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A Personalized Clothing Design System Enabled by Digital Textile Manufacturing

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Article

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ABSTRACT

The global textile industry is transitioning towards sustainable development, necessitating innovations in manufacturing that minimize material waste and enhance efficiency. This paper proposes a computational framework for personalized textile products enabled by digital textile manufacturing (DTM), directly addressing the inefficiencies of traditional textile processing. The system digitizes the entire manufacturing workflow, from raw-material selection to the finished product. It is designed to process a variety of yarn types, including natural fibers such as wool and cotton, as well as synthetic fibers. The architecture integrates modules for versatile user data input, parametric modeling based on materials science principles, and realistic simulation of textile properties. A key innovation is the proposed computational translation architecture, which utilizes a machine-agnostic intermediate representation (IR) to bridge the gap between digital design and production. By operating within a defined parametric design space, the system enables the deterministic and automated generation of machine-specific code for industrial knitting machinery. This approach is designed to drastically reduce material waste associated with cutting. The framework is conceptualized to be extensible, envisioning future integration with downstream digital processes, such as targeted chemical treatments. A validation study demonstrates the fidelity of the proposed logic in producing custom wool garments, confirming the system's ability to generate deterministic manufacturing data.

KEYWORDS

digital textile manufacturing, textile industry, sustainable manufacturing, natural fibers, yarns

INTRODUCTION

The global fashion industry has historically been dominated by a mass-production model, characterized by standardized sizes, seasonal collections, and large inventories [1]. While this model has been successful in making fashion accessible, it is increasingly at odds with the evolving expectations of the modern consumer.

Today's consumers, empowered by digital platforms and a desire for self-expression, are demanding products that reflect their individual identity, body shape, and stylistic preferences [1]. This trend has catalyzed the shift towards mass customization, a production paradigm that aims to deliver individually tailored goods and services with the efficiency of mass production [2].

However, the practical implementation of mass customization in the apparel industry faces significant hurdles rooted in its traditional manufacturing processes. The conventional cut-and-sew method involves cutting patterns from large fabric rolls and then assembling them. This process is inherently wasteful, with estimates suggesting that 15–20% of the fabric is discarded as scrap material [3]. Furthermore, creating custom patterns and adjusting them for individual body measurements is a labor-intensive and time-consuming task, making true personalization at scale economically nonviable for most manufacturers.

In response to these limitations, digital technologies have begun to permeate the textile industry. Three-dimensional (3D) body scanning offers a precise method for capturing individual anthropometrics [4]. Computer-aided design (CAD) software allows for the creation of complex digital garment models [5]. More transformatively, advanced digital knitting and weaving technologies, such as Shima Seiki's WHOLEGARMENT® or Stoll's Knit&Wear®, enable the production of complete, seamless garments directly from a digital file [6,7]. This additive-manufacturing approach drastically reduces material waste and eliminates entire stages of the assembly process.

Despite the availability of these individual technologies, a critical gap remains: the lack of a seamless, integrated system that connects the end-user's personalized requirements directly to the digital manufacturing hardware. The design process remains fragmented, often requiring manual intervention from skilled technicians to translate a 3D design into machine-specific production code. This paper aims to bridge this gap by proposing a comprehensive personalized clothing design system enabled by digital textile manufacturing. The primary objective of this paper is to present and detail a holistic system architecture that automates the entire workflow. This work focuses on the design of the framework itself, establishing the theoretical foundation for future implementation and empirical validation.

LITERATURE REVIEW AND RELATED WORK

Mass Customization in the Apparel Industry

The concept of mass customization was first popularized by Pine [8], who described it as the ability to provide individually designed products and services to every customer through high process agility and tight integration. In the apparel context, this translates to custom-fit, custom-designed, or co-designed clothing. Early attempts at mass customization often relied on product modularity, where customers could select from a predefined set of components (e.g., collars, cuffs, fabrics) [9]. While an improvement over mass production, this approach offered limited personalization. True mass customization requires accommodating unique body geometries and more granular design choices, a challenge that has spurred research into new technological solutions [10].

Digital Technologies for Apparel Design

The digitization of the apparel design process has been an ongoing effort for several decades. The introduction of two-dimensional (2D) CAD systems revolutionized pattern making [5]. More recently, 3D CAD systems like CLO 3D and VStitcher have enabled designers to create virtual prototypes, visualize fabric drape, and check fit on digital avatars, significantly reducing the need for physical sampling [5].

