Toward Electronic Design Automation for Electronic Textiles: A Knowledge-Based Design Framework and Case Study of Design Rules for Electronic Textile Circuits

A Dissertation

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Olaitan Adeleke

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Dr. Lucy Dunne

Dr. Brad Holschuh

Dr. Elizabeth Bye

Dr. John Sartori

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Dedication

To my late mum, Bukola Omolola Adisa, I hope I have made you proud. I couldn't have asked for a better mother. Rest peacefully in God's bosom. The thoughts of you and the countless ways you shaped my life gave me strength to keep going. I truly found courage in your love. I heard you calling me "Dr." long before this moment came to pass and you made this happen in your own way.

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Abstract

Textile circuit boards (TCBs) present a promising solution to the limitations of rigid printed circuit boards (PCBs) in wearable electronics applications. However, the development of TCBs remains fragmented, lacking standardization and structured design methodologies. This dissertation addresses this gap by developing a system-level framework to support the design and fabrication of textile circuits, with a focus on the stitching method as a representative manufacturing approach. The research was conducted in three distinct phases. Phase one focused on collecting and formalizing expert knowledge, drawing from multiple sources, including expert interviews with e-textile practitioners, a synthesis of existing literature, and experiential insights gained through research through design (RtD) case study conducted by the designer-researcher. Phase one uncovered key challenges, major variables, performance indicators used to evaluate system requirements, and common pain points in current design and manufacturing practices. The analysis of these data sources revealed core categories and design variables essential for enabling a more structured approach to textile circuit development. In phase two, these identified categories were translated into a hierarchical design framework tailored to electronic design automation (EDA) for e-textiles, that was validated through a second round of interviews with lead experts. Phase three involved characterizing selected circuit design and fabrication variables, such as trace (pathway) spacing, trace width, trace straightness, and trace resistance to translate the framework into design rules and to explore how these parameters influence manufacturers' documentation, such as datasheets. The goal of phase three is to inform the development of data-driven electronic design automation systems that enhance repeatability, reliability, and communication between designers and manufacturers. Results from the three phases demonstrated that: (1) Key system variables, such as stitch type, substrate behavior, and circuit layout, interact in complex ways that are not currently documented or standardized, but are central to both design intent and system performance, (2) A hierarchical framework can successfully organize these variables into application objectives, standards, design rules, and methods, thus supporting structured decision-making and enabling integration with EDA tools, and (3) Experimental characterization revealed how fabrication parameters like thread type, fill density, and cleaning status significantly impact trace geometry and electrical resistance, providing a foundation for translating framework logic into actionable, data-driven design rules. Overall, this work identifies the core functions an EDA tool for e-textiles must perform to support reliable and efficient design. By analyzing the design processes, input variables, and performance considerations specific to textile circuits, we outline the functional requirements such an EDA tool should fulfill. This includes understanding the types of input variables designers rely on, the constraints they navigate, and the outputs or guidance the tool should generate. Once these foundational elements are defined, a series of targeted, illustrative examples are used to show how these functions might be realized within an EDA tool. This approach formalizes TCB design practices by linking empirical data and expert knowledge through a conceptual framework, ultimately advancing standardization and enabling more scalable, consistent production in textile circuits.

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1. Introduction

1.1 Background

Printed circuit boards (PCBs) are the foundation of virtually all electronic systems, ranging from consumer electronics to automotive and aerospace applications. However, their rigid and conventionally planar form factor renders them ill-suited for integration into soft, flexible, and dynamic environments such as wearable technologies, smart textiles specifically. The growing field of wearable electronics necessitates a convergence between textile engineering and electronics manufacturing. This interdisciplinary challenge demands new materials, design approaches, and production techniques that leverage the strengths of both domains, such as the softness, breathability, and conformability of textiles and the functional precision and repeatability of electronics. Textile circuit boards (TCBs) have emerged as a promising alternative and complement to rigid PCBs in wearable technology applications. TCBs offer enhanced flexibility, drape, and integration potential with the human body, enabling on-body electronic applications that traditional PCBs cannot support (Baeg & Lee, 2020; Lee et al., 2009). However, the fundamental incompatibility between the soft, porous, and deformable nature of textiles and the rigid, impermeable, and flat structure of electronics present substantial integration challenges. Textiles are hydrophilic, stretchable, and conformable, while electronics are typically hydrophobic, rigid, and dimensionally stable.

Due to the absence of standardized methods, textile circuit design has largely depended on individually tailored and experimental approaches, forcing developers to rely on costly trial-and-error processes. Unlike the highly standardized PCB industry, where digital circuit designs are easily and reliably translated into physical products through globally recognized protocols, TCBs lack cohesive design frameworks and manufacturing standardization. As a result, TCB fabrication is often driven by iterative experimentation, which leads to fragmented knowledge, inconsistent outcomes, and limited scalability (Molla et al., 2017; Somerset, 2021). To move toward industrial adoption, it is essential to formalize TCB design and production through generalizable design rules that apply across various manufacturing methods.

However, the complexity and variability inherent in textile materials and fabrication techniques make it difficult to create reliable design rules without some degree of standardization. Standardization introduces constraints that make design outcomes more predictable, which in turn makes it easier to anticipate performance results. However, different types of constraints can lead to different results, as illustrated in Figure 1 below. TCB design and fabrication also struggles with immaturity of fabrication processes. For example, if a conductive trace (pathway) does not maintain consistent resistance along its length due to variability in the manufacturing process, it becomes impossible to define effective design guidelines for circuit design to ensure performance or safety. In TCB design, there remain areas where methods are not yet mature enough for standards or rules to be effectively defined.

While a range of fabrication methods, such as weaving, knitting, embroidery, and printing, can be used to create textile circuits, this study focuses on stitching as a representative case. Stitching is widely used and accessible, making it a practical platform for prototyping and production. To support the development of design rules, this research identifies and analyzes key variables involved in textile circuit fabrication, using stitched circuits to explore how different parameters influence manufacturability, electrical functionality, and integration.

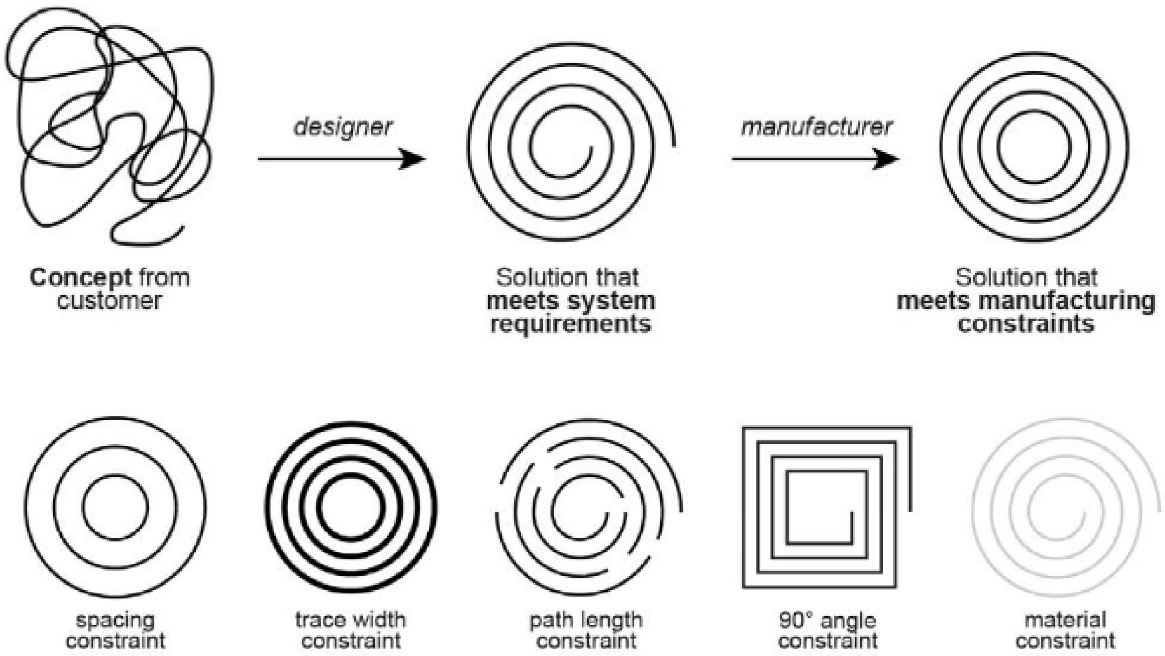


Figure 1 - Impact of manufacturing constraints on design (Each figure shows different manufacturing constraints yields different results (Knowles 2023))

1.2 Defining Core Terms and Their Connections

Designing functional, reliable, and safe electronics requires a structured approach that integrates standards, design rules, application objectives, and method development. Each element plays a distinct but interconnected role in guiding the development process. **Standards** establish common terminology, define test methods, and set minimum performance thresholds, thereby ensuring consistency and comparability across materials, components, and systems. They help to align designers and manufacturers on how performance is measured and communicated. **Design rules**, on the other hand, define the specific conditions and constraints needed to ensure a circuit performs reliably under its intended use. These rules inform decisions about layout, material selection, integration strategies, etc.

While both standards and design rules may be tailored to specific applications, for instance, a waterproofing standard may define test methods, and design rules specify acceptable resistance ranges for washable circuits, the **application objective** provides the critical context. For example, a waterproofing standard may apply broadly but only becomes relevant if a product is intended for wet environments. In such a case, the standard outlines how to verify waterproof performance, while the design rule prescribes the specific design actions required to achieve it. Further, application objectives often include performance considerations that, while essential to a specific application, do not generalize to other applications (such as accuracy tolerances for a specific sensor or actuator). As new applications emerge and gain popularity, standards and/or design rules that pertain to a group or class of applications (such as the waterproofing example) may be developed.

Finally, **method development** is a necessary precursor to standards and design rules. Consensus among experts, suppliers and manufacturers about effective, repeatable methods is necessary in order for those methods to be standardized or for design rules to be defined. Method development is accomplished by both researchers and practitioners, and more-effective methods gain traction by means of their practical feasibility. Application objectives may necessitate application-specific method development: here, we focus on development of more-generalizable methods such as methods of forming joints between components and traces, or methods of allowing traces to cross one another.

This section examines how standards, design rules, application objectives, and method development interact in electronic design, and how their alignment supports feasibility, interoperability, and manufacturability, especially as these principles are adapted to emerging domains like textile-based electronic circuits.

1.2.1 Standards

Standards are formalized, consensus-based documents developed by regulatory bodies, industry consortia, or international organizations (e.g., ISO, IEEE, IPC) to promote uniformity in products, materials, processes, and testing procedures. They serve several critical roles, including but not limited to:

- **Interoperability**: Standards ensure that components and systems can function together seamlessly across different manufacturers and platforms.
- **Quality Assurance**: Adherence to standards supports consistent manufacturing outcomes and helps minimize variability across production batches.
- **Safety and Compliance:** Regulatory standards define safe operating limits and testing protocols in electronics. For example, IPC-A-610, Acceptability of Electronic Assemblies, establishes industry-accepted criteria for the workmanship and inspection of electronic assemblies. This standard outlines performance benchmarks for solder joints, component placement, and overall assembly quality. It also classifies different levels of acceptability based on the intended end-use environment and introduces standardized terminology and visual examples to guide manufacturers and inspectors.
- **Benchmarking**: Standards such as ASTM test methods for assessing tensile strength in traditional textiles, offer reference data for evaluating product performance.

1.2.2 Design Rules

Design rules are explicit constraints and best practices derived from the properties of materials and the capabilities of fabrication methods. These exist in order to help developers ensure that their design will function as intended when fabricated. Unlike standards, which are often broad, externally imposed and focus on assessing performance after a device has been fabricated, design rules are focused on ensuring functionality in the design before the device is fabricated. They are specific to material-method combinations and can evolve over time as new materials and techniques are introduced into PCB manufacturing. Design rules serve several key functions, including:

- **Manufacturability:** They ensure that layout features, such as trace spacing, trace width, via (vertical interconnect access) size, and component clearance, are compatible with the tolerances of fabrication processes like PCB etching, surface mount assembly, or automated soldering.
- **Electrical Performance**: They help define acceptable limits for parameters such as resistance, voltage drop, and insulation, which depend on the length, geometry, and material of conductive paths.

As these rules accumulate, they form the foundation for automating circuit development and design validation in electronics production. Using electronic design automation (EDA) tools, PCB designers and engineers can apply these rules to streamline development and reduce the need for costly trial-and-error iterations, ultimately accelerating innovation while maintaining reliability and consistency.

1.2.3 Application Objectives: Context-Driven Design Constraints

While standards and design rules are foundational tools that ensure minimum, generalizable requirements such as circuit functionality, reliable interconnects, and repeatable component performance are consistently met, **application objectives** are driven by the specific context in which the end product will be used. These requirements define the ultimate design objectives and are shaped by user needs, environmental conditions, and regulatory expectations**.** Application requirements are typically measured against performance indicators defined for the specific application and may span both electronics and textiles. For example:

- **Environmental Conditions**: A wearable designed for outdoor use must account for factors such as washability, UV exposure, and temperature fluctuations.
- **User Interaction:** Wearables intended for infants must avoid materials like nickel in areas that come into direct contact with the skin due to the risk of allergic reactions.
- **Functional Targets**: A phototherapy garment for neonatal jaundice, for instance, must deliver specific light wavelengths and irradiance levels, which influence decisions about LED placement, thermal management, and light shielding.

In many cases, application objectives intersect with additional domain-specific standards. For example, an electronic system embedded in firefighter turnout gear must not only comply with electronic reliability standards but also meet textile performance standards related to flame resistance and thermal insulation.

