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Integrating 3D Virtual Garment Simulation and Pre-Order Systems to Reduce Production Waste in Fashion Small and Medium-Sized Enterprises

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ABSTRACT: Physical sampling and forecast-based production contribute substantially to material waste in fashion small and medium-sized enterprises (SMEs). However, 3D virtual garment simulation and demand-driven production have generally been investigated as separate waste reduction strategies. This study aimed to develop and validate a proof-of-concept model (Technology Readiness Level 3, TRL 3) integrating 3D virtual garment simulation and a pre-order system as sequential decision-making stages before production. A five-stage research and development approach was employed, incorporating a structured literature review, a needs assessment involving 22 informants from 15 purposively selected fashion SMEs in Malang, Indonesia, and expert validation. Five experts evaluated the proposed model using 12 indicators on a five-point Likert scale, with feasibility percentages and Aiken's V applied to assess feasibility and content validity. Two major sources of waste were identified: physical sampling during product development and production–demand mismatches. The proposed model incorporated two decision gates: design and fit validation using CLO3D (Gate 1) and order confirmation based on a minimum order quantity (Gate 2). Production was initiated only after both requirements were satisfied. The model achieved an overall feasibility score of 89.33% (mean = 4.47/5) and an Aiken's V coefficient of 0.87. Eleven of the 12 indicators satisfied the content validity criterion, whereas consumer interface accessibility remained below the threshold (V = 0.75). These findings demonstrated the model's preliminary feasibility and content validity, although its effectiveness in reducing material waste has not yet been empirically established. Future studies should evaluate its performance through fabric utilization efficiency, production lead time, and inventory management indicators.

KEYWORDS: Virtual prototyping; demand-driven manufacturing; stage-gate decision model; deadstock prevention; material efficiency

1. Introduction

The textile and fashion industry is among the largest contributors to global waste generation, producing more than 92 million tonnes of textile waste annually, while only approximately 1%

of discarded textiles are recycled into new garments [1]. Fabric remnants, unsold garments, and inefficient production practices contribute substantially to this environmental burden. Addressing these challenges requires a fundamental transformation of production processes rather than relying solely on end-of-pipe waste management strategies [2]. Conventional garment development frequently involves repeated physical sampling to evaluate design accuracy, garment fit, and product quality, resulting in additional material consumption and waste generation [3]. Although digital transformation offers opportunities to improve production efficiency and sustainability, its adoption in fashion manufacturing remains uneven, particularly among SMEs, where technological applications are often implemented independently rather than integrated into comprehensive production workflows [4].

Fashion SMEs face two interconnected sources of material waste. The first arises during product development, when repeated physical sampling consumes fabric, accessories, labor, and production resources before a design is finalized. The second originates from forecast-based production, in which garments are manufactured according to anticipated rather than confirmed consumer demand. This practice increases the likelihood of overproduction, excess inventory, and unsold products [5]. Both processes involve committing materials and production resources before design suitability or market demand has been adequately verified. Consequently, reducing waste at these stages is essential not only for improving environmental performance but also for strengthening operational efficiency and business competitiveness. Sustainability-oriented innovation can further enhance SME competitiveness when supported by collaboration among producers, customers, and other stakeholders [6].

In this study, production waste refers specifically to materials and resources committed before design validation or demand confirmation. This includes fabric, accessories, labor, and machine time associated with repeated or unsuccessful physical sampling, as well as finished garments produced beyond confirmed demand that subsequently become unsold inventory. Other sources of production waste, including cutting offcuts, defective garments, and manufacturing rework, are acknowledged but are not directly addressed by the proposed model. Fabric utilization efficiency is instead considered a potential performance indicator for subsequent empirical evaluation. Establishing this scope is necessary to distinguish waste prevention during pre-production decision-making from waste minimization during manufacturing operations.

Three theoretical perspectives provide the foundation for addressing these challenges: lean manufacturing, postponement theory, and the stage-gate approach. Lean manufacturing identifies overproduction as a major source of inefficiency because it contributes to excessive inventory and generates additional waste throughout the production system [7]. Postponement theory emphasizes delaying material and production commitments until reliable demand information becomes available, thereby reducing uncertainty and unnecessary resource utilization [8]. Meanwhile, the stage-gate approach structures product development into sequential stages separated by decision points, at which predefined criteria determine whether a product should proceed to the next stage [9]. Integrating these perspectives suggests that physical sampling and forecast-based production represent two forms of premature resource commitment that could be addressed through sequential validation mechanisms before mass production.

Three-dimensional (3D) virtual garment simulation offers a promising technological approach to reducing waste during product development. Virtual design technologies enable

designers to construct, visualize, and evaluate garments digitally before producing physical samples, potentially reducing material consumption, development costs, and production lead times [10]. A review of CLO3D, Optitex, Lectra, and Browzwear demonstrated the potential of virtual garment simulation to improve sampling efficiency while identifying technological and organizational barriers to implementation [11]. Previous studies have reported improvements in sample development efficiency through virtual simulation [12], reductions in energy consumption compared with conventional sampling [13], and positive experiences among designers using virtual prototyping to minimize sample-related waste [14]. In Indonesia, 3D virtual technologies have also been introduced to accelerate fashion product development [15]. Nevertheless, these applications primarily address design validation and do not directly resolve overproduction caused by uncertain consumer demand.

Demand-driven production offers a complementary strategy by aligning manufacturing decisions with confirmed customer orders. A pre-order system enables producers to obtain information about product quantities, sizes, and specifications before committing materials to production. Previous research has demonstrated that presenting products through digital visualizations before manufacturing can help reduce unnecessary production and material waste [16]. Similarly, mass customization approaches have shown that production planning, sizing, and cutting decisions can be optimized when actual customer requirements are known [17]. However, the effectiveness of demand-driven production depends on the availability of sufficiently validated product designs. Consequently, integrating virtual garment simulation with pre-order confirmation could address both design-related and demand-related waste within a single pre-production workflow.

A structured literature review was conducted to identify existing approaches and clarify the research gap. The reviewed studies were classified into three principal research areas, as summarized in Table 1. The first focused on technological advances in virtual garment prototyping, including the integration of 3D simulation into garment development [3], virtual fitting using CLO3D [18], and improvements in cloth simulation accuracy [19]. Research has also examined the relationship between simulated and actual fabric behavior [20], virtual fitting and consumer satisfaction [21], computational pattern generation [22], immersive garment visualization [23], and designers' competencies in 3D-to-2D fit correction [24]. Previous studies have additionally demonstrated the application of artificial intelligence in fashion visualization [25], garment defect detection [26], and dynamic 3D visualization of modest wear designs [27]. Collectively, these studies have advanced the technical capabilities of digital garment development but have generally placed less emphasis on integrating design validation with subsequent production quantity decisions.

The second research area addressed demand-responsive production and customer-oriented digital technologies. Studies have examined the use of digital product visualization before manufacturing [16], demand-driven approaches to reducing fashion overproduction [5], and the importance of integrating virtual fitting technologies into customer-facing processes [28]. Related research has explored digital transformation and metaverse applications in fashion [29], mass customization through improved sizing and cutting strategies [17], and artificial intelligence-assisted garment design based on consumer preferences and body measurements [30]. Although these approaches support more responsive production systems, they do not consistently incorporate a formal digital design validation stage before customer orders are confirmed.

The third research area concentrated on improving material efficiency during garment manufacturing. Previous studies have investigated intelligent cutting order planning [31], optimization techniques capable of achieving fabric utilization rates exceeding 87% [32], and heuristic approaches to cutting order planning, fabric spreading, and marker efficiency [33−35]. These studies provide valuable methods for measuring and improving material utilization. However, their primary focus is on optimizing manufacturing operations after production decisions have been made, rather than preventing unnecessary material commitments during product development and demand confirmation.

Table 1. Positioning of the Present Study within the Existing Literature.