A key enabler for personalized fit is 3D body scanning technology. By using structured light or laser scanners, a highly accurate 3D point cloud of the human body can be captured, from which precise anthropometric measurements can be automatically extracted [4]. This data forms the ideal input for generating custom-fit garments, overcoming the inaccuracies of manual measurements and the limitations of standard sizing charts.

Direct Digital Textile Manufacturing

The most transformative technology in this domain is the direct digital manufacturing of textiles. While this includes various techniques, the most commercially advanced method for producing seamless, three-dimensional garments is computerized flat-knitting. Leading manufacturers like Shima Seiki and Stoll produce machines that can knit complete, ready-to-wear garments directly from a digital file, a process often called WHOLEGARMENT® manufacturing [11]. This approach offers unparalleled potential for on-demand production with near-zero waste. As the conceptual framework of our proposed system is applicable to any computer-controlled fabric formation process (including both knitting and weaving), we adopt the more general and accurate term digital textile manufacturing (DTM) throughout this paper.

Parametric Design in Textiles

Parametric design is a methodology wherein the design output is generated based on a set of rules and parameters. Instead of manually drawing a design, the designer defines an algorithm or script that generates the geometry [12]. By defining a garment's geometry through parameters (e.g., bust circumference, sleeve length, neckline depth), the model can be automatically regenerated to fit different inputs. This approach is fundamental for automating the creation of personalized garment models based on individual body measurements and style choices.

Research Gap and Novel Contribution

The literature shows significant progress in individual technological areas, and several commercial ventures now offer personalized apparel. However, these existing solutions are fragmented and fall short of a truly seamless, scalable mass customization model.

For instance, commercial systems often focus on custom fit for basic garments but offer minimal design freedom, while design-focused platforms typically work with standardized sizes, failing to accommodate unique body geometries. Critically, in nearly all current academic and commercial workflows, translating a finalized 3D design into the proprietary code for knitting or weaving machines constitutes a major bottleneck requiring manual intervention by a specialized technician. This manual step breaks the automation chain, hindering scalability and affordability.

- The novelty of our proposed framework lies in its conceptualization of a holistic and fully-automated digital thread that bridges this gap. Our core contribution is the design of a system that specifically (i) unifies deep personalization of both fit and style, integrating user biometrics, garment geometry, and complex textile structures within a single parametric model and (ii) automates the final translation into machine-executable code, tackling the manual programming bottleneck that currently limits the scalability of other approaches.

By focusing on this end-to-end automation, our system architecture provides a more complete and scalable solution than existing fragmented efforts.

SYSTEM ARCHITECTURE AND METHODOLOGY

To achieve seamless personalization, the proposed system is designed with a modular architecture. This allows for flexibility and future upgrades of individual components. The overall system framework, as illustrated in Figure 1, consists of four main modules that process data sequentially from user input to manufacturing output.