1.2.4 Method Development

In addition to the categories of **Standards (S)**, **Design Rules (DR)**, and **Application Objectives (AO)**, there is **Method Development (MD)**. This category captures the *procedural techniques* that enable material–component integration, circuit realization, and fabrication processes in e-textiles, many of which are developed through experimentation and field practice, long before they are codified into design rules or standards.

Where AO defines *what* should be designed (based on use case), S defines *what must be followed* (to ensure safety and compliance), and DR defines *how to optimize within constraints*, MD addresses the critical question of **how the work gets done**. These are not mere assembly instructions; they are often innovative, trial-and-error processes that push the boundaries of what is currently possible, and in doing so, lay the groundwork for scalable, automated systems.

Several examples illustrate the importance of MD across the evolution of the field:

- Buechley et al.'s introduction of the **LilyPad Arduino** system went beyond providing sewable components, it established a method for **soft, thread-based interconnection** and significantly influenced how electronics are taught and prototyped within textile contexts (Buechley et al., 2013).
- Linz et al. developed a novel method for integrating electronics into fabric circuits using nonconductive adhesive bonding, offering a practical alternative where traditional techniques like soldering or stitching are unsuitable, particularly in soft or layered circuits (Linz et al. 2012).

- Dunne et al. introduced a **multi-layer stitched circuit technique** that enabled vertical routing of conductive threads across fabric layers using controlled stitch and crimped component vias. This method established a fabric-compatible routing method that overcomes key limitations in traditional planar e-textile layouts, such as limited vertical routing challenges. By allowing traces to pass between layers while maintaining electrical isolation and mechanical flexibility, this approach expanded the spatial design possibilities for wearable and textile-embedded circuits (Dunne et al., 2012).

Taken together, these examples show how MD operates upstream of formalization. These techniques can evolve into standard practice or automated tools if proven to be repeatable, manufacturable, and compatible with existing systems. For example, a reliable stitched-joint method may later inform a **design rule** for pad geometry or stitch count or be embedded into a **component library** in an EDA environment as a selectable termination strategy. By formally incorporating **MD** into the e-textile design framework, we acknowledge the central role of tacit, procedural knowledge in shaping the field's trajectory. Capturing and sharing these methods as shown in Figure 2 below, not only enhances reproducibility and transparency but also ensures that future tools, rules, and standards remain grounded in the practical realities of fabrication.

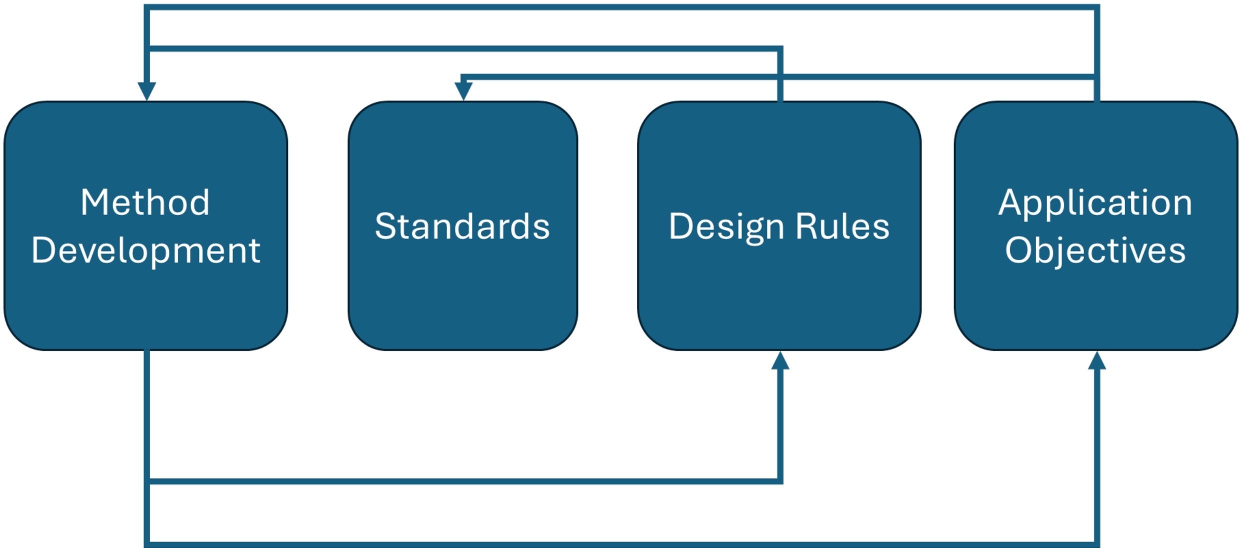


Figure 2 - Image showing the connections between MD, S, DR, and AO

1.3 Motivation

While each of these elements (standards, design rules, application objectives, and method development) serves a distinct role, effective and robust design arises from their alignment. Method development is the exploratory phase in which fabrication and design innovation happens, and more-successful solutions are refined. Standards establish the baseline requirements for safety, quality, and interoperability and the ways in which developers demonstrate that their design meets those requirements. Design rules are actionable constraints, considering specific materials, fabrication techniques, and system-level considerations, that help designers avoid errors in their system design that might not otherwise be discovered until the device is fabricated. Application requirements define the end goals by articulating functional performance, user needs, and environmental constraints for a particular use case, along with corresponding methods for measuring device performance. With this understanding, the goal of this dissertation is not to produce new standards, although existing standards were reviewed and analyzed as part of the literature review to inform our design rule development. Similarly, application-specific requirements were used to define certain variables relevant to the case study, and our efforts to define design rules encounter several challenges related to immature method development. However, the primary focus is on charting a path toward a comprehensive set of design rules that can guide circuit development for scalable and manufacturable e-textiles across application domains, a gap that currently exists in the field. This need stems from limitations in current practices, which often depend on iterative, ad hoc prototyping without a structured framework to support decision-making. By introducing a rule-informed approach, the intention is to streamline the development process, reduce inefficiencies, and help bridge the gap between concept and production readiness.

Although previous work has identified and characterized specific TCB parameters (e.g., Eichinger et al., 2007; Ismar et al., 2020; Zheng et al., 2022), many variables remain unexplored, particularly those involving interdependent relationships such as leads (components' metal connection), traces, and pads (conductive areas where leads are attached) in textile substrates. Also, when parameters have been studied, they are often considered in isolation, without addressing how they collectively influence system performance or manufacturability. This dissertation bridges this gap by developing a system-level framework for textile circuit design, grounded in empirical data, expert insights, and structured characterization. The goal is not to develop the entire range of design rules that a full EDA system would require, the scope of that effort exceeds the available resources, and the work involved does not align with the higher-level intellectual goals of a PhD. Rather, the overarching goal is to establish a roadmap toward reliable, repeatable, and scalable textile circuit design, and to demonstrate a few examples of how this roadmap would be reduced to practice. This is critical because effective design modeling, repeatability, and manufacturability are key requirements for streamlining prototyping and transitioning from prototyping to production (Venturi & Taylor, 2022). The cost associated with long iterative prototyping presents a significant barrier for wearables, where development cycles are often constrained by resource limitations, skilled labor requirements and the need for functional integration across diverse materials and components (Molla et al 2020, Stoppa & Chiolerio, 2014).

1.3.1 A Historical Perspective on Circuit Design and Its Relevance to E-Textiles

The e-textile field is at a pivotal moment where automation and scalable manufacturing are not only desirable but increasingly feasible. While the concept of the PCB emerged in the 1930s, it wasn't until the 1970s, with the advent of Electronic Design Automation (EDA) tools, that circuit design became truly scalable, standardized, and manufacturable (Figure 3). Similarly, while textile circuits began to emerge around the early 2000s, the field has since matured, with a growing body of materials, integration methods, and use cases. Today, we have accumulated enough fabrication methods, design variables, performance indicators, and real-world applications to begin formalizing design rules and automation frameworks for e-textiles. This makes it the right time to shift from one-off prototyping toward structured, repeatable design methodologies, paving the way for EDA-like systems that can bring the same transformation to e-textiles that EDA once brought to PCB design.

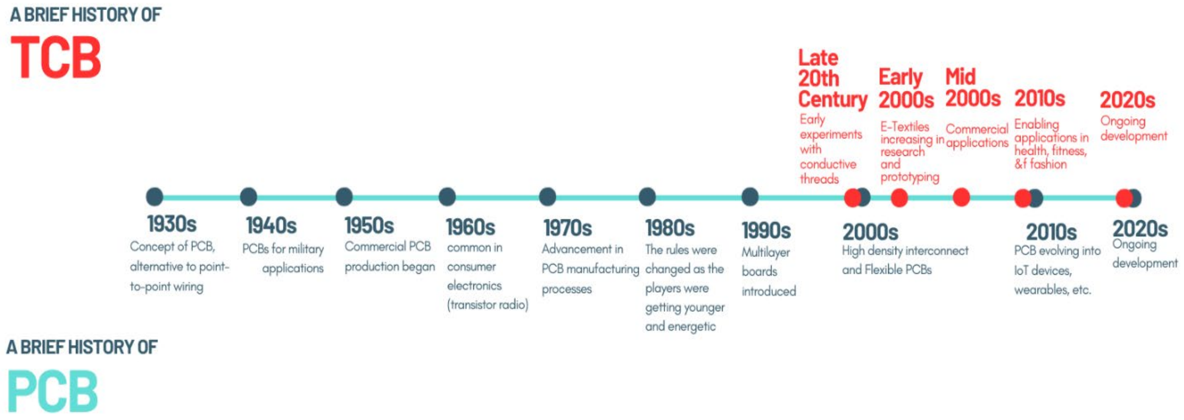


Figure 3 - Historical chart comparing TCB and PCB development timelines

1.4 Research Gap and Questions

As stated earlier, a key gap in the field is the lack of detailed, comprehensive understanding of how TCBs differ from traditional PCBs, and what an EDA tool for TCBs would need to encompass. While PCB design benefits from well-established standards and automation tools, TCBs lack a holistic framework that identifies and organizes the variables involved in their design and fabrication. This missing foundation limits the ability to develop design rules that would enable automated, scalable, and reliable e-textile circuit development. This study aims to begin addressing that gap by mapping key TCB manufacturing variables, exploring their interrelationships, and characterizing a subset of these variables into generalizable design rules for a future EDA tool. While we do not aim to fully resolve the gap, we hope to provide a foundational structure that future research can build upon to further advance the development of EDA tools for TCBs. To try and fill this identified gap, we divided our study into three phases, and each phase has research question(s) as summarized in Table 1.

Table 1 - Table Summarizing Research Questions at Different Research Phases

Research Phase	**Research Questions**
Phase 1: Literature Review / Interviews / Case Studies (Chapters 2, 3, 4)	What are the defining design variables that experts consider when developing effective TCBs? What performance indicators are used to characterize TCB performance? How do design variables and performance indicators relate to each other in TCB design?
Phase 2: Framework Development & Validation (Chapter 5)	How can design variables, performance indicators, and their interrelationships be formalized to inform the design of an EDA system for TCBs?
Phase 3: Design Rule Development (Chapter 6)	What example variables and method characteristics and relationships must be established to implement TCB design rules in practice?

1.5 Research Methodology

1.5.1 Study Design

To achieve this, the study was carried out in three interconnected phases:

Phase 1- Variables Identification and Synthesis: This phase focused on identifying key variables and challenges associated with the design and fabrication of TCBs. To achieve this, we adopted a triangulated qualitative research strategy that included (1) a systematic literature review, (2) in-depth semi-structured interviews with e-textile experts, and (3) a Research Through

Design (RtD) case study. This triangulation was employed to provide a more comprehensive understanding of the field, particularly given the early-stage and rapidly evolving nature of e-textile characterization (Cherenack et al., 2010). It reflects a qualitative research strategy aimed at gaining deep insight into complex phenomena (Creswell et al., 2007). Collectively, these methods enabled the exploration of critical pain points, recurring variables, and broader integration challenges across the e-textile domain, contributing to the development of a hierarchical structure of design variables that inform design-for-manufacturing (DFM) considerations in textile-based circuits.

Data collection focused on both input variables, such as trace width, stitch length, spacing, stitch type, yarn type, and thread diameter, and associated performance indicators like electrical resistance. These variables were considered independently of specific fabrication methods to ensure an inclusive and flexible mapping of the design space. The literature review surveyed academic publications and relevant PCB and printed electronics standards from 2000 onward, reflecting the period during which e-textile research began to gain momentum (Post et al., 2000). Expert interviews were conducted with professionals possessing at least five years of experience in e-textile circuit design. Participants, recruited through targeted recruitment and snowball sampling, brought people with diverse disciplinary backgrounds and offered access to tacit knowledge often missing from the published record.

The RtD case study served as a generative and reflective process grounded in iterative prototyping and hands-on fabrication. RtD was selected for its ability to generate situated, practice-based knowledge and to surface tacit and emergent insights inaccessible through conventional empirical methods. This approach was especially valuable for addressing knowledge gaps in areas where academic and industry literature lacked specificity, contextual detail, or actionable design guidance. Phase 1 thus laid the conceptual and empirical groundwork for the framework, establishing an evidence-based understanding of the key variables and conditions shaping textile circuit design.

Phase 2 - EDA Framework Development and Validation: The second phase focused on constructing and validating a decision-support framework specifically tailored to EDA for textile circuits. Drawing from literature findings, expert input, and researcher insights from Phase 1, we identified key categories and variables that could inform EDA development and organized them into a structured, hierarchical framework through an iterative process. This phase involved both the classification of variables and the design of the framework's architecture. The validation study aimed to refine the framework through targeted expert engagement. We presented a visual representation of the framework in a Miro board and a Neo4j graph database alongside a structured interview guide to prompt feedback on its logic, terminology, completeness, and usability. Experts were asked to evaluate whether the hierarchical structure aligned with real-world design workflows, to identify any missing variables or categories, and to assess whether the level of abstraction was appropriate for practical decision-making. Thematic analysis of expert responses highlighted key areas for refinement and also prompted us to revisit and recontextualize findings from Phase 1, ensuring coherence and alignment across both phases.