References	Research focus	Research gap addressed by the present study
[3, 18]	3D virtual prototyping and CLO3D-based garment fitting	Limited integration between design validation and production quantity decisions
[12, 13]	Virtual sampling efficiency and environmental impacts	Demand confirmation is not incorporated into the sampling process
[19-21]	Cloth simulation accuracy, fabric properties, and virtual fit prediction	Emphasis on technical accuracy rather than production decisions
[22, 24]	Computational pattern making and 3D-to-2D fit correction	Limited consideration of demand-driven production mechanisms
[16, 28]	Digital visualization and virtual fitting for customer engagement	Absence of an explicit sequential design validation mechanism
[5, 17]	Demand-driven manufacturing and mass customization	Limited integration of virtual design validation before order confirmation
[29, 36]	Digital transformation and metaverse applications in fashion	Lack of a unified pre-production decision-making framework
[31, 32]	Cutting optimization and fabric utilization	Focus on manufacturing efficiency after production commitments
[25, 27]	AI-assisted fashion visualization and digital garment development	Limited integration with demand confirmation and production planning
This study	Integration of 3D virtual garment simulation and a pre-order system	Sequential validation of garment design and confirmed demand before production

As presented in Table 1, existing research has predominantly examined virtual garment simulation, demand-driven production, and material optimization as separate approaches. Although these technologies can independently improve resource efficiency, their fragmented implementation may limit their overall contribution to waste prevention [36]. Virtual simulation can reduce unnecessary physical sampling, whereas pre-order systems can minimize production based on uncertain demand. However, the reviewed literature did not identify a model that explicitly integrates both interventions as sequential decision gates within a unified pre-production process. This represents an important research gap, particularly for fashion SMEs that require practical, resource-efficient strategies to reduce material waste without substantial investment in complex manufacturing technologies.

The novelty of this study lies in the development of an integrated pre-production decision-making model rather than the introduction of new simulation or pre-order technologies. Specifically, the proposed model combines 3D virtual garment simulation and demand confirmation into two sequential decision gates. The first gate evaluates garment design and fits using CLO3D, while the second verifies customer orders against a predetermined minimum order quantity before authorizing production. This approach introduces explicit decision criteria to prevent premature material commitments and provides a structured framework tailored to the operational characteristics of fashion SMEs. Furthermore, the model incorporates expert-based feasibility and content validity assessments

and proposes measurable indicators, including fabric utilization efficiency, production lead time, and inventory performance, for subsequent field evaluation. Thus, the principal contribution concerns process design and decision-making methodology rather than the demonstrated effectiveness of waste reduction technologies.

Accordingly, this study aimed to develop and validate a proof-of-concept model integrating 3D virtual garment simulation and a pre-order system as sequential decision gates for reducing potential material waste in fashion SMEs. Specifically, the study sought to identify the principal sources of waste during conventional garment development and production planning, establish an integrated pre-production decision-making framework, and evaluate its feasibility and content validity through expert assessment. The model was developed at TRL 3, with its operational effectiveness intended for evaluation in subsequent field studies. The findings are expected to provide a foundation for integrating digital garment development and demand-driven production into more resource-efficient and sustainable fashion manufacturing practices.

2. Materials and Methods

2.1. Research Design.

This study employed a Research and Development (R&D) approach adapted from Borg and Gall [37], involving the systematic development and evaluation of a conceptual model through predefined stages and assessment criteria. The research focused on developing a decision-making model rather than a software application or physical product. The model was positioned at TRL 3, representing an analytical and experimental proof of concept [38]. Accordingly, the primary outcome was a conceptually validated framework rather than a fully implemented production system. The research was conducted through five sequential stages: problem identification and literature review, industry needs analysis, model development, expert validation, and comparative evaluation. Each stage incorporated specific data sources, analytical procedures, and expected outputs, as summarized in Table 2.

Table 2. Stages of the R&D Process, With Data, Analytical Methods and Outputs.

Stage	Research activity	Data sources	Analytical methods	Outputs	Ref
1	Problem identification and literature review	Peer-reviewed studies on virtual prototyping, demand-driven production, and cutting efficiency	Structured literature review and thematic classification	Research gap identification	[39]
2	Industry needs analysis	Observations and semi-structured interviews with 22 informants from 15 fashion SMEs	Process mapping, deductive coding, data reduction, matrix analysis, and conclusion drawing	Identification of material waste sources	[40]
3	Model development	Identified waste sources and theoretical frameworks	Deductive model development using lean manufacturing, postponement theory, and stage-gate principles	Conceptual model	[7−9]
4	Expert validation	Questionnaire responses and written feedback from five experts	Feasibility percentage, Aiken's V, and qualitative content analysis	Validated and refined model	[41]
5	Comparative evaluation	Validated model and literature-based performance benchmarks	Comparative projection and identification of verification indicators	Comparative assessment and verification plan	[31, 42]

2.2. Participants and Sampling.

The participating SMEs were selected using purposive sampling [43] through the Indonesian Fashion Chamber (IFC), Malang Chapter, which served as the principal industry partner. The inclusion criteria required that each SME: (1) designed and manufactured its own fashion collections in Malang, Indonesia; (2) conducted physical sampling before production; (3) had operated for at least five years; and (4) agreed to participate in observations and interviews. These criteria ensured that the selected enterprises had sufficient operational experience and were directly involved in garment development and production planning. A total of 22 informants from 15 fashion SMEs participated in the study. Informants included business owners and, where available, personnel responsible for garment design or production management. These participants were selected because of their direct involvement in decisions concerning physical sampling, production quantities, and material allocation. Data were collected between March and August 2026 through direct observations of production activities and semi-structured interviews covering the workflow from garment design to product delivery.

The qualitative data were analyzed using deductive coding based on production stages, including design, sampling, manufacturing, and sales, and waste categories derived from lean manufacturing principles [7]. Observation notes and interview transcripts were systematically reviewed, coded, reduced, and organized into matrices according to SME and production stage. The resulting patterns were compared across participating enterprises to identify recurring sources of material waste and establish the principal areas requiring intervention [40]. Table 3 presents the characteristics of the participating SMEs. The enterprises manufactured various garment categories, including women's wear, modest wear, men's wear, and children's wear. Their workforce sizes ranged from 6 to 19 employees, with monthly production volumes of approximately 100–500 garments. Most enterprises combined offline and online sales channels and conducted two to three rounds of physical sampling for each new design. Unsold samples and excess inventory were generally sold at discounted prices or discarded.

Table 3. Characteristics of Participating Fashion SMEs (n = 15).

Characteristic	Profile of participating SMEs
Number of participating SMEs	15 fashion SMEs in Malang, Indonesia
Main product categories	Women's wear, modest wear, men's wear, and children's wear
Number of employees	6–19 employees
Monthly production volume	100–500 garments
Sales channels	Combination of offline and online sales
Physical sampling frequency	2–3 sampling rounds per new design
Management of unsold samples and inventory	Discounted sales or disposal

Note: Values represent the ranges or categories reported by participating SMEs during the needs analysis.

The proposed model was subsequently evaluated by five experts with 12–22 years of professional experience. The panel comprised two academics specializing in fashion design and apparel production management, two practitioners specializing in 3D fashion technology and pre-order business models, and one garment supply chain specialist. The number of validators was consistent with recommendations suggesting that three to ten experts are appropriate for content validation [44]. The panel was selected to ensure representation of the three principal research areas identified in the literature review. For confidentiality and reporting purposes, the experts were designated V1–V5.

2.3. Literature Review Procedure.

A structured literature review was conducted to establish the theoretical foundation of the proposed model and identify gaps in existing research [39]. Relevant publications from 2015 to 2026 were retrieved from Scopus, ScienceDirect, and Google Scholar. Foundational publications on lean manufacturing, postponement theory, stage-gate approaches, and content validity were included separately to support the conceptual framework [7−9, 41]. The literature search incorporated three groups of keywords corresponding to the principal research areas. The first group addressed virtual garment development using the search terms ("3D virtual" OR "virtual prototyping" OR "CLO3D" OR "virtual sampling") AND (garment OR apparel OR fashion). The second focused on demand-responsive manufacturing using ("pre-order" OR "made-to-order" OR "demand-driven" OR "on-demand" OR "mass customisation") AND (fashion OR apparel). The third examined material efficiency using ("cut order planning" OR "marker planning" OR "fabric utilisation") AND (apparel OR garment). Peer-reviewed publications written in English or Indonesian were included if they addressed fashion or garment manufacturing and reported empirical findings, methodological approaches, or conceptual models relevant to at least one research area. The screening process involved an initial assessment of titles and abstracts, followed by full-text evaluation. A total of 36 studies met the inclusion criteria, comprising 17 studies on virtual prototyping, eight on demand-driven production, nine on cutting efficiency, and two cross-disciplinary reviews. The selected publications were categorized according to their primary research focus, while studies integrating multiple research areas were identified separately. This classification provided the basis for the literature synthesis presented in Table 1 and supported the identification of the research gap concerning the integration of virtual garment validation and demand confirmation within a unified pre-production decision-making framework.