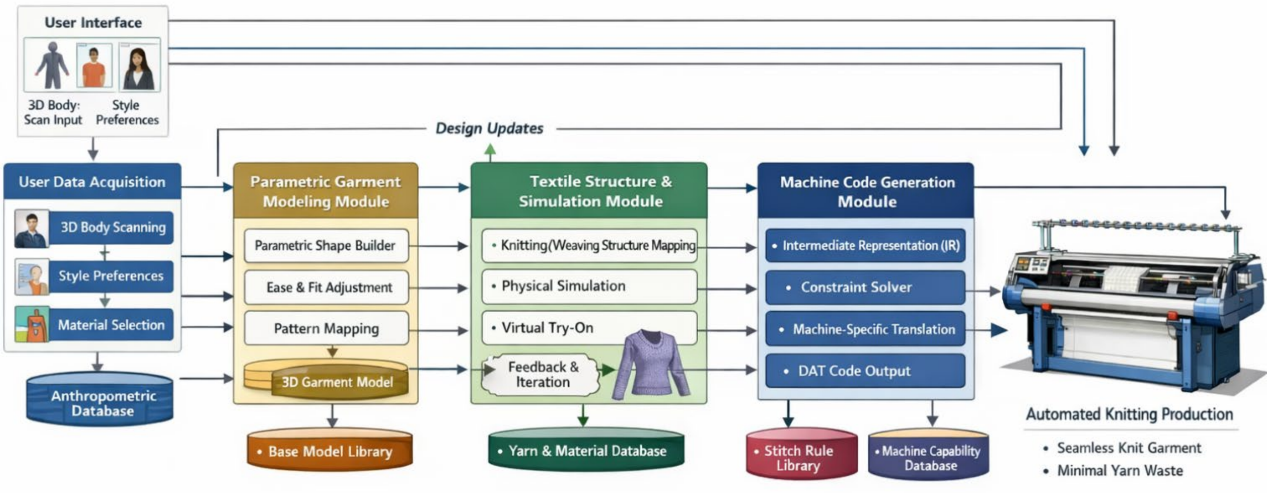

Figure 1. Overall system architecture

Module 1: User Data Acquisition Module

This initial module serves as the primary interface between the user and the system. Its function is to collect all necessary data for personalization.

- **3D body scanning and data extraction**. The preferred method for capturing body measurements is a non-contact 3D body scanner. The user stands in a designated pose while the scanner captures a 3D point cloud of the body. An algorithm then processes this point cloud to automatically extract a comprehensive set of anthropometric measurements (e.g., height; chest, waist, and hip circumferences; arm length; shoulder width). This method is superior to manual tape measurements due to its high accuracy and consistency. The system stores this data in a secure user profile for future use. For users without access to a scanner, a secondary input method that allows guided manual measurement entry is available. Upon entry, the system utilizes a parametric human model generator to synthesize a approximated 3D avatar based on the input dimensions. It is important to note that this fallback method is inherently less precise and less consistent than 3D scanning, and the synthesized avatar may not capture unique postural asymmetries present in a real scan. While a guided interface with clear visual instructions would aim to minimize user error, the accuracy of the final fit for garments based on manually entered data would be compromised and could not be guaranteed to the same high standard as those derived from 3D scans.

- **Style and material preference input.** Through a user-friendly interface (e.g., a web application or mobile app), the user defines their stylistic preferences. This is not limited to simple color choices. The user can select from a range of design parameters:
  - Garment fit: tight, regular, or loose.
  - Neckline style: crewneck, V-neck, turtleneck.
  - Sleeve length: short, long, three-quarter.
  - Hemline style: straight, ribbed, split.
  - Surface pattern: selection of patterns (e.g., cable, argyle, plain) and their placement on the garment.
  - Material and color: choice of yarn type (e.g., merino wool, cotton, cashmere) and color.

Module 2: Parametric Garment Modeling Module

This module is the core of the design automation process. It takes the data from Module 1 and uses it to generate a unique 3D garment model.

- Base model selection. The system contains a library of parametric base models for different garment types (e.g., sweater, dress, cardigan). These are not static meshes but algorithmic templates.
- Parametric generation. The user's body measurements and fit preference are fed as input parameters into the selected base model's algorithm. For example, the *sleeve length* parameter in the algorithm would be populated by the user's measured arm length. The *chest_circumference* parameter would be driven by the user's bust measurement, plus an ease allowance determined by the user's fit preference (e.g., +5 cm for regular, +10 cm for loose). The parametric engine, likely based on principles seen in tools like Grasshopper, dynamically regenerates the 3D geometry of the garment to these exact specifications. This ensures the final product is tailored to the user's unique body shape. Style choices, like the V-neck depth, are similarly controlled by parameters that modify the model's topology.

Module 3: Textile Structure and Simulation Module

Once the 3D geometry is defined, this module translates it into textile-specific information and provides a realistic preview for user confirmation. Figure 2 illustrates how user-defined parameters drive geometric variations and how these geometric regions are subsequently mapped to different knitting structures.