Phase 3 - Translation of Framework into Design Rules through Example Characterization Studies - The final phase focused on reducing the EDA framework to practice by developing design rules. This began with the empirical characterization of key fabrication variables emerging from the Phase 1 data collection, such as stitch spacing, trace diameter, and electrical resistance, in relation to the stitching method specifically. The goal was to measure the interrelated variables identified in the framework such that they could be converted to rules that would automate decision-making during the circuit development process, and to understand how this kind of characterization and rule development would interface with EDA developers' and manufacturers' documentation practices. In particular, the study highlights how relational insights, such as the interplay between trace dimensions and electrical resistance, can inform parameter selection for textile circuit applications. Based on these findings, this phase concludes by proposing design rules that can be implemented in a future EDA system. Additionally, it offers recommendations for improving manufacturer datasheets. Figure 4 below shows the diagram showing the study design workflow.

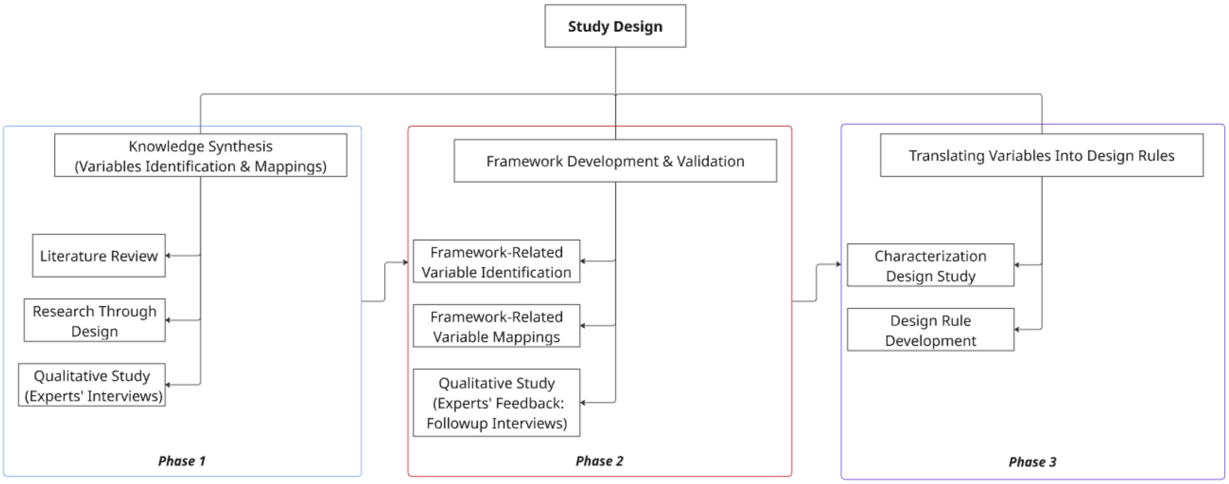


Figure 4 - Study design workflow

By combining insights from knowledge formalization and empirical characterization, this work contributes to the long-term goal of establishing design automation and standardization practices for textile circuit board development across various fabrication methods.

1.6 Dissertation Structure

The structure of this dissertation is as follows and shown in Figure 5:

- Chapter 1 introduces the motivation, background, and scope of the study, and the research objectives outlining the need for a system-level framework in textile circuit design and its study design.
- Chapter 2 reviews relevant literature, including different manufacturing methods for e-textiles, circuit development practices, performance considerations, standardization challenges, existing standards, EDA approaches, and conventional PCB manufacturing processes.
- Chapter 3 presents the case study of the BiliOnesie neonatal e-textile product application, in which an RtD approach was used as a data source for identifying critical design variables, providing insights into current limitations in practice, and highlighting key challenges and opportunities in e-textile circuit development.
- Chapter 4 presents the methodology, results, and key findings from interviews with e-textile experts. This includes a second round of identification of critical design variables, recurring challenges, and insights into current limitations in industry practices.
- Chapter 5 describes the synthesis of the results of chapters 2, 3, and 4 in the development of the hierarchical design framework, detailing its structure, the processes involved in building it, and its validation through a follow-up expert focus group.
- Chapter 6 discusses a set of examples of the reduction of the EDA framework to practice through experimental characterization of selected fabrication parameters related to the

stitching method, such as trace spacing, trace width, trace straightness, electrical resistance, and occurrence of shorts, and the translation of these results into design rules.

- Chapter 7 concludes the dissertation by discussing the broader implications of this work, outlining future research directions, and proposing how different stakeholders across the e-textile ecosystem can collaborate to expand, adopt, and apply the framework in scalable and interdisciplinary ways.

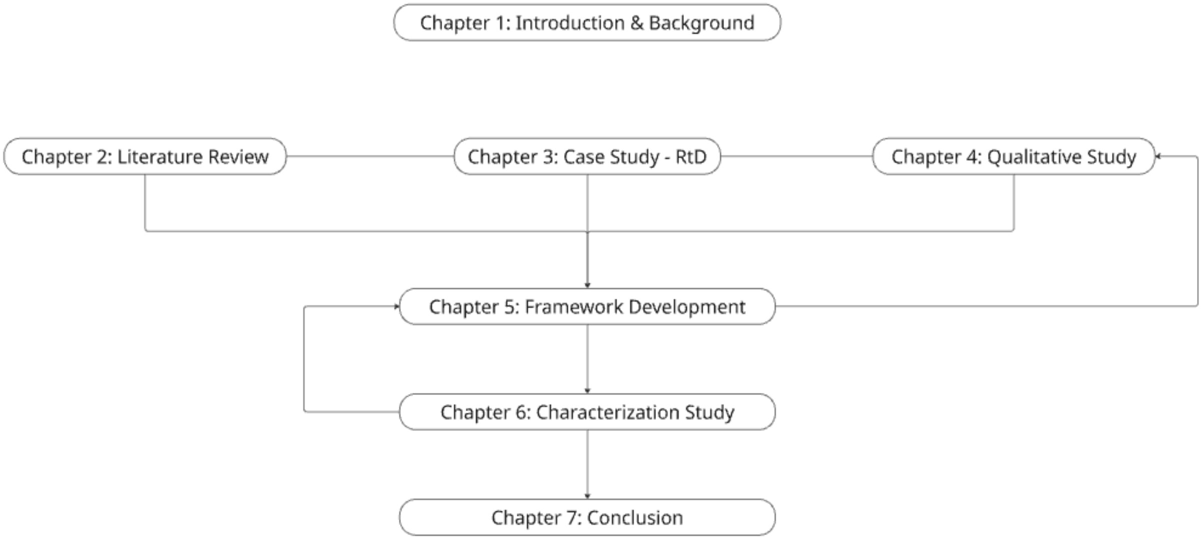


Figure 5 -Organizational Structure of the Dissertation

2. Literature Review

Although it forms a critical component of the triangulation method used to identify important TCB design variables and their relationships, this literature review does **not follow a formal systematic review protocol** (e.g., PRISMA), as the goal is not to exhaustively catalog all prior studies but rather to synthesize key insights relevant to the development of an EDA framework for e-textiles. The emphasis is on extracting **critical variables**, **performance indicators**, and the **relationships among them**, rather than producing a comprehensive survey of the field.

To facilitate clarity and cross-comparison, variables and performance indicators discussed throughout the review (and in the subsequent two chapters) are presented in **bold** (e.g., **trace width**, **resistance stability**, **stitch density**). This formatting helps the reader track recurring factors and observe how they influence different aspects of material, circuit, and system behavior.

Where appropriate, these relationships are **interpreted, abstracted, or modeled**, often in the form of "if–then" design logic or parameter dependencies, to support their later use in the decision framework. At the end of each section, key insights are synthesized to highlight recurring themes, gaps, and implications for design. A summary table at the end of each chapter consolidates these insights and shows how they map onto the proposed EDA logic structure.

This review thus serves both as a **knowledge synthesis** and a **design-logic scaffold**, identifying how material behaviors, fabrication methods, and performance indicators can be modeled relationally for use in tool development.

2.1 Textile Circuit Approaches

Generally, electronic circuits are composed of one or more electrical components, such as diodes, resistors, amplifiers, and capacitors, connected by conductive pathways that allow electric current to flow. These pathways may be conductive wires (typically made of copper or aluminum) to establish electrical connections between components. For a system to be considered an electronic circuit, it generally must include at least one active component that requires electrical power to operate and can control or manipulate the flow of current.

In the same vein, electronic textiles (e-textiles), sometimes called smart textiles, incorporate electronic components/materials into a textile's fiber, yarns/thread, or fabric (Ruckdashel et al., 2022; Stoppa & Chiolerio, 2014). Different techniques for incorporating electronics in textiles include knitting, weaving, crocheting, stitching/embroidery, welding, laminating, and printing as shown in Figure 6 below. Knitting, weaving, and crocheting can be grouped into the **“into”** approach of incorporating electronics, while stitching, welding, laminating, and printing can be grouped in the **“onto”** approach (Veja, 2014). The major difference between the "into" and "onto" approaches is whether the electronics are integrated *into* the fabric architecture/construction or if electronics are integrated *onto* a fabric substrate (Figure 6). A quick disambiguation must be made here that yarn is often referred to as thread in e-textile applications (Castano & Flatau, 2014).

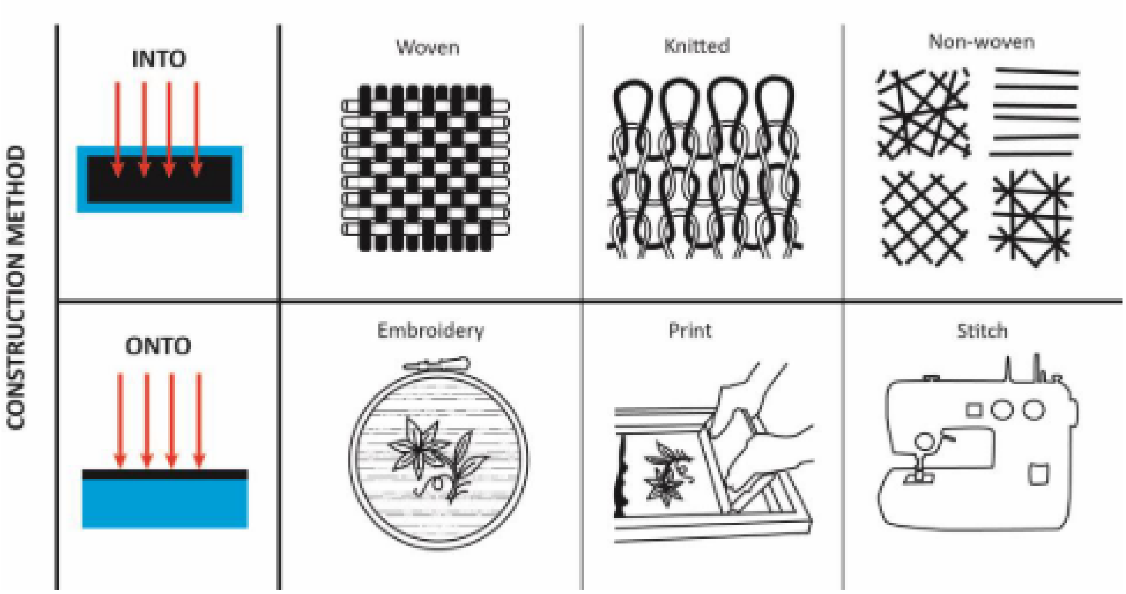


Figure 6 - E-textile construction methods categorized into "onto" and "into" fabrication approaches (Veja, 2014)

2.1.1 Into Approach

The "*into*" approach can be classified as incorporating electronics ***into*** the fiber or yarn that makes up a fabric during the e-textile manufacturing process. The major benefit of incorporating electronics into a fabric using the *into* approach is that the electronics are usually less visible to the eyes and have less impact on textile properties like drapability in the resulting product (Cherenack et al., 2010; Veja, 2014). Integrating electronics at the fiber or yarn level can take two primary forms: (1) replacing traditional conductive connections, such as wires, with conductive fibers or yarns to route electrical current, and (2) embedding electronic functionality directly into the fiber or yarn, effectively turning them into components. In the first approach, conductive fibers or yarns serve as routes within a textile circuit, enabling current flow between discrete electronic components. In the second, the fibers or yarns themselves are engineered to perform specific electronic functions, such as sensing, switching, or energy storage. Figures 7 - 9 illustrate the distinction between these two approaches: conductive fibers/yarns used as routes versus those configured as functional electronic components.

2.1.1.1 At the Fiber level

2.1.1.1.1 Conductive Fibers

This approach requires the fabrication of conductive metals and polymers, nanoparticles/nanowires, and carbon-based micron/nano materials in a fibrous form. Conductive fibers are individual fibers that are inherently conductive due to the inclusion of conductive materials in their manufacturing process. Conductive materials can be included by blending conductive fibers with a base polymer fiber, coating base polymer fibers with conductive material, or spinning conductive metals into thin fibers (Figure 7). The conductive metals are usually spun into metallic fibers through the wire drawing process (Veit, 2022). Wire drawing is a mechanical process of reducing the diameter of metals into thin sheets or fibers. The dimensions of these metals will be in hundredths of microns. Most metals can be spun, including silver, copper, bronze, etc. (Veit, 2022). These fibers can then be incorporated into textiles using the different manufacturing processes (Figure 16).