2.4. Expert Validation Instrument and Analysis.

The expert validation instrument consisted of 12 indicators organized into four assessment aspects: accuracy and visualization of 3D virtual garments, workflow integration and pre-order systems, potential for production waste reduction, and business implementation feasibility and industrial sustainability. The indicators were developed based on the material waste sources identified during the industry needs analysis and the performance dimensions established in previous studies. Each indicator was linked to a specific evaluation objective and supporting evidence to ensure its relevance to the proposed model. Table 4 presents the validation indicators, their assessment objectives, and their theoretical or empirical foundations. The instrument was designed to assess whether the proposed model adequately addressed the identified material waste problems and whether its decision-making mechanisms were considered feasible for fashion SMEs. Content validity was evaluated using Aiken's V coefficient. However, no separate pilot test of the questionnaire was conducted, which was acknowledged as a methodological limitation.

Table 4. Expert Validation Indicators, Assessment Objectives, and Supporting References.

Assessment aspect	Code	Validation indicator	Assessment objective	Reference
A1. Accuracy and visualization of 3D garments	1.1	Accuracy of garment drape, fit, and fabric texture in 3D rendering	Assess the realism of virtual samples for design validation	[19, 20]
	1.2	Avatar proportions and digital size grading	Evaluate the accuracy of virtual fitting across garment sizes	[21, 24]
	1.3	Ability of 3D visualization to reduce physical sampling	Assess the potential effectiveness of Gate 1 in addressing sampling-related waste	[10, 12]
A2. Workflow integration and pre-order systems	2.1	Clarity of the workflow from virtual catalogues to pre-order confirmation	Evaluate integration between virtual design and demand confirmation	[16, 28]
	2.2	Effectiveness of minimum order quantity (MOQ) determination and production batch planning	Assess the decision criteria for Gate 2	[17]
	2.3	Accuracy of production lead time estimation based on confirmed orders	Evaluate the reliability of demand-driven production planning	[5]
A3. Production waste reduction potential	3.1	Potential to reduce fabric waste during prototyping	Assess the expected reduction in sampling-related waste	[13]
	3.2	Prevention of deadstock and overproduction through order-based manufacturing	Evaluate the potential reduction in demand-related waste	[5, 7]
	3.3	Material utilization efficiency before cutting	Assess the relevance of fabric utilization efficiency as a verification indicator	[31, 32]
A4. Business implementation feasibility and industrial sustainability	4.1	Accessibility of the 3D interface for consumers	Evaluate the usability of digital product presentations	[28, 29]
	4.2	Scalability of the model for local fashion SMEs	Assess compatibility with SME resources and operational capacities	[6, 45]
	4.3	Financial feasibility and long-term operational cost efficiency	Evaluate potential financial barriers to implementation	[45, 46]

Each indicator was evaluated using a five-point Likert scale ranging from 1 (very infeasible) to 5 (very feasible). The validators were also invited to provide written comments and recommendations for model improvement. The overall feasibility percentage was calculated using Equation (1).

$$P = (So / Smax) \times 100\% \quad (1)$$

Where P is the feasibility percentage, so is the total score obtained from all validators and Smax is the maximum possible score.

Results were interpreted as very feasible (81.00–100.00%), feasible (61.00–80.99%), fairly feasible (41.00–60.99%), less feasible (21.00–40.99%) or very infeasible (0.00–20.99%), with 61.00% set as the minimum for acceptance. Agreement among validators on each indicator was assessed with Aiken's content validity coefficient, calculated using Equation (2) [41].

$$V = \Sigma s / [n(c - 1)], \; s = r - lo \quad (2)$$

Where r is the score given by a validator, lo is the lowest possible score (1), n is the number of validators (5) and c is the number of rating categories (5). For five validators and five categories, a coefficient of at least 0.80 indicates content validity at a right-tail probability below 0.05 [41]. Written comments were grouped by aspect and traced to the changes they produced in the model.

2.5. Comparative projection and verification metric

Because the study is a proof of concept, the potential waste reduction was projected comparatively from the waste point mapping and from earlier findings on the effect of virtual sampling on material and energy efficiency [10, 12, 13]. For the empirical verification that should follow, fabric utilisation efficiency (FUE), an established indicator of material performance in garment cutting [31, 42], was selected as the main metric and is calculated using Equation (3).

$$FUE = (Ap / Af) \times 100\% \quad (3)$$

Where Ap is the total area of the pattern pieces placed in the marker and Af is the total area of fabric consumed for the marker length and number of plies.

Comparing FUE before and after the model is applied will allow its material contribution to be expressed quantitatively. Lead time and end-of-season inventory are proposed as complementary indicators for Category B waste [5, 17].

3. Results and Discussion

3.1. Waste Points in the Conventional Production System.

The needs analysis examined the conventional production workflow of participating fashion SMEs, from initial garment design to product delivery. The findings identified two principal categories of material waste: waste generated during product development (Category A) and waste resulting from mismatches between production quantities and market demand (Category B). These categories represented different stages of premature material commitment and provided the basis for developing the proposed waste reduction model.

Category A comprised three waste points associated with garment development: material consumption during physical sample production (A1), samples that were not accepted by the market (A2), and repeated sampling cycles resulting from design revisions (A3). All three waste points were directly observed and confirmed through interviews with participating SMEs. Repeated physical sampling increased fabric and accessory consumption, required additional labor and machine time, and extended product development lead times. These findings were consistent with previous research demonstrating that limited visualization during conventional garment development contributes to repeated sampling [3] and that sampling activities generate additional textile waste [1].

Category B comprised three waste points associated with production–demand mismatches: production quantities determined by forecasts or previous sales (B1), overproduction beyond actual market demand (B2), and unsold inventory that accumulated as deadstock (B3). Informants from 11 of the 15 participating SMEs reported these problems. According to the informants, production decisions were frequently based on estimated demand rather than confirmed customer orders, increasing the risk of excess inventory. However, the actual quantities of overproduction and deadstock were not measured. Therefore, the identification of Category B was supported by interview findings and previous studies rather than direct quantitative measurements. This interpretation was consistent with research identifying forecast-based production as a major contributor to fashion overproduction [5] and recognizing overproduction as a source of additional operational waste [7].

Table 5 summarizes the six waste points identified during the needs analysis, including their characteristics and supporting evidence. The findings demonstrated that Category A waste was directly observed and corroborated through interviews, whereas Category B waste was primarily identified through informant reports. This distinction is important because the proposed model addresses two different forms of waste: directly observed inefficiencies during garment development and reported production inefficiencies associated with uncertain market demand. The classification also established the operational problems targeted by the two proposed decision gates.

Table 5. Material waste points identified in the conventional production workflow of fashion SMEs.

Code	Waste point	Description	Evidence
Category A	**Product development waste**		
A1	Physical sample production	Consumption of fabric, accessories, labor, and machine time during physical sample development	Direct observation and informant interviews
A2	Unaccepted physical samples	Samples not accepted by the market, resulting in unused materials or discarded products	Direct observation and informant interviews
A3	Repeated sampling cycles	Repeated sample production following design revisions, increasing material consumption and development lead time	Direct observation and informant interviews
Category B	**Production–demand mismatch waste**		
B1	Forecast-based production	Production quantities determined using forecasts or previous sales rather than confirmed customer orders	Reported by informants from 11 of 15 SMEs
B2	Overproduction	Manufacturing quantities exceeding actual market demand	Reported by informants; not quantitatively measured
B3	Deadstock accumulation	Unsold garments retained in inventory, discounted, or discarded	Reported by informants; not quantitatively measured

Figure 1 illustrates the distribution of material waste points throughout the conventional garment production workflow. Category A waste occurred during design development and physical sampling, before garments were approved for production. In contrast, Category B waste emerged during production planning and inventory management, when manufacturing quantities were determined without confirmed customer demand. The figure highlights the sequential relationship between these two categories, demonstrating that waste prevention requires interventions at both the design validation and production authorization stages. Accordingly, the identified waste points provided the conceptual foundation for integrating virtual garment simulation and demand confirmation into a unified pre-production decision-making framework.