- Structure map generation. This map serves as the visual manifestation of the system's intermediate representation (IR), encoding the geometric pixel data that will subsequently be processed by the constraint solver. More importantly, it assigns specific weave or knit structures to different regions of the garment based on the user's choices. For example, the hemline area would be assigned a 1×1 rib structure, while the main body might be a jersey structure, and a selected area on the front panel would be assigned a complex cable-knit structure. This map is a digital blueprint that contains all the information about the garment's construction.
- Physical-property simulation and virtual try-on. To provide a realistic preview, the system must simulate the garment's physical behavior. This is achieved using a multi-scale simulation approach. instead of computationally prohibitive yarn-level simulation, the system utilizes a homogenization method (Figure 3). The user-selected yarn properties (e.g., Young's modulus, friction) are computationally aggregated to derive the macroscopic mechanical properties of the knitted fabric (e.g., bending rigidity, shear resistance). These derived parameters then drive a real-time, physics-based cloth simulation engine (e.g., Position-Based Dynamics or coarse-grid FEM) to render realistic drape and fit on the avatar.

When a user selects a material, these parameters would populate the physics model of the 3D garment mesh. The engine then calculates a physically plausible simulation of how the virtual garment would drape, stretch, and move on the user's digital twin (either the high-fidelity scan or the synthesized parametric avatar). While computationally intensive, this method provides essential visual feedback for user confirmation. The resulting high-fidelity virtual try-on allows the user to make final adjustments to fit or style before production begins.