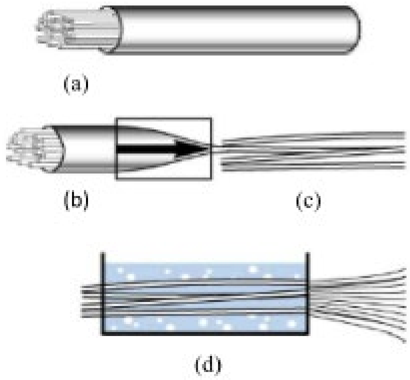


Figure 7 - (a) Metal-coated wire combined in an iron tube; (b) Several diameter reductions of a tube; (c) Bundling of tubes; (d) Leaching, realizing fibers. (Stoppa & Chiolerio, 2014)

2.1.1.1.2 Components in Fiber Form

The properties of electronic fibers can be manipulated to perform a specific function. The purpose of manipulating the properties of conductive fibers through any of the manufacturing techniques is to expand their functionality from performing basic conductivity to being able to perform a specific function as a resistor, transistor (Baeg & Lee, 2020), or antennae (Kiourti et al., 2015), etc. Fiber-based electronics have been used across different applications like sensing applications (Pasche et al., 2013), antennae applications (Song et al., 2019; Winterhalter et al., 2005), and energy-harvesting applications (Chen et al., 2016; Liu et al., 2018).

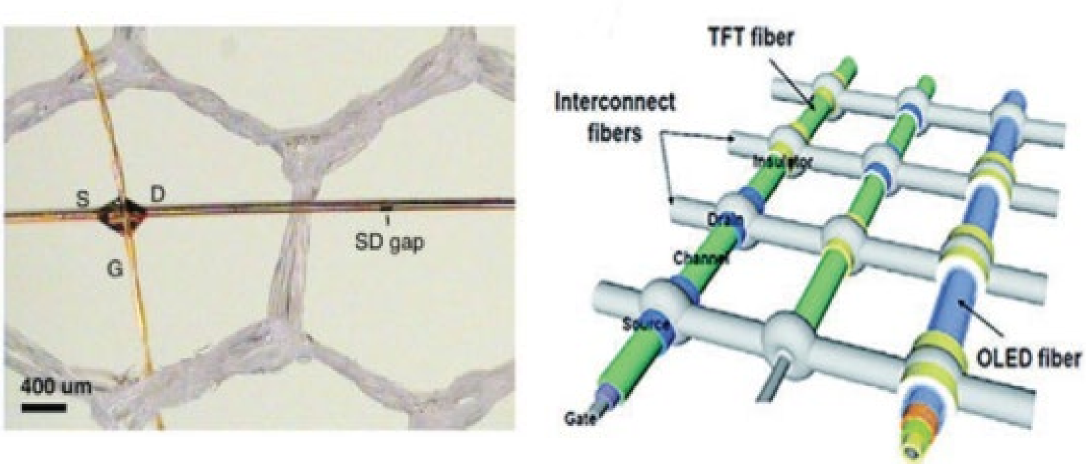


Figure 8 - (left) Microscopy image of two transistors created along the horizontal fiber and (right) 2D woven fiber electronics (Baeg & Lee, 2020)

2.1.1.2 At Yarn level

2.1.1.2.1 Conductive Yarns

Similar to conductive fibers, conductive yarns are yarns that can conduct electricity. Conductive yarns are made by twisting fibers such as metallic conductive fibers (like stainless steel, copper, or silver) and other polymer fibers to create continuous conductive yarns (Jansen 2020). The major difference between a conductive yarn and a conductive fiber is that conductive fibers are usually short individual strands of conductive spun metals (staple fibers). In contrast, conductive yarns are usually longer composite materials consisting of conductive and nonconductive fibers or all conductive fibers twisted together for mechanical strength and flexibility in e-textile applications. Apart from spinning the fibers into yarn, conductive yarns can also be made by twisting a conductive fiber (usually a soft wire) around a polymer yarn or coating a polymer yarn with a conductive material. Figure 9 below shows the three major ways of making conductive yarns.

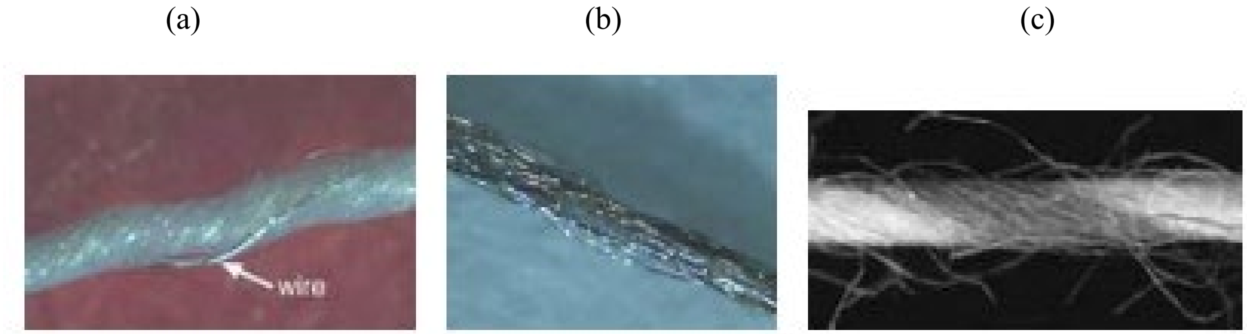


Figure 9 - Images showing the (a) Twisted metal wire: The metal wire is twisted around the polymer yarn; (b) Metal coating: The polymer yarn is physically/chemically coated with a thin metal layer; (c) Metal fibers: The conductive yarn consists of metal multifilament. (Stoppa & Chiolerio, 2014)

2.1.1.2.2 Components in Yarn Form

Components in yarn form refer to electronic elements that are embedded directly within the yarn structure, enabling seamless integration during conventional textile manufacturing processes such as weaving, embroidery, or knitting. A particularly effective example is the use of strip-type electronics engineered to mimic the dimensions and mechanical behavior of traditional yarns, allowing them to replace standard threads without disrupting textile functionality. These yarn-based components can incorporate sensing elements, interconnects, or even microcontrollers while maintaining flexibility and compatibility with fabric structures. For instance, Chen et al. (2024) introduced IDYarn, a novel RFID tag design in which an RFID transponder chip is soldered to a conductive filament that serves as an antenna. This assembly is then encased in non-conductive fibers, resulting in a yarn-like structure suitable for direct integration into fabric through weaving, embroidery, or seam attachment. By shaping the IDYarn into different geometries, various dipole antenna configurations were achieved, offering both structural and electronic functionality within the textile.

2.1.1.3 At Fabric level

2.1.1.3.1 Conductive Fabric

At the fabric level, conductive pathways serve primarily as routes, enabling electrical signal transmission across a textile surface or structure. These pathways are formed by integrating conductive yarns into the fabric through any of the manufacturing methods. Unlike rigid circuit boards, textile-based routes provide mechanical flexibility and stretchability, making them suitable for wearable electronics. At the fabric level, conductive pathways can be formed using knitting or weaving techniques that integrate metal fibers directly into the textile structure, to serve as routes for electrical current, offering a mechanically compliant alternative to traditional wiring in electronic circuits. The structure and geometry of the fabric play a crucial role in determining its stretchability and electrical performance. In a study by Yun et al. (2021), three types of stretchable textiles, woven, knitted, and cylindrical braided fabrics, were fabricated using metal fibers on industrial machines. The woven and knitted textiles were engineered to have open-loop or rhombus-shaped geometries between fiber intersections for stretchable electronics, allowing them to stretch significantly while maintaining conductivity. These fabric-integrated conductive traces do not function as electronic components themselves but play a critical role in routing power and signals to and from components embedded elsewhere on the textile.

2.1.1.3.2 Components in Fabric-form

Components can be developed by weaving or knitting two or more conductive yarns. The functionality of the yarn component also depends on how the yarns are manipulated using any of the manufacturing techniques. A research center in Germany developed an RFID transponder (a transmitter-responder) by manipulating the weaving structure. Extra layers of the warp were added to achieve this functionality. Three layers were woven on a jacquard loom to form interaction points, making a coil configuration enabling the structure to work as an RFID transponder (Gimpel et al., 2004). Figure 10 (left and right) represents two coated yarns, one serving as the transistor's gate contact while the second serving as the drain and source contact, and at the crossing of the two yarns, an electrolyte is placed (Dong et al., 2020).

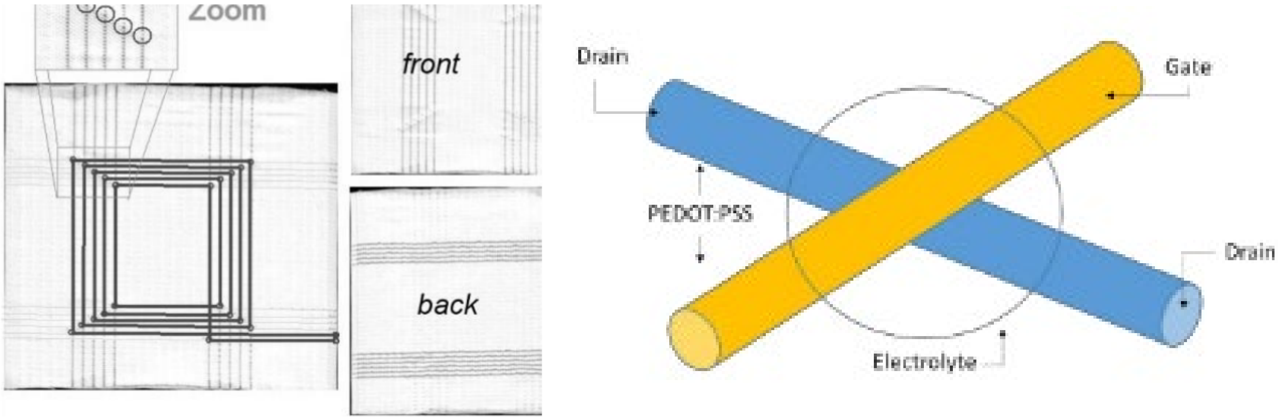


Figure 10 - (left) Woven RFID tag and (right) schematic of a yarn-based resistor (Dong et al., 2020)

2.1.2 Onto Approach

The onto approach is where the electronic components are incorporated onto a fabric surface, usually after the fabric is woven or knitted. The *onto* approach uses three main ways of applying electronics to fabrics. The first approach is by applying conductive pathways *onto* textiles. Applying conductive pathways onto a textile surface is usually done through stitching or printing the conductive tracks on the textile surface (Ismar et al., 2020; Molla, 2020). The second approach is attaching components *onto* the textile's surface and connecting these components with wires/adhesives (Lehn et al., 2004). The third approach is mounting complete flexible printed circuit boards onto a textile's surface (Baeg & Lee, 2020; Lee et al., 2009). In this third approach, the whole printed board is attached *onto* the textile surface by stitching, gluing, or using connectors on the textile surface (Al-Huda Hamdan et al., 2018). Figure 11 – 13 below show some approaches to attaching electronics *onto* a textile surface.

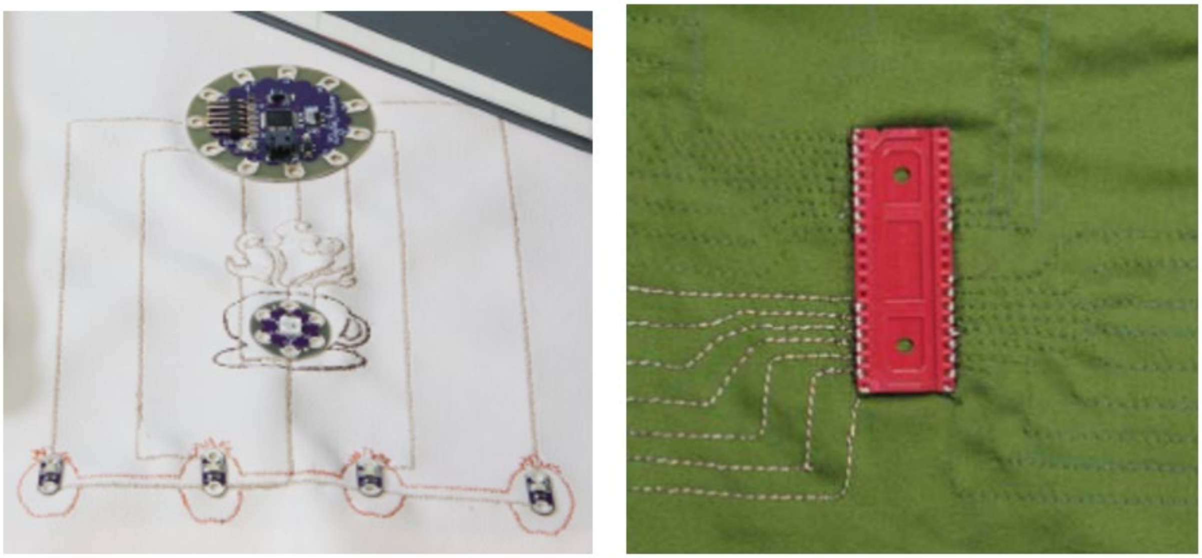


Figure 11 – (left) Lilypad Arduino PCB (Hamdan et al., 2018) and (right) a microcontroller (Buechley et. al. 2009) mounted on a fabric substrate