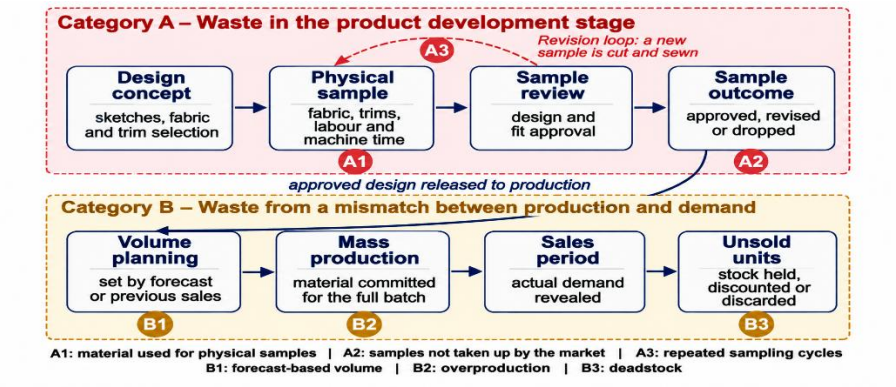


Figure 1. Waste Points in the Conventional Production Flow of Fashion Smes, Grouped into Product Development Waste (Category A) and Production–Demand Mismatch Waste (Category B).

3.2. Integration Model of 3D Virtual Garment Simulation and the Pre-Order System.

Based on the identified waste points, an integrated model was developed to combine 3D virtual garment simulation and a pre-order system within a sequential pre-production decision-making framework. The model incorporated the stage-gate principle, in which production activities proceed only after predefined validation criteria have been satisfied [9]. Rather than treating virtual garment simulation and pre-ordering as independent interventions, the proposed framework established two consecutive decision gates designed to prevent premature material commitments during garment development and production planning.

The first stage, Phase A, focused on digital garment development and design validation. Initial garment designs and two-dimensional patterns were simulated using CLO3D, incorporating the measured mechanical properties of the selected fabrics. The resulting virtual garments were evaluated for design accuracy, garment fit, and visual appearance. Gate 1 required approval of the design and fit before proceeding to the next stage. If the validation criteria were not satisfied, modifications were made directly to the digital patterns without producing additional physical samples. This process was intended to address waste points A1–A3 by reducing material consumption and repeated sampling during product development.

The second stage, Phase B, involved digital product presentation and demand confirmation through a pre-order system. Approved garment designs were rendered using standardized high-dynamic-range imaging (HDRI) lighting and International Color Consortium (ICC) color profiles to improve visual consistency. The resulting digital representations were presented to potential customers, together with estimated production lead times. Following the pre-order period, confirmed orders were consolidated according to quantities, sizes, and product specifications. Gate 2 evaluated whether the accumulated orders satisfied the predetermined minimum order quantity (MOQ). If the MOQ was not achieved, the pre-order period could be extended or the product design reconsidered, while production authorization remained suspended. This mechanism was intended to reduce forecast-based production, overproduction, and deadstock accumulation associated with waste points B1–B3.

Following successful completion of both decision gates, Phase C involved production preparation and execution based on confirmed customer demand. The approved production quantity and size distribution were finalized, and the validated digital patterns were exported in DXF-AAMA format for subsequent marker preparation. Fabric utilization efficiency (FUE) was designated as a performance indicator during cutting, while production progress could be communicated to customers until order fulfillment. By linking design validation with confirmed demand, the proposed model operationalized the postponement principle, which emphasizes delaying production commitments until sufficient information becomes available [8]. This approach was expected to improve resource allocation and reduce the risk of unnecessary material consumption.

Figure 2 presents the proposed integration framework, illustrating the relationships among digital garment development, design validation (Gate 1), pre-order confirmation (Gate 2), and production authorization. The framework also identifies the information exchanged between the different phases, including fabric mechanical properties used during virtual simulation, validated digital garment files used for product presentation and pattern preparation, and confirmed customer order data used to determine production quantities. The sequential structure demonstrates how decisions made during product development influence

subsequent demand validation and production planning. Expert recommendations were incorporated into the refined framework.

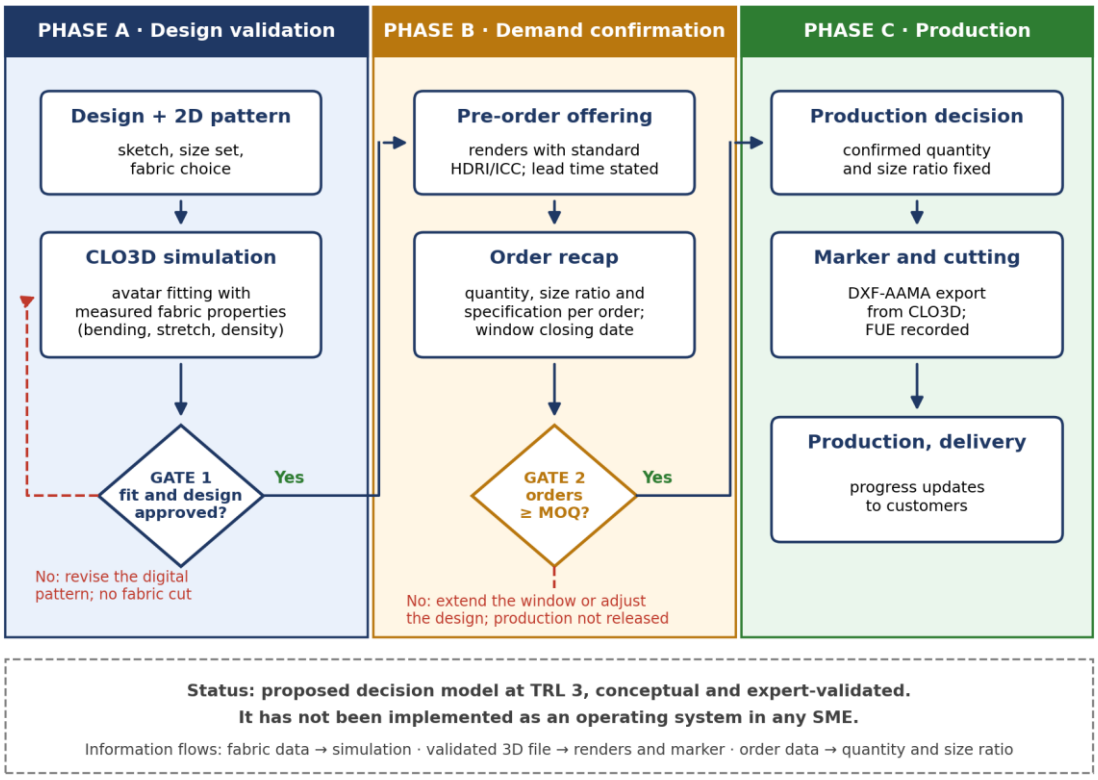


Figure 2. Integration Framework Linking CLO3D Simulation, Digital Design Validation (Gate 1), Pre-Order Confirmation Against the MOQ (Gate 2) and the Production Decision. The Framework is A Proposed Model at TRL 3, not an Operational System.

Importantly, the proposed framework remained at TRL 3, representing an analytical proof of concept rather than an operationally implemented production system. Although its structure, decision criteria, and information flows were established and evaluated through expert validation, its effectiveness in reducing material waste had not yet been demonstrated through field implementation. Consequently, the framework provides a basis for subsequent experimental evaluation using measurable indicators such as fabric utilization efficiency, production lead time, and inventory performance.

3.3. Expert Validation of the Model.

The proposed model was evaluated by five experts using 12 indicators across four assessment aspects. Table 6 presents the validation scores, feasibility percentages, and Aiken's V coefficients. The model obtained an overall score of 268 out of 300, corresponding to a feasibility percentage of 89.33% and a mean score of 4.47 on a five-point scale, indicating that it was highly feasible. All four aspects were classified as very feasible. Production waste reduction potential received the highest score (93.33%; mean = 4.67), followed by accuracy and visualization of 3D virtual garments (92.00%; mean = 4.60), workflow integration and the pre-order system (86.67%; mean = 4.33), and business implementation feasibility and industrial sustainability (85.33%; mean = 4.27).