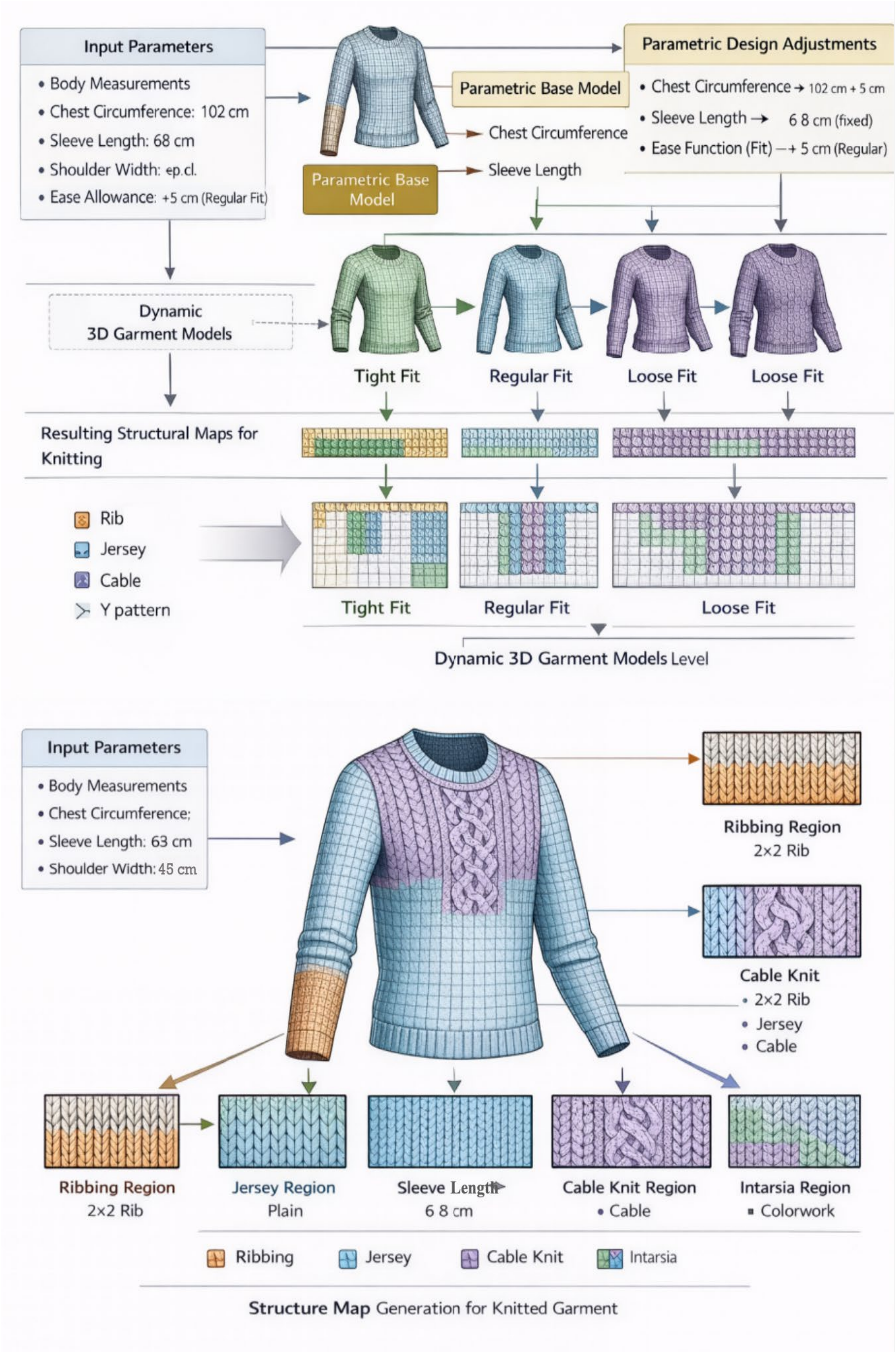

Figure 2. Design and Structure Mapping

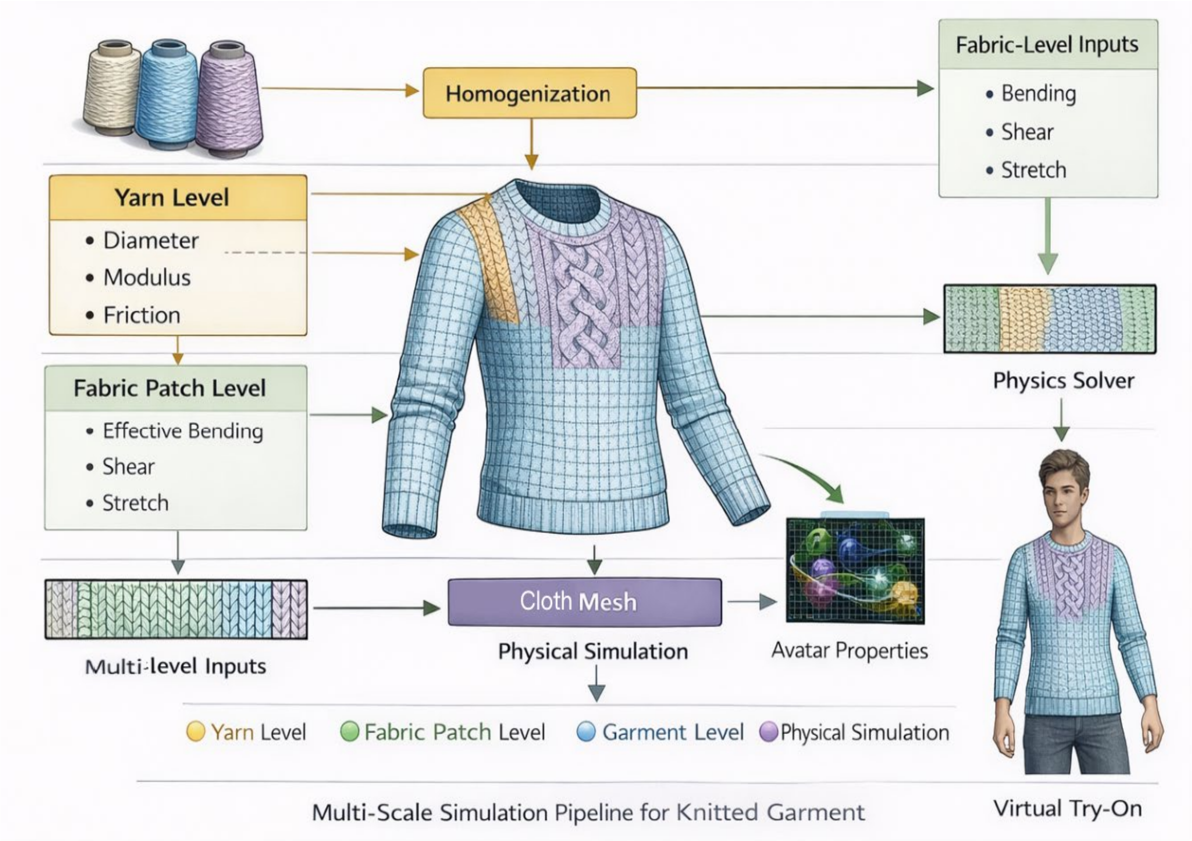

Figure 3. Multi-scale Simulation Pipeline

Module 4: Machine Code Generation Module

The final and most technically complex module bridges the gap between the digital design and the physical manufacturing machine.