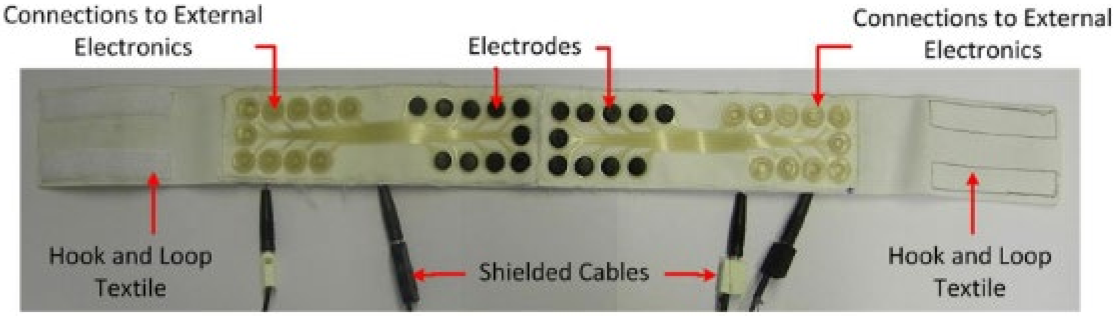


Figure 12 – Printed flexible conductive paths on a textile (Stoppa & Chiolerio, 2014)

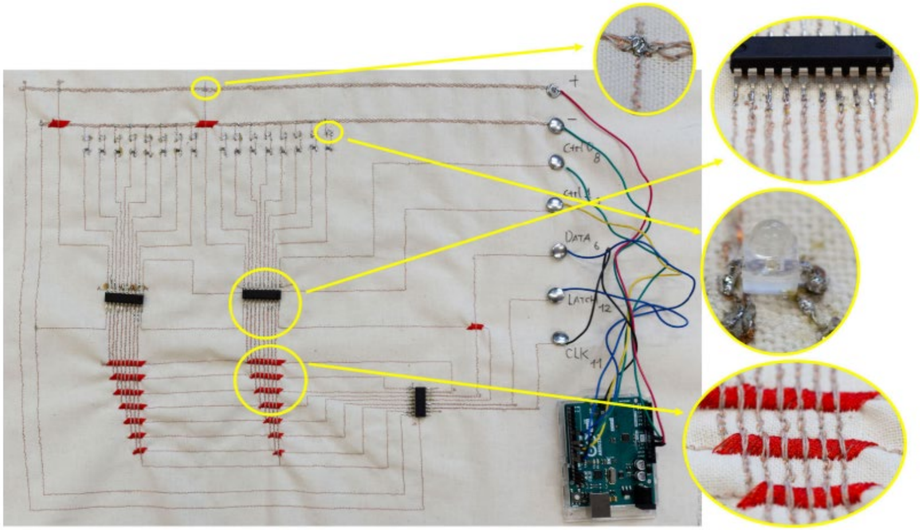


Figure 13 - Stitched conductive paths on a textile substrate connecting different electronic components. (Ismar et al. 2020)

2.2 E-textile Fabrication Methods

2.2.1 Common E-Textile Techniques

2.2.1.1 Weaving

Weaving is one of the oldest textile techniques and continues to be relevant across industrial, technological, and computational contexts (Fernaeus et al., 2012). In weaving, horizontal yarns (weft) are interlaced perpendicularly with vertical yarns (warp) to form a two-dimensional fabric structure (Devendorf & Lauro, 2019). This grid-like architecture provides a high degree of structural stability, making weaving particularly suitable for embedding and anchoring electronic components within e-textile circuits. From an EDA standpoint, weaving introduces a unique set of structural constraints and design opportunities that must be considered when routing conductive traces, positioning components, and modeling mechanical-electrical performance.

A defining characteristic of woven structures is their **orthogonal yarn alignment**, which naturally facilitates ordered, predictable trace layouts. Conductive yarns or wires can be selectively inserted into either the warp or weft directions to define circuit paths. However, the warp direction is typically subjected to significant friction during the weaving process, making it less favorable for embedding delicate or breakable conductive materials. Consequently, components and conductive pathways are more often positioned along the weft, where tension and abrasion can be more easily managed.

Several circuit-specific variables emerge in the context of weaving. **Yarn placement and layering** are critical design considerations. For example, Mikkonen et al. (2015) constructed a two-layer woven circuit in which conductive yarns replaced warp threads, and components were sandwiched between layers to establish power (5V) and ground (GND) connections. This approach introduced vertical integration and shielding, offering better circuit isolation. In contrast, Chen et al. (2016) demonstrated a single-layer photovoltaic e-textile circuit in which polymer-based fiber solar cells were woven alongside conductive electrodes and insulating polymer yarns to create a deformable circuit with mechanical stability (Figure 13). Here, **the use of insulating yarns to separate conductors within a single plane** was a key structural strategy, highlighting the need to model insulation pathways in EDA workflows. In some instances, conductive yarns or wires are used in weaving. **Trace breakage between weaves**, especially after component insertion, is a common failure mode. These breaks are difficult to trace post-fabrication and locating them within the woven grid can be labor-intensive. This necessitates EDA tools that can incorporate **trace continuity verification** into the design of woven circuits

Another weaving-relevant design method involves **plying**, twisting a wire together with a non-conductive yarn to improve mechanical durability and textile compatibility. Devendorf et al. (2019) used this technique in combination with double-weave structures to create a responsive circuit that changes color upon touch. The plying approach, while effective, raises questions of long-term mechanical integrity, as single-ply structures may unravel over time. Devendorf et al. (2015) noted that many existing yarns are not optimized for weaving with electronics and emphasized the importance of developing custom yarn types specifically for this purpose. This points to the role of **yarn construction**, including plying method, twist stability, and diameter uniformity, as an important parameter in woven circuit reliability.

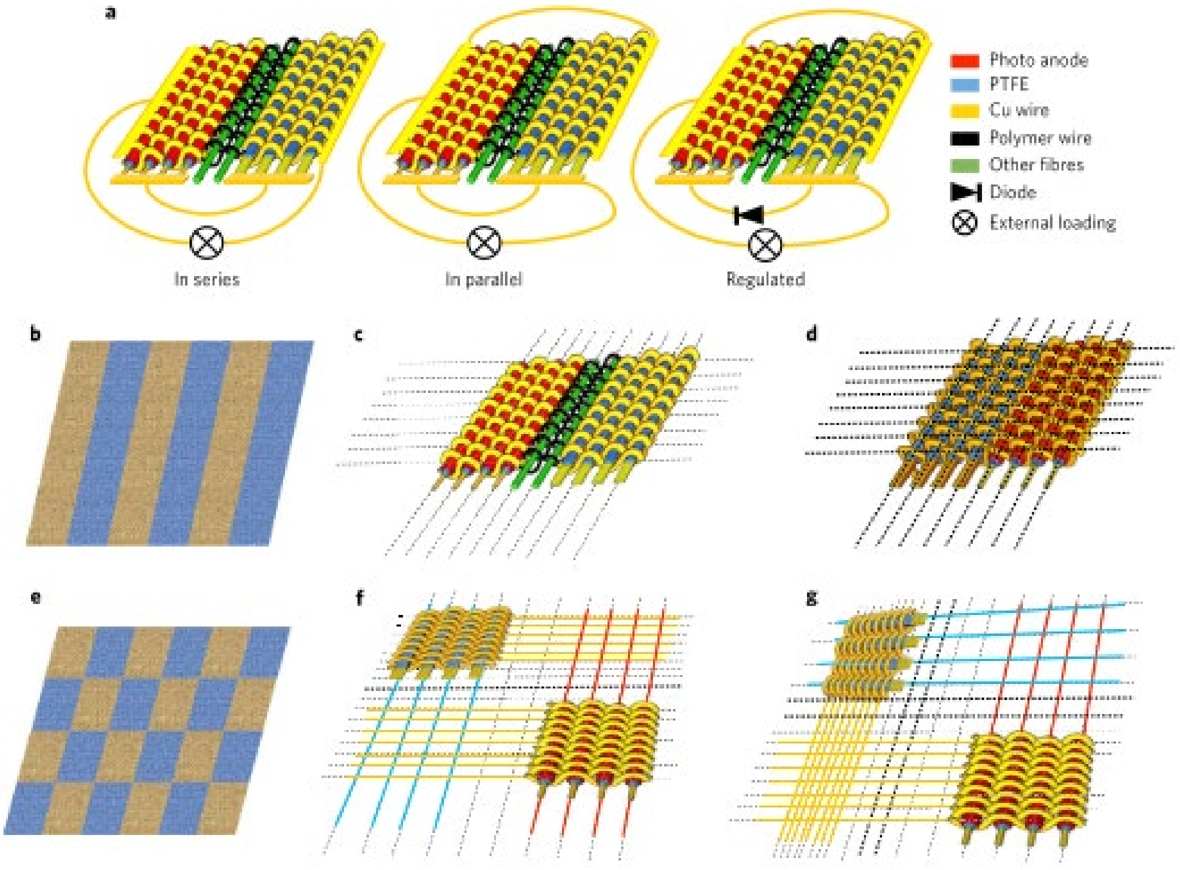


Figure 14 - A diagram showing an optimized weaving pattern for a power e-textile circuit (Chen et al., 2016)

Overall, weaving introduces several structural design variables with direct implications for e-textile EDA tools:

- **Yarn directionality** (warp vs. weft) and associated friction/tension exposure
- **Trace routing geometry** enabled by orthogonal yarn interlacing
- **Component layering strategies** (e.g., two-layer vs. single-layer designs)
- **Use of insulating yarns** to manage electrical separation in-plane
- **Plying configuration** of conductive and non-conductive yarns

- **Yarn composition and mechanical properties**, including unraveling risk
- **Mechanical-electrical failure risks**, such as trace breakage at crossovers or after component placement

2.2.1.2 Knitting

Knitting is a textile technique that forms fabric by looping a single yarn into consecutive rows (**courses**) or columns (**wales**). Unlike weaving, which relies on the perpendicular intersection of yarns, knitting builds structure through continuous loops. This inter-looping nature results in fabrics with exceptional **flexibility**, **stretchability**, and **breathability**, qualities that make knitting especially attractive for e-textile applications requiring close fit and body conformity (Jansen, 2020).

In the context of e-textiles, knitting can be leveraged in three primary ways. First, electronic components can be knitted separately and later attached to a system, commonly referred to as the *onto* approach. Second, components such as strain sensors can be integrated directly into the fabric during knitting, becoming part of the textile structure itself as shown in Figure 15 below. Third, **conductive yarns** or wires can be substituted for standard yarns to route **circuit traces** within the knitted fabric. This structural versatility and capacity for built-in **deformation tolerance** provides unique advantages for embedding functional circuitry directly into textile substrates.

From an EDA perspective, knitting introduces a set of **design-relevant variables** that directly influence circuit performance, especially when **conductive yarns** are used in place of traditional ones to form circuit traces. Unlike weaving circuits with fixed trace geometries, **knitted traces** are subject to **structural deformation**, and their **electrical resistance** varies with **mechanical**

strain. Importantly, **resistance changes** may vary depending on the **direction of mechanical strain**, conductive traces knitted along the **course direction** (horizontal) behave differently from those aligned along the **wale direction** (vertical). For example, Paradiso et al. (2014) found that a **piezoresistive response** was more stable when conductive yarns were oriented in the course direction, highlighting a **directional design consideration** for **routing signals** in stretchable fabrics. Zhang et al. (2006) further showed that **contact resistance between yarn loops** is a primary determinant of **electromechanical behavior**. In their study, knitted traces made from pure **stainless-steel yarns** exhibited a **linear resistance response** of up to **10% strain**, with a **gauge factor** of approximately, 10, demonstrating how **material** and **loop configuration** jointly determine circuit performance.

Uninsulated conductive yarns used in knitted structures function inherently as **variable resistors under strain**, even when not intended as sensors. This behavior must be considered in EDA workflows: any **conductive trace** in a knitted circuit will introduce **resistance variation** due to **body motion** or **fabric deformation**. Therefore, EDA tools for textile circuits must account for **mechanical-electrical coupling**, incorporating parameters such as **fabric orientation**, **loop geometry**, and **anticipated strain ranges** into **resistance modeling**. In practical terms, each **knitted trace** introduces an **unstable resistance component**, and **design rules** must reflect this inherent **variability** to ensure **circuit reliability** and **signal integrity**.

Knitting also allows for the integration of **complex routing geometries** and **multi-functional regions**, but this **design freedom** comes with **variability challenges**. Studies have shown that **sensor or trace performance** degrades after initial **mechanical loading cycles** (Ehrmann et al., 2014), with **resistance stabilizing** only after **initial stretch**. **Material selection** is equally critical.

Yarns blended with non-conductive fibers, such as cotton, have been shown to yield **inconsistent resistance behavior** (Atalay et al., 2017), while **complex-shaped knitted geometries** introduce additional **noise** and reduce **measurement repeatability** (Raji et al., 2020). These findings reinforce the importance of characterizing **yarn composition**, **stitch configuration**, and **directional layout** during **circuit planning**.

Although knitting can be fully automated and **knitted fabrics** can stretch up to **100%** (Gonçalves et al., 2018; Jansen, 2020), the absence of **standardized design rules** for reliably modeling **electrical behavior under deformation** remains a challenge. For EDA in e-textiles to be effective, it must not only map **circuit functionality** but also integrate **fabric-specific mechanical and structural properties** into **trace design**. This includes understanding how **yarn orientation**, **stitch type**, and **fabric density** affect **loop length**, **resistance stability**, and the **long-term durability** of **circuit pathways**. Mapping these interrelated variables will be essential for developing accurate design tools that support **verification**, and **manufacturability** of knitted e-textile systems.