Table 6. Expert Validation Results by Indicator and Assessment Aspect (Five Validators; Five-Point Likert Scale).

No.	Aspect and indicator	V1	V2	V3	V4	V5	Score	Mean	Feasibility (%)	Aiken's V
A1	**Accuracy and visualization of 3D virtual garments**						**69/75**	**4.60**	**92.00**	**0.90**
1.1	Accuracy of garment drape, fit, and fabric texture	5	5	4	5	4	23/25	4.60	92.00	0.90
1.2	Avatar proportions and digital size grading	4	5	4	4	5	22/25	4.40	88.00	0.85
1.3	Potential of 3D visualization to replace physical samples	5	5	5	4	5	24/25	4.80	96.00	0.95
A2	**Workflow integration and pre-order system**						**65/75**	**4.33**	**86.67**	**0.83**
2.1	Clarity of the workflow from virtual catalogues to pre-ordering	4	5	5	4	4	22/25	4.40	88.00	0.85
2.2	Effectiveness of MOQ determination and production batch planning	4	4	5	4	5	22/25	4.40	88.00	0.85
2.3	Accuracy of lead time estimates based on confirmed orders	4	4	4	5	4	21/25	4.20	84.00	0.80
A3	**Production waste reduction potential**						**70/75**	**4.67**	**93.33**	**0.92**
3.1	Potential to eliminate fabric waste during prototyping	5	5	5	5	4	24/25	4.80	96.00	0.95
3.2	Prevention of deadstock and overproduction	5	4	5	5	5	24/25	4.80	96.00	0.95
3.3	Material utilization efficiency before cutting	4	5	4	5	4	22/25	4.40	88.00	0.85
A4	**Business feasibility and industrial sustainability**						**64/75**	**4.27**	**85.33**	**0.82**
4.1	Accessibility of the 3D interface for consumers	4	4	4	4	4	20/25	4.00	80.00	0.75
4.2	Scalability of the model for local fashion SMEs	4	5	5	4	4	22/25	4.40	88.00	0.85
4.3	Financial feasibility and long-term operating cost efficiency	5	4	4	4	5	22/25	4.40	88.00	0.85
Overall							**268/300**	**4.47**	**89.33**	**0.87**

Figure 3 illustrates the differences in feasibility percentages and Aiken's V coefficients across the four assessment aspects. All aspects exceeded the 81% threshold for the very feasible category, while their Aiken's V coefficients ranged from 0.82 to 0.92, exceeding the adopted content validity criterion of 0.80. The highest values were observed for production waste reduction potential, whereas business implementation feasibility and industrial sustainability received the lowest values.

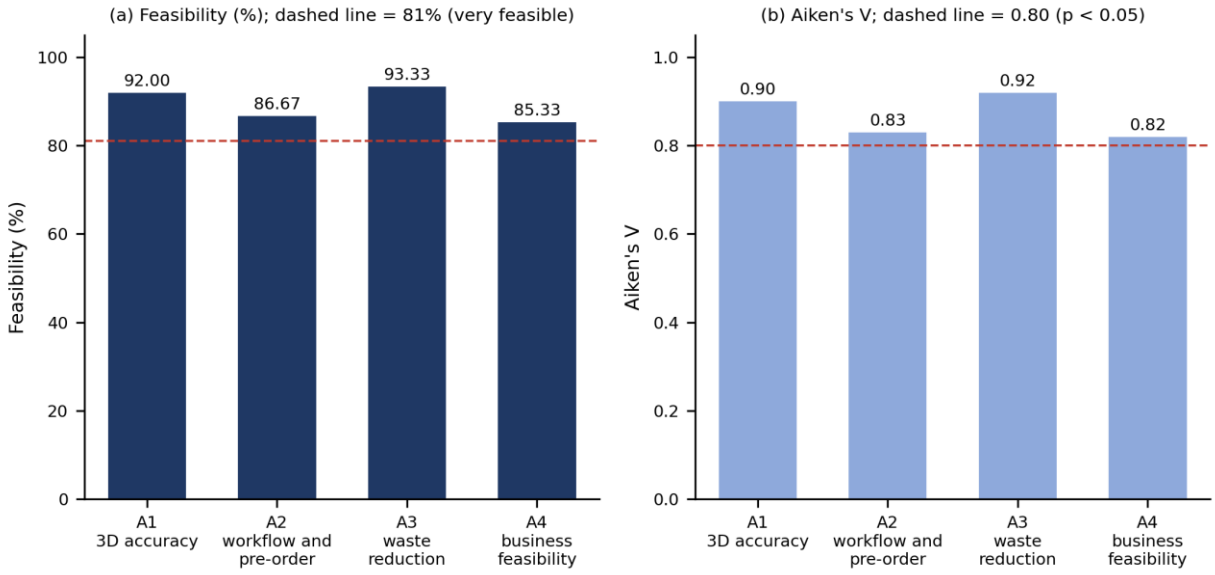


Figure 3. Feasibility Percentage (a) and Aiken's V (b) for the Four Evaluation Aspects. Dashed Lines Mark the Very Feasible Threshold (81%) and The Content Validity Criterion (V ≥ 0.80).

At the indicator level, three indicators achieved the highest scores (96%; V = 0.95): replacing physical samples through 3D visualization, reducing fabric waste during prototyping, and preventing deadstock through order-based production. Eleven of the 12 indicators satisfied the content validity criterion ($V \geq 0.80$). Consumer interface accessibility was the only exception (80%; V = 0.75), followed by lead time estimation, which reached the minimum validity threshold (V = 0.80).

Although these findings demonstrated strong expert support for the proposed model, they did not establish its actual effectiveness in reducing material waste. The five-member expert panel was consistent with recommended content validation practices [44]. However, the relatively small panel made individual coefficients sensitive to rating changes. Therefore, the model's operational performance requires further verification using fabric utilization efficiency, production lead time, and inventory data.

The two lowest-scoring indicators concerned consumer interface accessibility and production lead time estimation, both associated with Gate 2. Experts highlighted potential difficulties in presenting virtual garments through the social media and messaging platforms commonly used by SMEs. Uncertain pre-order completion times could also affect customer satisfaction and increase order cancellations. Previous studies similarly emphasized that successful virtual fitting depends on effective integration with customer-facing processes [28], while garment fit remains an important factor influencing customer satisfaction and product returns [47]. Accordingly, the model was refined to incorporate accessible digital presentations, defined pre-order periods, estimated delivery ranges, and production progress updates.

~~It~~Table 7 summarizes the written feedback from the five validators and the corresponding model refinements. The recommendations addressed fabric simulation accuracy, rendering consistency, customer communication, waste reduction measurement, and integration with garment cutting systems. These refinements were incorporated into the proposed framework (Figure 2) and the verification approach described in Equation (3).

Table 7. Expert feedback and corresponding refinements to the proposed model.

Validator	Assessment focus	Expert feedback	Model refinement
V1	3D simulation accuracy	Specify fabric mechanical properties, particularly bending stiffness, stretch resistance, and density	Incorporated measured fabric properties as inputs for Phase A simulation
V2	Rendering and color accuracy	Standardize HDRI lighting and color profiles to minimize differences between virtual and physical garments	Specified HDRI lighting and ICC color profiles for digital product presentations
V3	Pre-order management	Clearly communicate production lead times to reduce customer uncertainty and cancellations	Added pre-order closing dates, estimated lead times, and production progress updates
V4	Waste reduction measurement	Quantify material efficiency before and after model implementation	Adopted fabric utilization efficiency (FUE) as a verification indicator
V5	SME scalability and production integration	Enable the transfer of validated digital patterns to partner workshops	Incorporated DXF-AAMA pattern export into Phase C

3.4. Potential Material Efficiency and Prevention of Inventory Accumulation.

Because the proposed model had not yet been implemented in an operational production environment, its potential contribution to material waste reduction was evaluated comparatively. The assessment considered differences between conventional production practices and the proposed integrated model, particularly the timing of material commitments, physical sampling requirements, production decisions, and inventory accumulation. These

comparisons were based on the identified waste points, expert assessments, and findings from previous studies rather than direct experimental measurements. Figure 4 illustrates the differences between conventional production and the proposed integrated model. Conventional production requires physical sampling before design approval and relies on forecast-based manufacturing, potentially generating unnecessary samples and excess inventory. In contrast, the integrated model introduces digital design validation and confirmed pre-orders before production authorization. This sequence is intended to minimize premature material commitments, although the resulting waste reductions remain ~~theoretica~~theoretical.