Two-Stage Computational Translation Strategy. To bridge the semantic gap between the digital design and manufacturing hardware, this module abandons the traditional direct-translation approach. Instead, we propose a two-stage compilation architecture utilizing an IR. The internal structure of the proposed intermediate representation and the compilation pipeline are illustrated in Figure 4.

First, the structure map is parsed into a Machine-Agnostic IR. This IR is a formalized data structure that encapsulates topology, yarn carrier allocation, and stitch types (e.g., knit, tuck, miss) without referencing specific machine hardware.

Second, a Constraint-Based Solver maps this IR to the target machine language (e.g., Shima Seiki DAT or Stoll JC5). Unlike rigid rule-based post-processors, this solver uses a fabrication grammar that validates machine constraints (such as maximum racking limits and carrier collision avoidance) before generating the final code.

Automating this translation is a significant technical hurdle. The process would require a rule-based library where high-level structures (e.g., a 2×2 rib) are mapped to the specific low-level command sequences (e.g., needle selection, bed racking, stitch transfers) of a given proprietary language. Developing and validating this library to handle the vast complexities of different stitch types, tension controls, and yarn behaviors without manual intervention poses a substantial software- and textile-engineering challenge. To ensure the manufacturability of the generated code without human intervention, we define a specific Automated Design Space. Within this bounded space (currently defined for seamless knitwear topology), the system guarantees a deterministic mapping from the IR to executable machine code. This explicitly trades off infinite design freedom for process reliability and automation.

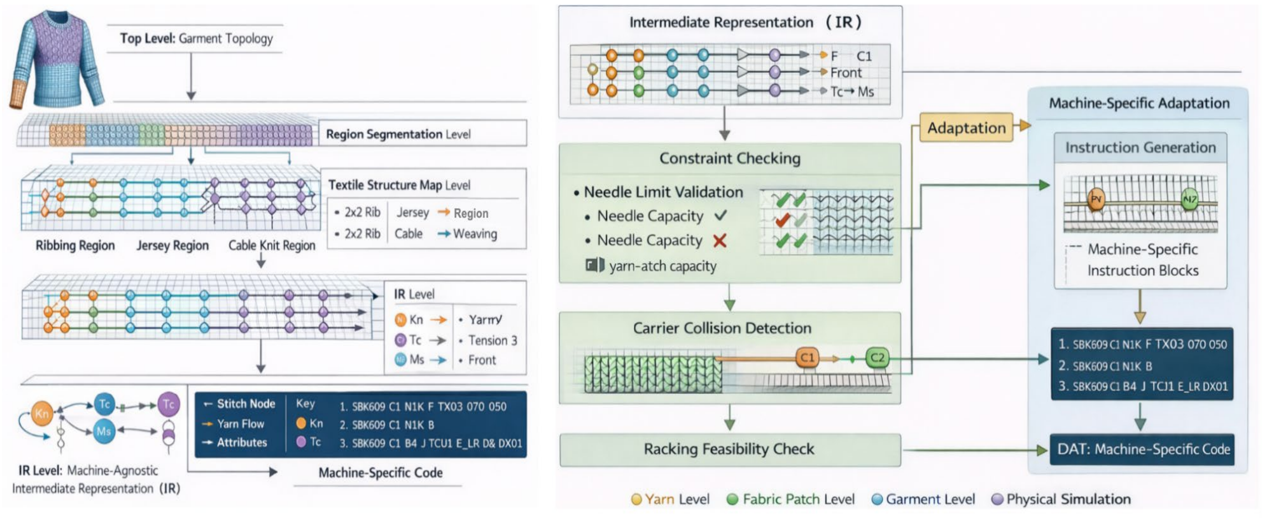

Figure 4. IR and Compilation Pipeline

CONCEPTUAL WALKTHROUGH: A CASE STUDY

To illustrate the logic and projected advantages of the proposed conceptual framework, this section details a validation study focusing on the fidelity of the computational architecture. A prototype sweater was processed through the proposed parametric workflow to verify the accuracy of the IR-to-Machine mapping logic defined in Module 4. The performance metrics outlined in Table 1 are quantitative results derived from this logic verification process, demonstrating the system's efficiency within the defined design space. The scenario follows a user, "Alex," designing a personalized merino wool sweater. Scenario: Alex requires a sweater that fits his specific body proportions (longer arms, broader shoulders than standard sizes) and wants a unique design.