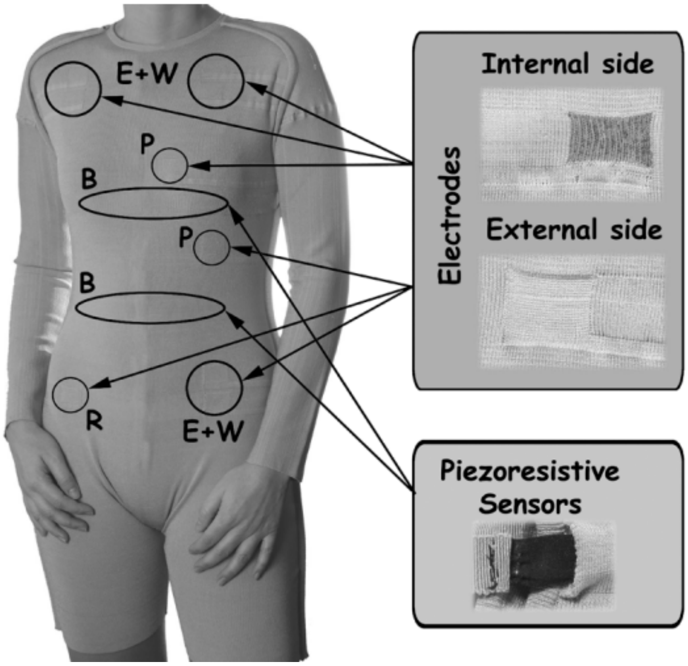


Figure 15 - Components knitted as a part of the entire knitted fabric structure (Paradiso et al., 2014)

2.2.1.3 Printing and Lamination

Printing is a solution-based fabrication method used in e-textiles to deposit conductive inks in precise circuit patterns directly onto textile substrates. These conductive inks, typically composed of metallic particles such as silver or gold suspended in solvents (often water-based), allow for the creation of functional circuit traces, sensors, and interconnects (Dong et al., 2020). Unlike dyeing, which traditionally alters a textile's color through pigment infusion, printing in e-textile applications serves a structural-electrical function by forming active conductive pathways. That said, dyeing is still used to impart conductivity in yarns, and studies have shown, for example, that changes in dye color can influence the electrical resistance of stainless-steel yarns (Sezgin et al., 2016).

Printing introduces specific design variables and constraints that differ substantially from yarn-based or structural fabrication methods. One major challenge is the **surface roughness and porosity of textiles**, which affect **ink adhesion and pattern continuity.** To address this, two primary surface preparation techniques are used: applying a polymer base layer to smooth the fabric (Stoppa & Chiolerio, 2014), or printing onto a pre-fabricated film that is later laminated onto the textile (Lee et al., 2009). The **choice of substrate treatment** becomes a design variable itself, influencing **trace fidelity, print resolution, and mechanical durability.**

There are two dominant printing techniques: **screen printing** and **inkjet printing**. Both enable the deposition of conductive inks to form circuit traces or passive components such as piezoresistive or temperature sensors (Parashkov et al., 2005; Sauer et al., 2004; Ruckdashel et al., 2022). Screen printing uses stencils to define pattern areas, while inkjet printing deposits ink drop-by-drop through nozzles, enabling higher resolution. In either case, **feature resolution, layer alignment, ink viscosity, and curing parameters** must be modeled as part of a textile-aware EDA process. While inkjet methods offer trace widths in the nanometer range, achieving stable and continuous electrical paths often requires printing over a uniform, non-porous surface.

In terms of design trade-offs, printing offers a **high degree of pattern precision and circuit customization**, but it also introduces several fabrication constraints. Conductive inks typically require **sintering** at elevated temperatures to achieve sufficient conductivity, which can damage heat-sensitive fabrics (Karim et al., 2017). Additionally, the inks are often **expensive and non-biodegradable**, presenting environmental and cost-related concerns (Molla et al., 2017). These trade-offs must be considered in early-stage design models, particularly when evaluating circuit durability, substrate compatibility, and lifecycle impact.

In some applications, printing is entirely bypassed by **laser-cutting conductive textiles into circuit pathways**, which are then laminated onto the fabric, offering a mechanical alternative with its own layout constraints. Regardless of approach, printing-based circuits demand EDA tools capable of accounting for **material-substrate interactions, trace geometry, thermal process limits, and multi-layer registration**. Unlike woven or knitted systems, printing does not rely on yarn structure, but rather on **2D surface topology, ink flow dynamics, and post-processing behaviors.** As such, printing requires a distinct module within an e-textile EDA framework that treats inks, surface preparation, and curing steps as critical parameters in **layout, simulation, and reliability modeling.**

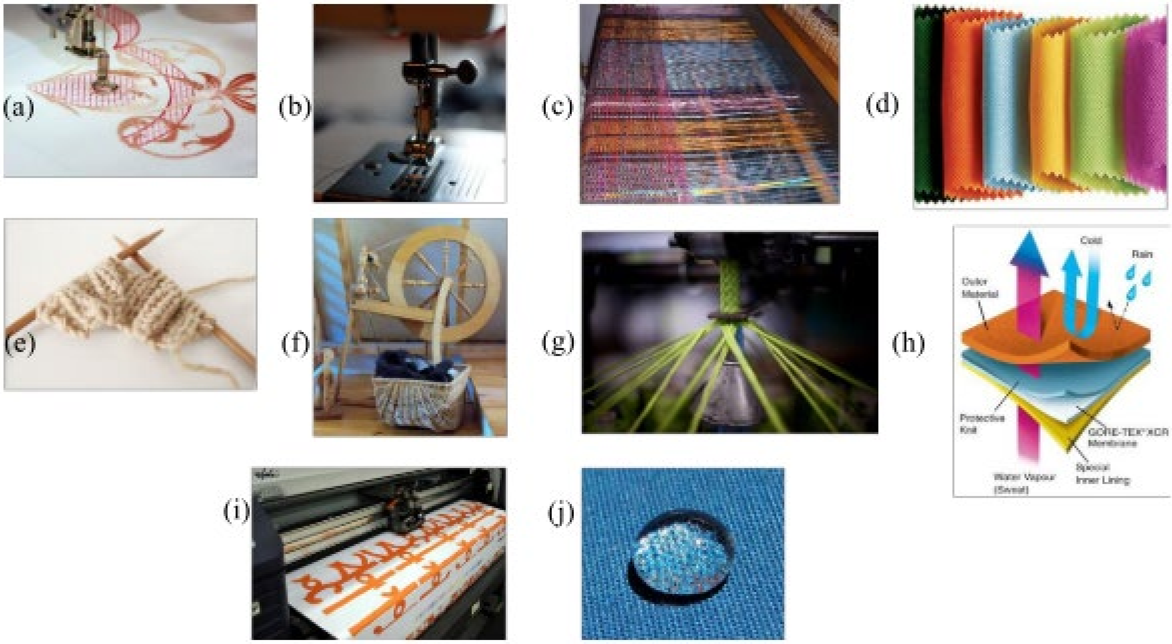


Figure 16 - Different kinds of textile manufacturing and treatment. (a) Embroidery; (b) sewing; (c) weaving; (d) non-woven; (e) knitting; (f) spinning; (g) breading; (h) coating/laminating; (i) printing; and (j) chemical treatment. (Stoppa & Chiolerio, 2014)

2.2.1.4 Stitching and Embroidery

Stitching and embroidery are long-established textile fabrication techniques that are increasingly leveraged in the development of e-textile circuits. They have been used extensively in developing wearable electronics as sensors and actuators (Post et al., 2000; Roh, 2014; Sanchez et al., 2021; Nabil et al., 2019; Persson et al., 2018). From an **EDA** perspective, these methods present a rich and highly tunable parameter space that can be systematically captured, encoded as design rules, tied to application-specific objectives, and, in some cases, governed by emerging standards. While traditionally distinct, stitching is typically used for structural assembly and embroidery for decorative surface treatment, their shared material behaviors and tooling capabilities make it logical to group them in this literature review as part of a unified framework for design variable mapping. In both cases, the process involves depositing conductive or non-conductive threads onto textile substrates using needles, either manually or through machine, making them highly relevant to circuit design in e-textile applications (Sanchez et al., 2021; Molla, 2020).

Stitching, traditionally used to assemble fabrics, has found new applications in e-textiles as a means of routing conductive paths and constructing functional elements such as stretch-responsive sensors (Dupler & Dunne, 2019). This makes **stitch type and stitch geometry** critical **design rule variables**. A range of stitch types, including straight, zigzag, backstitch, and cover stitch, can be manually executed or programmed into commercial embroidery machines, with each type producing distinct mechanical and electrical behaviors. Molla (2020) emphasized the importance of this adaptability, highlighting how conventional apparel manufacturing equipment is, to an extent, well-suited for integrating conductive threads. The choice of stitch type directly impacts performance indicators such as **resistance stability and strain response,** making it essential to encode this parameter into automated design tools.

Other important **design rule parameters** include **stitch length**, **stitch density**, and **stitch tension**, all of which influence both the mechanical durability and electrical conductivity of the final stitched trace. Several studies have explored these variables in detail. Bekampien and Domskien (2014) demonstrated that **stitch orientation relative to fabric tension** significantly influences the deformation behavior of woven textiles. Their study specifically examined the effect of stitching patterns during **fabric forming**, a process in which fabric is shaped into a desired structure using techniques like darts, gathering, and pleating. From an EDA standpoint, **stitch orientation** should be encoded as a **design rule**, particularly as it relates to the grain direction and the mechanical behavior of a substrate. In contrast, the **influence of stitching patterns on fabric shaping during forming** represents an **application objective**, as it is context-specific and tied to garment functionality or aesthetic requirements. Similarly, Warrior et al. (1999) and Simegnaw et al. (2021) found that stitch length and thread tension impact the **structural integrity** and **electrical continuity** of stitched lines, parameters which, if optimized, can mitigate failure modes such as **open circuits and fatigue-related degradation.**

Thread type is another central parameter affecting e-textile circuit behavior. Conductive threads vary in resistance, mechanical strength, and interaction with different textile surfaces. These differences make thread selection a key **design rule variable**. Threads that **fray**, **oxidize with time**, or exhibit **high variability in resistance** are less suited for precision applications. Despite it is mostly manual origins, stitching remains one of the most **widely accessible, low-cost, and flexible** e-textile fabrication techniques. Sanchez et al. (2021) noted that its primary limitation lies in **production speed**, especially for customized designs, which still require skilled human labor. However, the extensive body of knowledge around stitch mechanics, its compatibility with **industrial equipment,** and the sheer number of **controllable design variables** make stitching and embroidery ideal candidates for structured, rule-based integration into EDA systems. With continued variable mapping and design rule formalization, this method is well-positioned to serve as a foundational platform for developing flexible, robust, and mass-customizable electronic textiles.

The functional performance of stitched e-textile circuits is highly dependent on how the stitch interacts with the textile substrate and its intended use context. Gioberto et al. (2016) conducted an in-depth evaluation of textile-based stretch sensors and showed that stitch type and geometry directly affect signal responsiveness and stretchability. They identified **electrical resistance** as a key output metric, noting that specific stitch patterns yielded more reliable signal behavior when sewn onto knitted fabrics. However, their results also revealed **application-specific challenges** such as motion artifacts, e.g., buckling and deformation, that occur when e-textiles are used in clothing. Body motion can interfere with sensor signal quality, particularly near joints of the body. Dupler & Dunne (2019) extended this work by highlighting the role of **thread type, stitch layout,** and **fabric structure** in shaping long-term signal consistency.

Component attachment and sensor calibration in **high-mobility areas** such as elbows or knees further underscore the need for intelligent pattern layout algorithms. **Stitch placement** relative to anatomical joints can lead to signal distortion or even inverse sensor responses under repeated mechanical stress (Gioberto et al., 2016). These phenomena highlight important application-specific constraints that may fall outside the scope of standard design rules but should still be incorporated into **context-aware design considerations** in an EDA framework. Additionally, performance issues such as sensor drift due to wear, deformation, or fatigue indicate the need for configurable thresholds and adaptive compensation strategies within the context-aware design considerations in an EDA framework.

2.2.2 E-Textile Joining Methods

2.2.2.1 Soldering

Soldering is a widely used technique for forming durable electrical connections in e-textile systems by melting solder paste to join two or more components. This method is commonly employed for long-term, stable connections and has been used to attach a range of lightweight components such as LEDs (Molla et al., 2020), resistors (Post et al., 2000), and other surface-mounted devices. It is especially prevalent in surface-mounted e-textile applications because soldering is compatible with both sewn and printed conductive traces. Additionally, soldering has been used in woven e-textile processes, for instance, Mikkonen (2015) soldered component leads directly to conductive yarns during weaving to create integrated circuitry.

From a design perspective, several variables influence the reliability and functionality of soldered joints in e-textile contexts. For example, Molla et al. (2020) demonstrated that **trace width** directly affects the mechanical durability of solder joints; narrower traces can fail more easily under repeated mechanical stress, while wider traces improve load distribution and enhance joint longevity. Other critical design variables include **lead geometry, pad size and spacing, substrate flexibility, and the thermal profile** used during the soldering process.

These variables can be classified into three categories:

- **Standard-addressable variables**: Factors like **solder joint durability**, **thermal limitations**, and **toxicity of solder materials** can be guided by existing or emerging electronics manufacturing standards (e.g., IPC standards) that may be adapted or extended to e-textiles.
- **Design rules**: Parameters such as **trace width**, **pad diameter**, and **spacing between leads and traces** can be encoded as **design rules** to ensure electrical performance and mechanical reliability across applications.
- **Application-specific objectives**: Considerations like **skin-contact safety**, **wearability**, and **flexibility under motion** relate to the intended use of the e-textile (e.g., wearable health monitoring, illumination) and guide design trade-offs, especially where traditional soldering may pose risks due to sharp edges, brittleness, or discomfort.