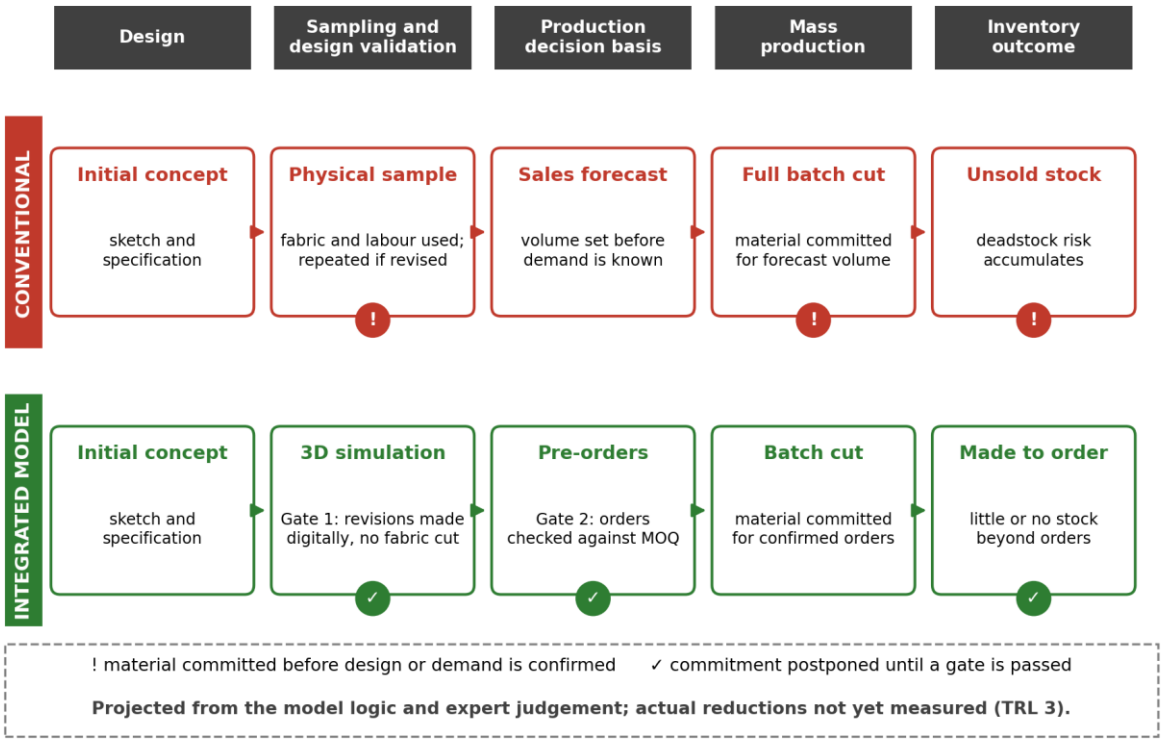


Figure 4. Conventional Production Flow Compared with the Integrated Model, Showing Physical Sampling, the Basis of the Production Decision, Potential Material Waste and Inventory Accumulation. Differences are Projected, not Measured.

Table 8 summarizes the potential improvements associated with the integrated model and distinguishes the evidence supporting each comparison. Virtual simulation was expected to reduce repeated physical sampling, while pre-order confirmation could minimize production beyond actual demand. Previous studies reported fabric utilization of approximately 70% under conventional cutting practices and more than 87% under optimized cutting order planning [32]. However, these values represent literature-based benchmarks rather than measured outcomes of the proposed model. Previous research supports the potential benefits of virtual simulation in reducing physical sampling requirements, material consumption, and development time [10-12]. Life cycle assessment studies have also demonstrated lower energy consumption when physical samples are replaced with virtual alternatives [13]. Similarly, digital product presentations before manufacturing have been associated with reduced overproduction [16]. Cutting optimization studies have reported improvements in fabric utilization through marker planning, heuristic optimization, and improved cutting strategies [32, 35, 42, 48−50]. Nevertheless, the magnitude of these improvements cannot be directly attributed to the

proposed model without field verification. Furthermore, although virtual sampling may shorten product development, waiting for sufficient pre-orders could extend overall delivery times. Therefore, future studies should assess both material efficiency and total production lead time.

Table 8. Potential Improvements of the Integrated Model Compared with Conventional Garment Production and Their Supporting Evidence.

Dimension	Conventional production	Proposed integrated model	Supporting evidence	Reference
Physical sampling	Repeated physical samples during design development (A1–A3)	Digital revisions before design approval	Needs analysis and expert assessment (V = 0.95); not experimentally verified	[10–12]
Material commitment	Fabric allocated before design and demand confirmation	Material commitment postponed until both decision gates are satisfied	Model design and expert assessment (V = 0.95)	[7–9]
Production decisions	Forecast-based production quantities	Confirmed pre-orders evaluated against MOQ	Model design and expert assessment (V = 0.85)	[5, 16, 17]
Inventory accumulation	Potential deadstock from production–demand mismatches (B1–B3)	Production quantities aligned with confirmed orders	Expert assessment (V = 0.95); actual reduction not measured	[5, 7, 16]
Cutting-stage material efficiency	Approximately 70% fabric utilization under conventional planning	Potential improvement toward literature benchmarks exceeding 87%	Literature-based benchmark; requires verification using Equation (3)	[32, 42]
Production lead time	Extended by repeated physical sampling	Reduced sampling time but additional waiting time for MOQ confirmation	Previous studies; net effect not measured	[11, 12]

3.5. Comparison with Previous Studies.

Previous studies have demonstrated the effectiveness of virtual garment simulation in improving product development efficiency. Papachristou et al. [3] proposed the integration of 3D virtual prototyping into garment development, while subsequent studies reported improvements in sampling efficiency, material consumption, and environmental performance [11−13]. However, these investigations primarily focused on design development and did not explicitly connect virtual design validation with production quantity decisions. The present study extends this approach by incorporating digital design approval as the first decision gate within a broader demand-driven production framework.

Demand-driven manufacturing studies have emphasized the importance of aligning production quantities with actual market requirements. Gui and Long [5] identified demand-responsive manufacturing as a strategy for addressing fashion overproduction, while Greder et al. [16] examined digital product visualization as a pre-production offering mechanism. Xu et al. [17] further demonstrated the potential of order-based sizing and cutting optimization. Unlike these approaches, the proposed model integrates demand confirmation with prior digital design validation. The expert assessment also identified consumer interface accessibility and lead time estimation as important challenges, indicating that effective demand confirmation depends partly on the quality and accessibility of digital product representations.

Research on sustainable garment manufacturing has highlighted the importance of integrating digital technologies across production processes rather than implementing isolated solutions [4, 36]. Similarly, circular production strategies emphasize preventing waste through process redesign instead of relying exclusively on material recovery [2]. The proposed model supports these perspectives by introducing sequential decision gates before material commitment. However, its scope differs from studies addressing cutting-stage optimization

[31, 33, 34] and automated garment defect detection [26]. Its primary novelty lies in integrating virtual garment simulation and pre-order confirmation into a unified pre-production decision-making framework rather than improving either technology independently.

3.6. Theoretical and Managerial Implications.

Theoretically, this study integrates three established perspectives into a unified decision-making framework. Lean manufacturing identifies overproduction as a major source of waste [7], postponement theory emphasizes delaying material commitments until reliable demand information becomes available [8], and the stage-gate approach provides explicit criteria for determining whether production activities should proceed [9]. Their integration extends existing virtual prototyping research by connecting digital design validation with production quantity decisions, thereby establishing a conceptual basis for preventing material waste before manufacturing begins.

