.81, and 1.22 kg CO_2e; 13.73, 14.43, and 21.69 MJ; and 3.35, 3.52, and 5.30 L of freshwater, respectively. The proportional differences were identical because they were calculated directly from material Mass using fixed coefficients; consequently, the results do not demonstrate statistical correlation, mediating roles, or the impact of the product's entire life cycle.
The findings indicate that integrating marker-making data with screening-level environmental metrics can help designers identify options that minimize material use before physical prototyping. The study's practical value lies in its ability to provide quantitative feedback during the early design stage. Given that the scope is limited to three designs, one material type, and secondary fiber-level LCA data, the results are valid only for internal comparison under the stated conditions. They cannot be generalized to the entire fashion or apparel industry.
Based on these limitations, future studies could expand in the following directions:

- Compare various types of materials
- Integrate more detailed LCA data
- Scale up experiments
- Apply artificial intelligence to design optimization

Overall, the study demonstrates the potential of integrating digital design data with screening LCA to support decision-making in the product development phase. Further research is needed to expand the scope of experiments and lifecycle data to verify applicability under different manufacturing conditions.
In the three-design case study, the results demonstrate the practical feasibility of integrating screening LCA into a digital garment-design workflow while ensuring that conclusions are proportional to the defined system boundary.

REFERENCES

[1] United Nations Environment Program (UNEP), *Sustainability and Circularity in the Textile Value Chain*, 2020. https://www.unep.org/resources/report/sustainability-and-circularity-textile-value-chain.

[2] Ellen MacArthur Foundation, *A New Textiles Economy*, 2017. https://ellenmacarthurfoundation.org/a-new-textiles-economy.

[3] S. Ahmed, P. Sospiro, I. Voukkali, and A. Zorpas, "Advancing Organisational Life Cycle Assessment in the Fashion Industry: Strategies for Sustainable Corporate Practices", *Proceedings of GNC 2025*, vol. 19, Oct. 2025. https://doi.org/10.30955/gnc2025.00048.

[4] M. Bildirici, I. Türkkahraman, and Ö. Ö. Ersin, "Unraveling the Environmental Impacts of the Fashion Industry: A Fourier-Based Analysis of Pollution Dynamics and Causality Across Five Countries," *Sustainability*, vol. 17, no. 1, 2024. https://doi.org/10.3390/su17010069.

[5] A.-R. Ragab, A. Al-Gizawy, O. Al-Minyawi, A. Hassabo, and M. Mahmoud, "Environmental Impact of Clothing Manufacturing and the Fashion Industry", *Egyptian Journal of Textile and Polymer Science*, 2024. https://doi.org/10.21608/jtcps.2024.259253.1298.

[6] M. A. Browne, T. S. Galloway, and R. C. Thompson, "Accumulation of microplastic on shorelines worldwide: Sources and sinks", *Environmental Science & Technology*, vol. 45, no. 21, pp. 9175–9179, 2011. https://doi.org/10.1021/es201811s

[7] European Commission, *Circular Economy Action Plan*, 2020. https://ec.europa.eu/environment/circular-economy/.

[8] European Commission, *Ecodesign Directive*, 2019. https://ec.europa.eu/environment/eussd/smgp/.

[9]International Organization for Standardization *ISO 14040: Life Cycle Assessment*, 2006. https://www.iso.org/standard/37456.html.

[10] McKinsey & BoF, *The State of Fashion 2020*, 2020. https://www.mckinsey.com/industries/retail/our-insights/the-state-of-fashion-2020.

[11] M. P. Mizrachi and A. Tal, "Sustainable Fashion-Rationale and Policies," *Sustainability*, vol. 14, no. 13, 2022. https://www.researchgate.net/publication/361294519_Sustainable_Fashion-Rationale_and_Policies.

[12] C. E. Henninger, P. J. Alevizou, and C. J. Oates, "What is sustainable fashion?" *Journal of Fashion Marketing and Management*, vol. 20, no. 4, pp. 400–416, 2016. https://www.researchgate.net/publication/303546323_What_is_sustainable_fashion.

[13] P. Das et al., "Sustainable fashion and sustainable development goals nexus: A review," *Cleaner and Responsible Consumption*, vol. 11, 2026. https://www.sciencedirect.com/science/article/pii/S2666784326000112.

[14] M. Domingos, M. Vale, and A. Faria, "Slow Fashion Consumer Behavior: A Literature Review," *Sustainability*, vol. 14, 2022. https://etica.uazuay.edu.ec/sites/etica.uazuay.edu.ec/files/public/sustainability-14-02860-v2.pdf.

[15] M. A. Curran, *Life Cycle Assessment Student Handbook*, Hoboken, NJ, USA: Wiley, 2015.

[16] S. S. Muthu, *Assessing the Environmental Impact of Textiles and the Clothing Supply Chain*, Cambridge, UK: Woodhead Publishing, 2014.

[17] European Environment Agency, *Textiles and the Environment in a Circular Economy*, 2019. https://www.eea.europa.eu/publications/textiles-in-europes-circular-economy.

[18] UNEP/SETAC Life Cycle Initiative, *Global Guidance for Life Cycle Impact Assessment Indicators*, 2016. https://www.lifecycleinitiative.org.

[19] S. Ahmed, M. C. Liscio, I. Papamichael, P. Sospiro, I. Voukkali, and A. A. Zorpas, "Life cycle assessment to advance the fashion industry's sustainability: A review," *Waste Management & Research*, Jun. 2025. https://doi.org/10.1177/0734242x251343793.

[20] K. Dhiwar and M. Bedarkar, "Life cycle assessment in the fashion industry: a systematic review," *Discover Sustainability*, vol. 6, no. 1, Nov. 2025. https://doi.org/10.1007/s43621-025-02050-7.

[21] R. da Rosa Selhorst and A. Silva, "Bridging the gap: streamlining life cycle assessment for practical application in product development," *Proceedings of the Design Society*, vol. 5, pp. 791–801, Aug. 2025. https://doi.org/10.1017/pds.2025.10093.

[22] J. Fan and L. Hunter, *Engineering Apparel Fabrics and Garments*. Cambridge, UK: Woodhead Publishing, 2009. https://www.sciencedirect.com/book/9781845694112/engineering-apparel-fabrics-and-garments.

[23] International Organization for Standardization, *ISO 14040: Environmental Management – Life Cycle Assessment – Principles and Framework*, International Organization for Standardization, 2006. https://www.iso.org/standard/37456.html.

[24] Textile Exchange and SCS Consulting Services, Life Cycle Assessment for Polyester (Virgin and Recycled Production Systems): Technical Report. Textile Exchange, June 2026