Despite its advantages, soldering presents several challenges for e-textiles. The soldering process requires high temperatures, which can degrade textile substrates. Moreover, solder joints may be brittle, prone to cracking under bending or washing, and hazardous if not properly encapsulated, raising concerns for both **safety** and long-term **reliability** (Molla et al., 2020).

2.2.2.2 Welding

Welding is an alternative manufacturing technique increasingly explored in e-textile circuit integration, offering a means to form electrical connections by locally melting conductive or thermoplastic materials to create a fused joint, without the need for additional filler materials such as solder paste. Welding introduces a set of design variables and constraints that influence joint reliability, material compatibility, and electrical performance.

Among welding methods, **resistance spot welding** is the one most commonly used in e-textile applications. It leverages electrical current to generate localized heat at the interface of conductive materials, enabling a metallurgical bond. For example, Post et al. (2000) used this technique to fuse stainless steel threads with copper component leads, demonstrating its feasibility for textile-integrated circuits. Similarly, Michal et al. (2019) as shown in Figure 17 below, employed resistance welding to join polyester-based conductive threads to electronic components on textile substrates, an approach that bypasses traditional stitching methods and offers potential for a scalable, automated assembly.

Ultrasonic welding has also been adopted to establish robust conductive connections in textile networks, particularly where synthetic thermoplastic materials like nylon or polyester are used. Slade & Winterhalter (2015) applied ultrasonic energy to melt the insulating sheaths and polymer yarns, creating point-to-point electrical contacts by exposing and joining the conductive cores. This process enables rapid, repeatable connections, although its use is largely limited to specific textile chemistries.

Michal et al. (2019) further contributed to this space by **characterizing welded joints through thermal and mechanical stress testing**, validating that welded pads could consistently maintain electrical resistance below 1 ohm, an important **performance threshold** that could be encoded into **design rules** for EDA workflows.

Despite its advantages, welding in e-textiles still lacks the standardization seen in other joining methods. While ultrasonic welding is well-documented in the general textile industry, standards and reliability criteria for resistance and spot welding in textile circuits remain underdeveloped. As such, welding in e-textiles is best approached as a conditional fabrication option, guided by application-specific constraints, material properties, and emerging design rules derived from empirical studies.

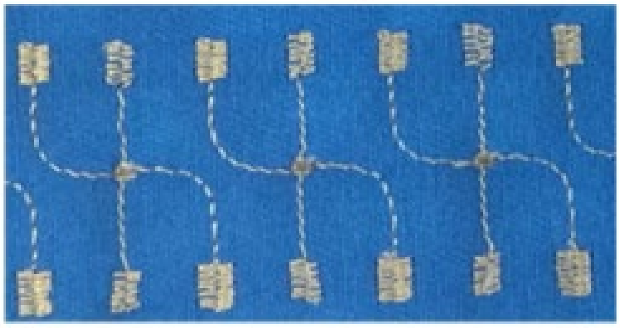


Figure 17 - Welded test samples with a contact pad (in the middle) of 2.5 mm × 2 mm (pad area 5 mm2) (Michal et al., 2019)

From an EDA perspective, welding processes introduce several **design variables** critical to joint performance such as:

- **Welding type (resistance spot and ultrasonic welding)**
- **Pad geometry and contact area**
- **Weld energy (e.g., current, pressure, ultrasonic amplitude)**
- **Material compatibility (conductive yarn vs. component lead)**
- **Thermal and mechanical stress resistance**

2.2.2.3 Adhesive bonding

Adhesive bonding is a component integration technique that extends conventional textile bonding using glue to enable electronic circuit assembly on fabric surfaces. In the context of EDA for e-textiles, adhesive bonding presents a **low-temperature**, material-compatible joining method with several critical design variables that affect electrical performance and mechanical integrity.

Adhesive bonding is a joining method in e-textile fabrication that uses glues, applied in tape, liquid, or paste form, to affix electronic components to textile substrates through either chemical or mechanical adhesion. This approach offers a flexible, low-temperature alternative to traditional soldering, making it especially suitable for delicate or thermally sensitive fabrics. Adhesives used in e-textile applications can be broadly divided into two categories. **Non-conductive adhesives** are primarily used for mechanical attachment, where no electrical connection is required. These are commonly used to mount circuit modules or encapsulate components when electrical isolation is desired. In contrast, **conductive adhesives** are designed to form electrical junctions between conductive traces and component leads. These are essential for enabling current flow within integrated textile circuits.

Conductive adhesives are further classified based on their electrical conduction behavior. **Isotropic Conductive Adhesives (ICAs)** conduct electricity uniformly in all directions, making them suitable for general-purpose electrical connections. **Anisotropic Conductive Adhesives (ACAs)**, on the other hand, conduct only along a single axis, typically through the thickness of the adhesive layer, providing better signal isolation and preventing lateral shorts (Stanley et al., 2022).

The choice and configuration of adhesives influence key electrical and mechanical performance parameters, including but not limited to **electrical resistance, bond strength, thermal stability, and durability under bending or washing.** These parameters are critical for system reliability and can be encoded into design rules in an EDA framework to support automated material and method selection. For instance, Linz et al. (2012) used a non-conductive adhesive to attach an LED module to an embroidered textile substrate, relying on separate electrical pathways for connectivity. In contrast, Simegnaw et al. (2021) and Scheulen et al. (2013) applied conductive epoxy adhesives to form direct electrical connections, such as bonding magnets or lead wires to conductive fabric surfaces. These examples illustrate how adhesive bonding can support both mechanical integration and functional connectivity, depending on the adhesive type and circuit requirements.

Compared to soldering or welding, adhesive bonding offers the benefit of **low-temperature processing**, making it suitable for **temperature-sensitive textile substrates** like polyester or spandex. This expands its usability across a wider range of e-textile applications, especially where garment flexibility and wearer comfort are critical. However, it is generally limited to **lightweight components** and may exhibit **degradation under thermal cycling**, limiting its reliability in harsh or high-temperature conditions (Molla, 2020).

From an EDA standpoint, examples of key design variables include:

- **Adhesive type (ICA vs. ACA)**
- **Curing temperature and time**
- **Adhesive pad area and thickness**
- **Pressure along the line of bonding**
- **Compatibility with textile substrate and component materials**

2.3 Electronic Circuit Development

In this section, we examined how circuits are formed in both traditional PCBs and TCBs. This section focuses on the **routing of conductive paths** within e-textile circuits, as well as the ways certain components can be fabricated using similar techniques discussed in Section 2.2.2 – *E-Textile Joining Methods*. Before exploring what circuit development means in PCBs and TCBs, it is important to establish a basic understanding of how electronic circuits function. At its core, a circuit is formed when **electronic components are connected through conductive paths or traces**, creating a closed loop that allows electric current to flow once a power source is applied. A power source in a circuit can be from different energy sources like solar, electric, mechanical, chemical (battery), motion, etc. (Chen et al., 2020; Magno & Boyle, 2017; Oshea Paul, 2017). The most common source is a **battery** (Molla et al., 2017). The flow of electricity in any circuit is referred to as an **electric current** measured in amperes (A) or coulombs per second. When current moves in a conductive material, it faces opposing forces that inhibit its flow; this opposing force is called the **resistance** and is measured in ohms(Ω). The pressure that pushes the electricity from the source point (power source) through a conductive material to its destination point in an electric circuit is what is referred to as the **voltage** measured in (volts). Voltage is also the potential difference between two points in an electric circuit (*National Institute of Standards and Technology*, 2023).

2.3.1 Printed Circuit Board

A printed circuit board is a board with etched or printed conductive traces (usually made of copper foil) and insulated by some insulating materials like fiberglass, ceramics, certain polymers, and, in some cases, Teflon. The insulating materials also provide mechanical support to the board. The development of PCBs created a more compact way of concentrating electric circuits in a more closely packed manner. A PCB can have single, double, or multiple layers (or multilayers). A PCB is a single layer if components are on one side of the board, a double layer PCB is when there are components or traces on two sides, and a multilayer PCB is when there are components or traces on multiple board layers.

Generally, in a PCB design process, two techniques for mounting components on the board are through-hole technology (THT) and surface mount technology (SMT) (Prasad, 1997). SMT is the most used technology in modern-day PCBs because it allows for smaller, more compact designs with high density (meaning, more components can be packed on the board). As the name implies, SMT components are mounted on the surface of the PCB using solder paste and a reflow oven (more will be discussed on the soldering process in *section 2.3.1.1*) (Traister, 1990). THT requires drilling a hole in the board to insert the components before being soldered at the opposite side of the board. SMT and THT are still used today, depending on the intended application. However, to harness strengths of both density and durability, both technologies are often combined.

There are four major layer types on each face of a PCB. In some cases, there can be more than four layers, depending on the complexity of the circuit and the design requirements. The four major layers include a (copper) trace layer, a resistive mask layer, a solder mask layer, and a silkscreen layer. The basic THT PCB design process will be discussed here in order to highlight the layers.

The first step is that a CAD software (e.g., Altium, Easy EDA, and Autodesk Eagle) is used to generate the circuit design files called Gerber files. These Gerber files represent the 2D layout of each layer, as well as the 3D model of the PCB circuit. Using these files, the traces (lines) and vertical interconnect access (vias/holes) are etched onto the copper layer in the PCB.

The first holes drilled on a PCB are the registration holes on the board's four corners. The registration holes provide reference points for further alignment of the PCB along different stages of PCB production. The holes that will house the components at the latter stage are next to be drilled on the board. Then, there is the resistive mask layer, which adds the traces on a PCB by an etching process. The traces are for routing and connecting the drilled holes and component pads (connection points for surface-mount component leads) on the PCB board. Then, the copper and resistive mask layer will be washed off in an alkaline solution at a certain temperature so that just the etched tracks and drilled holes on the PCB are left. The next step is a quality check to ensure the PCB board corresponds to the design file (Gerber file). At this stage, the board is inspected to check for broken or short traces on the board by photographically comparing the printed circuit with its original Gerber file.

The next layer is the solder mask layer, where the solder mask resin protective coating is laid on areas that will not be soldered. Solder masks can be silkscreened or 'photo imageable' to remove dust and prevent oxidation and are usually green in color (that is why PCBs are usually green). It is important to note that because the solder mask is insulating, it is necessary to remove it on the edges of the holes on the board so that components can electrically connect with the holes connecting with the traces. The solder mask at the hole's edge is then covered before undergoing an ultraviolet (UV) curing process. This process washes off the solder mask at the hole ring.

The last layer is the silkscreen or component designator layer. This layer is where components' location identifiers on the PCB are written. This step is needed more for the identification of components than for component position accuracy. The logos and markings are also added to the

PCB at this stage. Afterward, the components are soldered to pads and holes. These major PCB layers are shown in Figure 18 below.

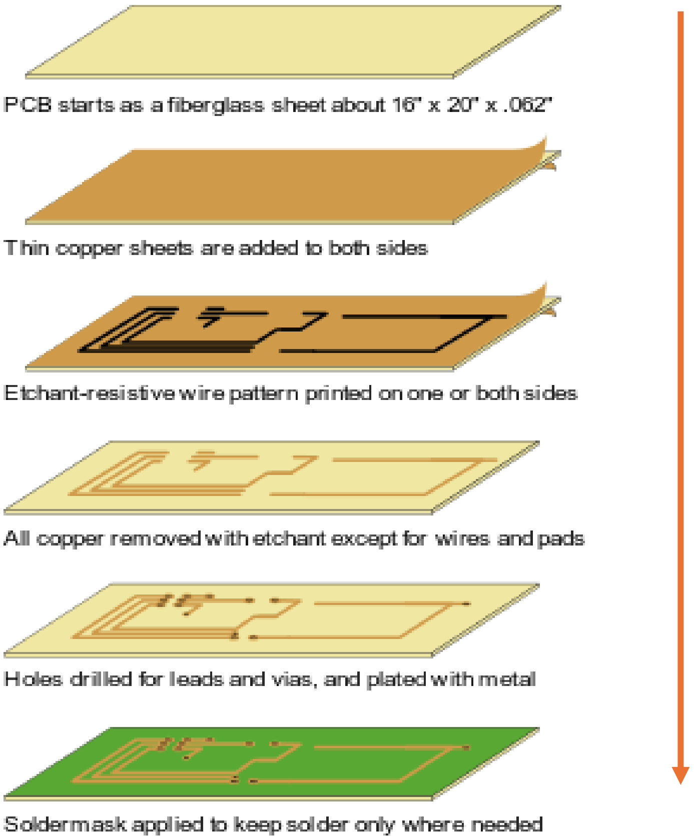


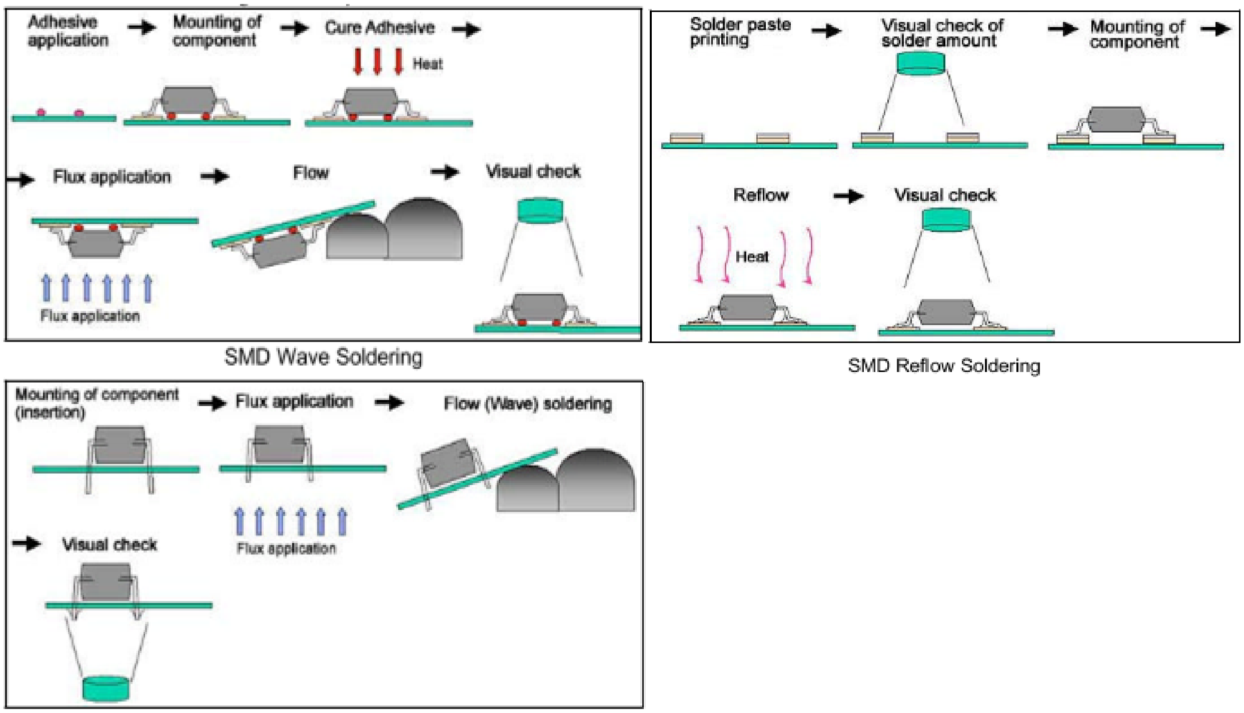
Figure 18 - Image showing the major layers and processes in basic PCB board manufacturing (Diligent Reference 2023)