From a managerial perspective, the proposed model offers fashion SMEs a structured approach to reducing premature production commitments. Implementation requires personnel capable of developing digital garment samples, reliable fabric property data, appropriate minimum order quantities, and accessible pre-order platforms. Digital training programs could support the development of the necessary technical competencies [51], while confirmed customer orders could facilitate improved production planning and mass customization [17, 30]. Previous research has also suggested that smaller firms using e-commerce channels may benefit from sustainable mass customization strategies [45], although technological, financial, and organizational barriers remain important considerations [46]. Future integration with digital quality inspection systems could further strengthen production efficiency [26].

Table 9 summarizes the theoretical contributions, managerial implications, implementation requirements, and expected sustainability benefits of the proposed model. The framework emphasizes delaying material commitments until design and demand have been validated. Its implementation depends on technical capabilities, effective customer communication, and coordination with production partners. Although the anticipated benefits include fewer physical samples and reduced unsold inventory, these outcomes require empirical verification.

Table 9. Theoretical Contributions, Managerial Implications, Implementation Requirements, and Expected Sustainability Benefits of the Proposed Model.

Dimension	Summary
Theoretical contributions	Integrates lean manufacturing, postponement theory, and stage-gate principles into sequential pre-production decisions; connects virtual garment validation with production quantity determination
Managerial implications	Delays material commitments until design approval and demand confirmation; emphasizes accessible digital presentations, transparent lead times, and customer communication
Implementation requirements	Personnel trained in CLO3D or equivalent software; reliable fabric property data; defined MOQ; accessible pre-order platforms; clear order deadlines; DXF-AAMA compatibility with production partners
Expected sustainability benefits	Potential reduction in physical sampling and unsold inventory; future verification through FUE, sampling frequency, production lead time, and end-of-season inventory

3.7. Limitations.

Several limitations should be acknowledged. First, the study was conducted at TRL 3, and the anticipated material waste reductions were derived from comparative assessments rather than experimental measurements. Second, expert validation involved only five participants, which

limited the stability of the content validity estimates. Furthermore, the questionnaire was not pilot-tested before validation. Third, the needs analysis involved 15 fashion SMEs from a single city, limiting the generalizability of the findings. Overproduction and deadstock quantities were also not measured, restricting the empirical evidence supporting the second decision gate. Finally, the proposed consumer-facing pre-order system had not been tested with actual customers. Future research should therefore prioritize field implementation and quantitative assessment of material utilization, production lead time, inventory performance, and customer acceptance.

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Author Contributions

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Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Competing Interests

The authors declare that they have no known financial or non-financial competing interests that could have influenced the research presented in this manuscript.

Declaration of Generative AI and AI-Assisted Technologies

During the preparation of this manuscript, the authors used DeepL AI to translate the manuscript from Indonesian into English. The translated content was subsequently reviewed, edited, and verified by the authors to ensure its accuracy and scientific integrity. The authors take full responsibility for the final content of the manuscript.

References

[1] Tang, K.H.D. (2023). State of the art in textile waste management: A review. *Textiles*, *3*, 454–467. https://doi.org/10.3390/textiles3040027.

[2] Shamsuzzaman, M.; Al Mamun, M.A.; Hasan, H.R.; et al. (2025). Fashion circularity: Potential of reusing and recycling remnant fabric to create sustainable products. *Sustainability*, *17*, 2010. https://doi.org/10.3390/su17052010.

[3] Papachristou, E.; Kalaitzi, D.; Pissas, V. (2023). A methodological framework for the integration of 3D virtual prototyping into the design development of laser-cut garments. *Journal of Engineered Fibers and Fabrics*, *18*, 1–18. https://doi.org/10.1177/15589250231194621.

[4] Islam, M.; et al. (2026). Digital transformation of fashion and textiles manufacturing: A systematic literature review. *Textile Research Journal*. https://doi.org/10.1177/00405175251375339.

[5] Gui, L.; Long, X. (2024). Curbing fashion waste and overproduction: A supply chain perspective. In Responsible and Sustainable Operations; Springer Series in Supply Chain Management; Springer: Cham, Switzerland; Volume 24. https://doi.org/10.1007/978-3-031-60867-4_5.

[6] Pardiyono, R.; Moengin, P.; Suryadi, K.; Safitri, D.M. (2026). The role of sustainability in innovation networks to enhance SME competitiveness: An integrative framework based on PRISMA and bibliometric mapping. *Spektrum Industri*, *24*, 103–114. https://doi.org/10.12928/si.v24i1.600.

[7] Womack, J.P.; Jones, D.T. (1996). Lean Thinking: Banish Waste and Create Wealth in Your Corporation; Simon & Schuster: New York, NY, USA.

[8] Pagh, J.D.; Cooper, M.C. (1998). Supply chain postponement and speculation strategies: How to choose the right strategy. *Journal of Business Logistics*, *19*, 13–33.

[9] Cooper, R.G. (1990). Stage-gate systems: A new tool for managing new products. *Business Horizons*, *33*, 44–54. https://doi.org/10.1016/0007-6813(90)90040-I.

[10] Habib, A.; Ullah, A.; Maha, M.M.; et al. (2025). Advancing sustainable fashion through 3D virtual design for reduced environmental impact. *Journal of Textile Engineering & Fashion Technology*, *11*, 135–142. https://doi.org/10.15406/jteft.2025.11.00415.

[11] Baria, B.; Shahid, M.A.; Misra, A. (2025). Transformative effect of 3D sampling technology for the ready-made garment industry: A review. *Textile Research Journal*.

[12] Liu, X.; Zhong, N. (2025). Research on improving the efficiency of garment sample production process based on virtual simulation technology. In Proceedings of the 2025 International Conference on Artificial Intelligence; Volume 2, pp. 389–397.

[13] Edem, S.B.; et al. (2026). Environmental benefits of virtual sampling for garment production. *Journal of Cleaner Production*, *538*, 147401.

[14] Yates, M.; Phinney, C. (2025). Virtual (re)visions: The impact of 3D prototyping technology on fashion design process. In Proceedings of the International Textile and Apparel Association (ITAA) Annual Conference; Volume 82. https://doi.org/10.31274/itaa.21950.

[15] Fitrihana, N. (2023). Penerapan teknologi virtual 3D untuk pengembangan produk fesyen [Application of virtual 3D technology for fashion product development]. *Prosiding Pendidikan Teknik Boga Busana*, *17*, 3–7.

[16] Greder, K.; Pei, J.; Kim, J.S. (2020). Design in 3D: A computational fashion design protocol. *International Journal of Clothing Science and Technology*, *32*, 537–549.

[17] Xu, Y.; Thomassey, S.; Zeng, X. (2020). Optimization of garment sizing and cutting order planning in the context of mass customization. *The International Journal of Advanced Manufacturing Technology*, *106*, 3485–3503. https://doi.org/10.1007/s00170-019-04866-w.

[18] Huang, S.; Huang, L. (2022). CLO3D-based 3D virtual fitting technology of down jacket. *Wireless Communications and Mobile Computing*, *2022*, 5835026.

[19] Li, X.; Li, X.; Li, Y.; Feng, W. (2023). Review of cloth modeling and simulation for virtual fitting. *Textile Research Journal*. https://doi.org/10.1177/00405175221135625.

[20] Petrak, S.; Mahnić Naglić, M.; Glogar, M.; Tomljenović, A. (2025). Assessment of textile material properties and the impact of digital ink-jet fabric printing on 3D simulation as a sustainable method for garment prototyping. *Sustainability*, *17*, 1388. https://doi.org/10.3390/su17041388.

[21] Oosterom, E.B.; Baytar, F.; Akdemir, D.; Kalaoglu, F. (2024). Predicting consumers' garment fit satisfactions by using machine learning. *AUTEX Research Journal*, *24*, 20230016. https://doi.org/10.1515/aut-2023-0016.

[22] Pietroni, N.; Dumery, C.; Falque, R.; Liu, M.; Vidal-Calleja, T.; et al. (2022). Computational pattern making from 3D garment models. *ACM Transactions on Graphics*, *41*, 1–14. https://doi.org/10.1145/3528223.3530145.

[23] Dai, J.; Dai, H.; Wang, J.; Wang, X. (2021). Children's clothing virtual simulation immersive design and show based on machine learning. *Mobile Information Systems*, *2021*, 2982729. https://doi.org/10.1155/2021/2982729.