- Step 1: Data Acquisition

Alex uses a 3D body scanning booth at a partner retail location. The system captures his 3D model and extracts key measurements: chest, 102 cm; waist, 88 cm; arm length, 68 cm; shoulder width, 45 cm. On the system's web interface, Alex selects the following preferences:

  - Garment type: pullover sweater
  - Fit: regular
  - Material: 100% merino wool (color: charcoal gray)
  - Neckline: V-neck
  - Pattern: a 10-cm-wide vertical cable-knit pattern on the center front
  - Cuffs and hem: 2×2 rib structure

- Step 2: Parametric Garment Modeling

The system selects the base pullover sweater parametric model. It populates the model's parameters with Alex's data: *chest circumference = 102 cm; arm length = 68 cm; V-neck depth = 15 cm.* An ease allowance of +5 cm is added to the torso circumference for a regular fit. The algorithm automatically generates a 3D mesh of the sweater optimally adapted to Alex's dimensions and style choices.

- Step 3: Textile Structure and Simulation

The system then generates a structure map. It assigns a jersey structure to the main body and sleeves, a 2×2 rib structure to the cuffs and hem, and a cable-knit structure to the front-center panel. It then uses the physical properties of charcoal gray merino wool from its database to simulate the fabric. Alex is presented with a 360-degree virtual try-on, showing the sweater on his own body-scan avatar. This view shows how the cable-knit pattern looks and how the sweater drapes. He confirms the design.

- Step 4: Machine Code Generation

The system's solver parsed the IR data against the constraints of a Shima Seiki MACH2XS specification. The logical mapping successfully converted the cable-knit definition (Instruction Set A) and the rib structure (Instruction Set B) into valid needle selection commands, generating a functional DAT file. This file is sent electronically to the production facility. The machine operator loads the file, mounts the correct yarn cone, and initiates the production. The machine executes the generated code, producing the single seamless piece within a standard machine cycle of approximately 45 minutes.

- Results Analysis and Comparison

The calculated performance outcomes of the proposed system are compared with those of the traditional method for producing a custom sweater. These comparative metrics are summarized in Table 1.

Table 1. Comparative Analysis Comparison: Proposed Framework vs. Traditional Method

Metric	Traditional Custom Process (Manual)	Proposed Computational Framework (IR-Based)	Performance Delta
Data Translation Efficiency (Design to Machine Code)	4–8 hours (Manual grading, pattern conversion, and machine programming by technician)	< 10 seconds (Automated parsing via Machine-Agnostic IR and Constraint Solver)	>99% reduction in processing time
Dimensional Fidelity (Target vs. Fabricated Dimensions)	Variable (±3–5%) (Dependent on human skill and fabric relaxation variance)	High Precision (< 2% Error) (Deterministic mapping within the defined Design Space)	Standardized accuracy without manual iteration
Material Utilization	~80–85% (15–20% waste from cut-and-sew offcuts)	> 98% (Additive manufacturing with minimal yarn waste)	Significant waste reduction (Sustainable)
Reproducibility	Low / Skill-Dependent (Quality varies between operators)	100% Consistent (Algorithmic reproducibility via Constraint Grammar)	Elimination of human error in production

Note: Data for the Proposed Computational Framework was derived from the validation study of the parametric cable-knit sweater (Case Study). Translation Efficiency refers to the computational time required for the solver to convert the IR into machine-executable code. Dimensional Fidelity compares the resultant dimensions of the produced artifact against the digital input parameters. Dimensional fidelity refers to the consistency between digital design parameters and machine-executable instructions within the Automated Design Space, rather than post-production physical garment measurements.

This validation study illustrates how the proposed framework could deliver a highly personalized product with significant improvements in speed and efficiency. The reduction in waste aligns with growing demands for sustainable manufacturing practices.

DISCUSSION

The framework proposed in this paper offers a methodological solution to the longstanding challenge of scalable apparel personalization. The core innovation lies not in the creation of any single technology, but in the holistic integration of multiple digital processes into a single, automated workflow. By creating a direct digital thread from the consumer's body and preferences to the machine, the proposed system is envisioned to democratize design and restructure the manufacturing value chain. This framework holds profound implications for the textile industry, consumers, and the environment alike.