[24] Galada, A.; Baytar, F. (2025). Developing an instrument with simulations to measure 3D to 2D fit correction skills in fashion design. *Fashion and Textiles*, *12*, 11.

[25] Kusuma, A.A.; Ahsan, R.S.H.F.; Hidayati, N.; Sunandar, A.; Rahayu, S.E.P.; et al. (2025). Transformasi desain fesyen virtual 3D dengan teknologi artificial intelligence Luma [Transforming virtual 3D fashion design with Luma artificial intelligence technology]. *JIPI (Jurnal Ilmiah Penelitian dan Pembelajaran Informatika)*, *10*, 2700–2713. https://doi.org/10.29100/jipi.v10i3.8885.

[26] Kusuma, A.A.; Amin, R.; Hidayati, N.; Sunandar, A.; Ahsan, R.S.H.F.; et al. (2025). Smart visual detection berbasis deep learning dengan menggunakan metode algoritma YOLO untuk identifikasi cacat pada produk garmen [Deep learning-based smart visual detection using the YOLO algorithm to identify defects in garment products]. *JIPI (Jurnal Ilmiah Penelitian dan Pembelajaran Informatika)*, *10*, 3704–3713. https://doi.org/10.29100/jipi.v10i4.9319.

[27] Sunandar, A.; Kusuma, A.A.; Ahsan, R.S.H.F.; Rahayu, S.E.P.; Zakaria, M.H.B. (2025). Utilization of AI-based motion diffusion for modest wear-based design transformation Wastra Nusantara. *Briliant: Jurnal Riset dan Konseptual*, *10*, 854–863. https://doi.org/10.28926/briliant.v10i4.2349.

[28] Zhang, Y.; Zheng, Z.; Liu, L. (2024). Design resource deployment for virtual fitting applications in the era of digital fashion: An analysis based on Kano-QFD. *SAGE Open*, *14*. https://doi.org/10.1177/21582440241296627.

[29] Profumo, G.; Testa, G.; Viassone, M.; Ben Youssef, K. (2024). Metaverse and the fashion industry: A systematic literature review. *Journal of Global Fashion Marketing*, *15*, 131–154. https://doi.org/10.1080/20932685.2023.2270587.

[30] Kusuma, A.A.; Rusydiana, A.A.; Aziza, R.N.; Aulia, Z.S.; Nadhifah, N. (2026). Personalize fashion design based on body data and consumer preferences using artificial intelligence technology. In Proceeding of the International Conferences on Engineering Sciences (ICONFES); Volume 3, pp. 10–17. https://doi.org/10.61132/iconfes.v3i1.186.

[31] Alsamarah, W.; Younes, B.; Yousef, M. (2022). Reducing waste in garment factories by intelligent planning of optimal cutting orders. *Journal of the Textile Institute*, *113*, 1917–1925. https://doi.org/10.1080/00405000.2021.1956711.

[32] Chrisnanto, Y.H.; Chrisnanto, J.E.; Oktavian, J. (2025). Comparative analysis of optimization methods for cut order planning in apparel manufacturing. *Jurnal Sistem dan Manajemen Industri*, *9*, 79–93. https://doi.org/10.30656/jsmi.v9i2.10502.

[33] Shang, X.; Shen, D.; Wang, F.; Nyberg, T.R. (2019). A heuristic algorithm for the fabric spreading and cutting problem in apparel factories. *IEEE/CAA Journal of Automatica Sinica*, *6*, 961–968. https://doi.org/10.1109/JAS.2019.1911573.

[34] Tsao, Y.-C.; Vu, T.-L.; Liao, L.-W. (2020). Hybrid heuristics for the cut ordering planning problem in apparel industry. *Computers & Industrial Engineering*, *144*, 106478. https://doi.org/10.1016/j.cie.2020.106478.

[35] Ünal, C.; Yüksel, A.D. (2020). Cut order planning optimisation in the apparel industry. *Fibres & Textiles in Eastern Europe*, *28*, 8–13. https://doi.org/10.5604/01.3001.0013.5851.

[36] Glogar, M.; Petrak, S.; Mahnić Naglić, M. (2025). Digital technologies in the sustainable design and development of textiles and clothing—A literature review. *Sustainability*, *17*, 1371. https://doi.org/10.3390/su17041371.

[37] Borg, W.R.; Gall, M.D. (1983). Educational Research: An Introduction, 4th ed.; Longman: New York, NY, USA.

[38] Mankins, J.C. (2009). Technology readiness assessments: A retrospective. *Acta Astronautica*, *65*, 1216–1223. https://doi.org/10.1016/j.actaastro.2009.03.058.

[39] Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research*, *104*, 333–339. https://doi.org/10.1016/j.jbusres.2019.07.039.

[40] Miles, M.B.; Huberman, A.M. (1994). Qualitative Data Analysis: An Expanded Sourcebook, 2nd ed.; Sage: Thousand Oaks, CA, USA.

[41] Aiken, L.R. (1985). Three coefficients for analyzing the reliability and validity of ratings. *Educational and Psychological Measurement*, *45*, 131–142. https://doi.org/10.1177/0013164485451012.

[42] Tsao, Y.-C.; Delicia, M.; Vu, T.-L. (2022). Marker planning problem in the apparel industry: Hybrid PSO-based heuristics. *Applied Soft Computing*, *123*, 108928. https://doi.org/10.1016/j.asoc.2022.108928.

[43] Palinkas, L.A.; Horwitz, S.M.; Green, C.A.; Wisdom, J.P.; Duan, N.; Hoagwood, K. (2015). Purposeful sampling for qualitative data collection and analysis in mixed method implementation research. *Administration and Policy in Mental Health and Mental Health Services Research*, *42*, 533–544. https://doi.org/10.1007/s10488-013-0528-y.

[44] Polit, D.F.; Beck, C.T. (2006). The content validity index: Are you sure you know what's being reported? Critique and recommendations. *Research in Nursing & Health*, *29*, 489–497. https://doi.org/10.1002/nur.20147.

[45] Hui, G.; Al Mamun, A.; Masukujjaman, M.; Makhbul, Z.K.M.; Ali, M.H. (2024). The relationship between mass customization and sustainable performance: The role of firm size and global e-commerce. *Heliyon*, *10*, e27726.

[46] Haryanto, A.; Sukma, I.; Darmawan, A. (2026). Barriers to green manufacturing implementation: A systematic literature review of internal and external challenges. *Spektrum Industri*, *24*, 176–191. https://doi.org/10.12928/si.v24i1.573.

[47] Liu, K.; Wu, H.; Zhu, C.; Wang, J.; Zeng, X.; et al. (2022). An evaluation of garment fit to improve customer body fit of fashion design clothing. *The International Journal of Advanced Manufacturing Technology*, *120*, 2685–2699.

[48] Al-Mahmud, S.; Cano, J.A.; Campo, E.A.; Weyers, S. (2025). Optimizing cut order planning: A comparative study of heuristics, metaheuristics, and MILP algorithms. *International Journal of Production Management and Engineering*, *13*, 1–26. https://doi.org/10.4995/ijpme.2025.22196.

[49] Hora, S.T.; Gruescu, C.-M.; Bungau, C.; Bodea, R. (2024). Innovative approaches to optimized cutting planning in the garment industry. *Industria Textila*, *75*, 441–447. https://doi.org/10.35530/IT.075.04.202386.

[50] Tsao, Y.-C.; Liu, C.-C.; Chen, P.-R.; Vu, T.-L. (2024). Design heuristics for cut order planning problems in the apparel industry. *International Journal of Clothing Science and Technology*. https://doi.org/10.1108/IJCST-07-2022-0087.

[51] Kusuma, A.A.; Sunandar, A.; Rahayu, S.E.P.; Ahsan, R.S.H.F.; Andrianto, S.N.K.; et al. (2025). Pembuatan modul digital dan desain moodboard kreatif untuk instruktur dan lembaga pelatihan [Development of digital modules and creative moodboard design for instructors and training institutions]. *Jurnal Pendidikan dan Pengabdian Masyarakat*, *8*, 464–471. https://doi.org/10.29303/jppm.v8i3.9736.

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