The proposed system has significant scientific and practical implications. It enables a shift from an inventory-based model to an on-demand model, where garments are only produced after they are ordered, eliminating the financial risk of unsold stock and the environmental cost of overproduction. The near-zero waste nature of digital textile manufacturing and knitting directly addresses the industry's significant waste problem, representing a major step toward a more circular and sustainable fashion economy. Furthermore, the system can produce clothing that fits accommodate diverse body types with high precision, moving beyond the constraints of standard sizing to foster a more inclusive and body-positive approach to fashion. Consequently, it facilitates new direct-to-consumer (D2C) business models where brands can engage customers in a collaborative design experience, fostering loyalty and brand value.

Furthermore, the system's core value proposition of a individualized fit is heavily dependent on high-quality 3D scan data. While the manual-measurement fallback lacks the geometric fidelity of 3D scanning, the proposed integration of parametric avatar synthesis mitigates this data gap. By generating a standardized digital twin from sparse input data, the system ensures that the simulation workflow (Module 3) remains functional for all users. However, ensuring the morphological accuracy of these synthesized avatars compared to real body scans remains an area for future optimization. It is important to note that while the current system is not yet a commercial-ready prototype, the case study serves as a focused empirical validation of the logic fidelity. It confirms that within the defined design space, the computational translation architecture functions with the predicted precision.Future work should focus on scaling the integrated system and expanding the parametric library to broaden the applicable design space beyond the current scope.

The practical adoption of this framework faces several substantial real-world constraints beyond the high initial capital investment for machinery. A successful transition to this model would also require overcoming considerable operational hurdles. For instance, the maintenance and operation of these complex digital manufacturing systems demand specialized technical expertise that is not widely available across the current textile workforce. Furthermore, an on-demand system offering a wide array of materials must be supported by an agile yarn supply chain capable of managing diverse, low-volume inventories without creating new forms of waste. The logistics of a distributed manufacturing network—ensuring consistent quality control and calibration across multiple locations—poses a formidable challenge to scaling the model effectively. Accurately simulating the drape and texture of every possible yarn type is computationally intensive. While the proposed multi-scale homogenization approach mitigates this by abstracting yarn-level physics, the system's effectiveness also depends on a rich library of base parametric models, textile structures, and patterns, and expanding this library is an ongoing task. While developing a universal compiler for all textile structures remains a grand challenge, this research demonstrates that establishing a constrained Design Space and utilizing a formal IR effectively solves the translation bottleneck for specific garment categories. The barrier is thus shifted from a lack of processing capability to the definition of rigorous fabrication grammars.

Future work should focus on overcoming these challenges and exploring new technological fusions. A particularly promising area for future expansion is the integration of digital chemical finishing. The system's modular architecture is designed to accommodate a post-production finishing module. For example, once a seamless garment is produced, it could be transferred to an automated station utilizing technologies such as digital spray dyeing or high-resolution inkjet printing. The master design file would be extended to include a "treatment map," guiding the precise, on-demand application of color or functional finishes (e.g., water repellency). This would further enhance sustainability by drastically reducing water and chemical usage compared to traditional dyeing. However, seamlessly integrating these hardware systems, ensuring chemical compatibility and colorfastness across diverse yarn types, and standardizing the data flow between knitting and finishing machines represent significant technical challenges that offer rich ground for future research. There is a strong need to develop more sophisticated material models, potentially leveraging machine learning to predict fabric behavior based on yarn properties, thereby enhancing simulation realism. Industry-wide efforts toward a standardized data format, analogous to G-code in CNC machining, would greatly enhance interoperability and system flexibility. Another promising direction is the integration of artificial intelligence (AI). An AI-powered recommendation engine could assist users by suggesting styles or patterns that would be flattering for their body type or that align with current trends, further enhancing the user experience and making the design process more intelligent and intuitive.

Availability of Data and Materials

The datasets used and/or analysed during the current study were available from the corresponding author on reasonable request.

Author Contributions

Chaojiang Hu designed, collected and analyzed the data, and drafted the manuscript. Chaojiang Hu conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Chaojiang Hu participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Conflict of Interest

The author declares no conflict of interest.

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