PCBs are governed by a robust set of industry standards developed over decades to ensure quality, interoperability, and efficient manufacturing. Among the most widely recognized are the IPC standards, such as IPC-2221 for generic design requirements and IPC-6012 for rigid PCB performance. These provide comprehensive guidelines covering everything from materials and layout rules to fabrication and inspection processes. These standards form the backbone of consistent, reliable PCB design and production across the electronics industry. They facilitate clear communication between designers, manufacturers, and assemblers, ensuring that each stage of the PCB lifecycle adheres to shared expectations for performance, reliability, and cost-effectiveness.

These standards are also deeply integrated with EDA software, which enables designers to implement rules and constraints directly within their design environment. EDA tools use IPC-driven libraries, footprint specifications, and design rule checks (DRCs) to streamline layout, simulate circuit behavior, and flag errors early in the process. This synergy between standardized design protocols and digital tools reduces the likelihood of costly iterations, supports design-for-manufacturing (DFM) best practices, and ultimately accelerates time to market. The maturity and depth of PCB standards highlight the contrast with emerging fields such as TCBs, where standardized frameworks are still in their infancy.

2.3.1.1 Soldering and Component Placement in PCB

Three types of soldering are used in PCB development: hand, wave, and reflow (Figure 19). Hand soldering is used for prototypes and small-scale production. Reflow soldering applies a paste (a mixture of flux and solder paste) on the board with a stencil before the components are placed on top and heated in an oven. Wave soldering passes the board with components through a molten solder bath. A combination of reflow and wave soldering can be used for through-hole and surface mount components. Soldering takes place after component placement in PCB manufacturing. Although soldering and component placement in the PCB process is largely automated by robotic arms, especially for large-scale production, some design process guidelines still guide the design before the actual placement and soldering process is carried out.



SMD Wave Soldering

SMD Reflow Soldering

Through-hole Wave Soldering

Figure 19 - Different types of soldering used in PCB development (Jones, 2004)

While small electronic devices (like resistors, capacitors, inductors, diodes, etc.) are usually soldered into the circuit board, the physical envelope for components is called the package (Figures 20 & 21). Component packages can be vastly different for the very same component. In Figure 20, some component packages have pinpointed leads (or legs). These pin-pointed components are also referred to as the through-hole components, while the component leads that are non-pin shaped are the surface-mounted components. Under the surface-mounted devices, there are different shapes for the lead types, as shown in Figure 21 below. There are gull-wing leads, J leads, L leads, solder ball leads, leadless leads, etc. The name of the component lead describes the shape of the lead. For instance, the gull-wing leads extend outwards from the component body and then curve back like the wings of a seagull, and the J-leads have a "J" shape with a straight section and a small hook at the end. The L-lead is similar to the J-lead but without the hook at the end. The solder ball leads are small spherical balls attached to the bottom of the leads. They are used mostly in ball grid array (BGA) packages, while leadless leads do not have any leads at all.

Figure 20 - (left) resistors in different packages (right) integrated circuits in different packages

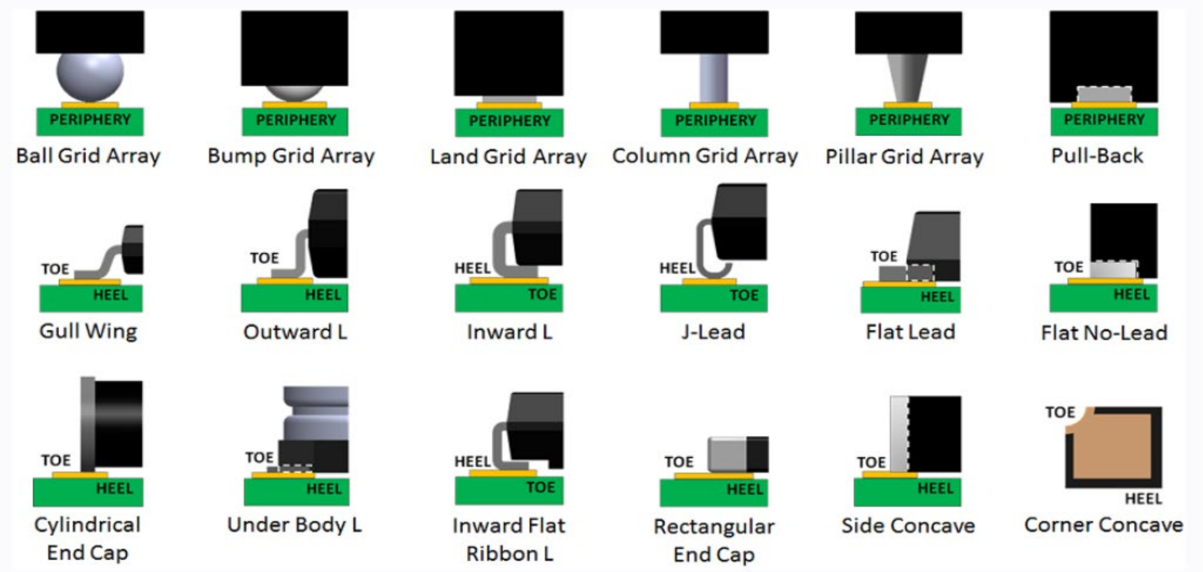


Figure 21 - Different SM components lead types (PCB Library Construction Guidelines, 2016)

Component placement in PCB design is a critical aspect that largely depends on the designer's discretion. A general guideline is that components are placed into blocks, and similar components, like resistors, capacitors, etc., are placed in common blocks. Also, components that do not coexist well should be placed in larger blocks to have enough room to separate them electrically and physically. For example, low current sensitive circuits and high current sensitive circuits need to be separated in a board. Additionally, aiming for **symmetry** is often recommended in component placement on a circuit board (Jones 2004). Finally, placement can enable more efficient or effective trace routing to avoid **trace crossings** and **minimize trace length.**

2.3.2 Textile Circuit Board

A TCB translates an electrical circuit into a textile-based implementation using manufacturing processes such as stitching, weaving, knitting, and other textile techniques. Like a traditional PCB, a TCB can consist of one or more layers, depending on whether the circuit is single- or multi-layered. However, PCBs generally support more layers than TCBs due to the constraints of textile-based fabrication. To achieve different layers in a TCB, traces are routed to connect these layers. Routing strategies in TCBs must accommodate the unique challenges of the textile medium, ensuring both circuit durability and consistent electrical performance.

2.3.2.1 Routing Strategies for E-textile Circuit

Earlier, we mentioned that *'onto'* methods commonly use planar fabrication, which involves creating conductive pathways on a flat plane (the textile surface) by coating the textile surface before routing traces or attaching a planar substrate to the textile. *Into* methods often use conductive yarns, wires, and cables to create these pathways in e-textiles (Lee et al., 2009; Andonovska, 2009; Ivo, 2006). In both cases, if the strategies used to iterate these pathways are not implemented properly, they can compromise the textile conformability and flexibility and/or the circuit's performance. Routing strategies in e-textile circuits refer to the approaches used to lay out conductive paths in ways that balance mechanical flexibility with electrical functionality, all within the constraints of the selected fabrication method. However, there is often a tradeoff between achieving optimal flexibility and maintaining reliable circuit performance (Molla, 2020; Sanchez et al., 2021). While many layout decisions, such as trace placement around joints, or integration into garment seams, are guided by application-specific objectives, there exists a foundational baseline of parameters that must be satisfied to ensure a functional circuit. These "minimum viable circuit" constraints include, for example, ensuring sufficient spacing between conductive traces to prevent electrical shorts, especially on compressible or foldable textiles and selecting conductive material (e.g., thread, ink, yarn) with a cross-sectional area and conductivity adequate for the expected current load.

To navigate this challenge of mechanical flexibility and functionality in weaving, some previous studies have proposed reducing the **diameters** of the wires or replacing the wires with e-fibers to make the e-textile more flexible and functional (Cherenack et al., 2010). Still, this approach comes with the limitation of the amount of current that can pass through these E-fibers without significant damage. In addition, these E-fibers are very prone to friction damage. Another suggested approach for weaving is to route the traditional wires in a strategic way to improve functionality and flexibility. Locher et al. (2004) suggested that a textile routing layout with wires should be entirely **perpendicular** with each component placed in a quadratic grid; the high resistance of thin copper wires is considered for the power supply layer. Also, for multi-layered circuits, the **via** should be placed at each **change of trace direction** while routing (Ivo, 2006; Mikkonen & Pouta, 2015). For stitched e-textiles, the rule of thumb used by e-textile developers is to use a **serpentine** routing or meandering stitch to distribute stress and strain across the conductive routed paths on the textiles (J. S. Roh, 2017; Sanchez et al., 2021) and to avoid trace crossing to avoid short circuits (Molla, 2020).

2.3.2.2 Strategies for Multilayer E-textile Circuits

A TCB can be a single-layer or multilayer like a PCB. However, the possibility of achieving multilayer circuits in textiles is more complex than a single layer. A few multilayer circuits will be examined here in order to explain the technicalities involved in TCB routing. As an example of using the weaving technique to create a multilayer circuit, Pouta et al. created a two-layer fabric magnetic circuit using a two-warp system (Pouta et al. 2015). In this two-warp system, four warp threads were replaced with conductive threads to route the circuit. The ground (GND) and Power (5v) were on different layers, while the components were placed in the middle of the layers. In the case of the stitching technique, a single-layer circuit uses only the fabric and an interfacing layer, depending on the **thickness of the fabric** used. A stitched multilayer circuit in fabric might require more layers, including stacks of different fabric types (e.g., spacer fabric) at different locations, e.g., a **seam tape layer, interfacing layer,** etc., to isolate traces from each other electrically (Zeng et al., 2014). Dunne et al. developed a stitched multilayer circuit on a piece of fabric by controlling the **tension** of a lock-stitch machine to allow traces to **float** on opposite sides of the non-conductive base fabric (Dunne et al., 2012). Dunne et al. also demonstrated layer crossing vias in a multilayered stitch e-textile circuit using **crimped textile metallic fasteners** like snaps or studs.

An alternative to routing a multilayer circuit on a single side of the base fabric is to **insulate** the conductive stitches by **stitching over them,** usually using a zigzag stitch of non-conductive thread. This process of stitching over another stitch for insulation is called **couching**. A second conductive stitch can then be laid over the couched area, and the non-conductive couching insulates the traces from each other. Buechley (2009) used the couching technique to secure stitched stainless-steel traces on a fabric and then performed a washability test to understand how secure the couching process was. The stitched traces performed well for the preliminary results after ten washing and two drying cycles. While couching can be useful in some cases, it has some limitations. One limitation of couching as an insulating technique in stitching multilayer circuits in textiles is that it is not a fail-proof insulator, especially when pressure is applied to the fabric. Also, couching adds an additional thickness to the fabric and requires more spacing width than a straight stitch, meaning that couching might not be the best option for a dense circuit in a textile. Not all sewing machines are designed to perform couching, especially with uniform couching stitches, CNC embroidery machines can achieve couching that provides sufficient insulation for e-textile circuits (Al-Huda Hamdan et al., 2018; Buechley & Eisenberg, 2009). The best that couching can be used for is to protect stitched traces from accidental shorts in less-dense textile circuits.

Another way to achieve a multilayer stitched circuit is to **stitch specifically on each layer** of the multi-circuit and separate the layers using a mesh spacer or insulating fabric. Roh (2016) used this approach to develop a multilayered electronic textile touch sensor. Both the sensing and circuit traces were stitched on the base layer of the circuit; the middle layer consisted of the insulating fabric, while the upper layer had the conductive fabric. In this case, the circuit connection was made when the conductive fabric connected with any conductive thread (Figure 22). Similarly, Sandler et al. (2019) developed a multilayer circuit for computational audio application. Conductive fabrics were used on the base and upper layers, separated by a mesh spacer. Spacers often has holes, and when pressure is applied, the two conductive fabrics make a complete connection through the holes in the spacer (Sandler et al., 2019).

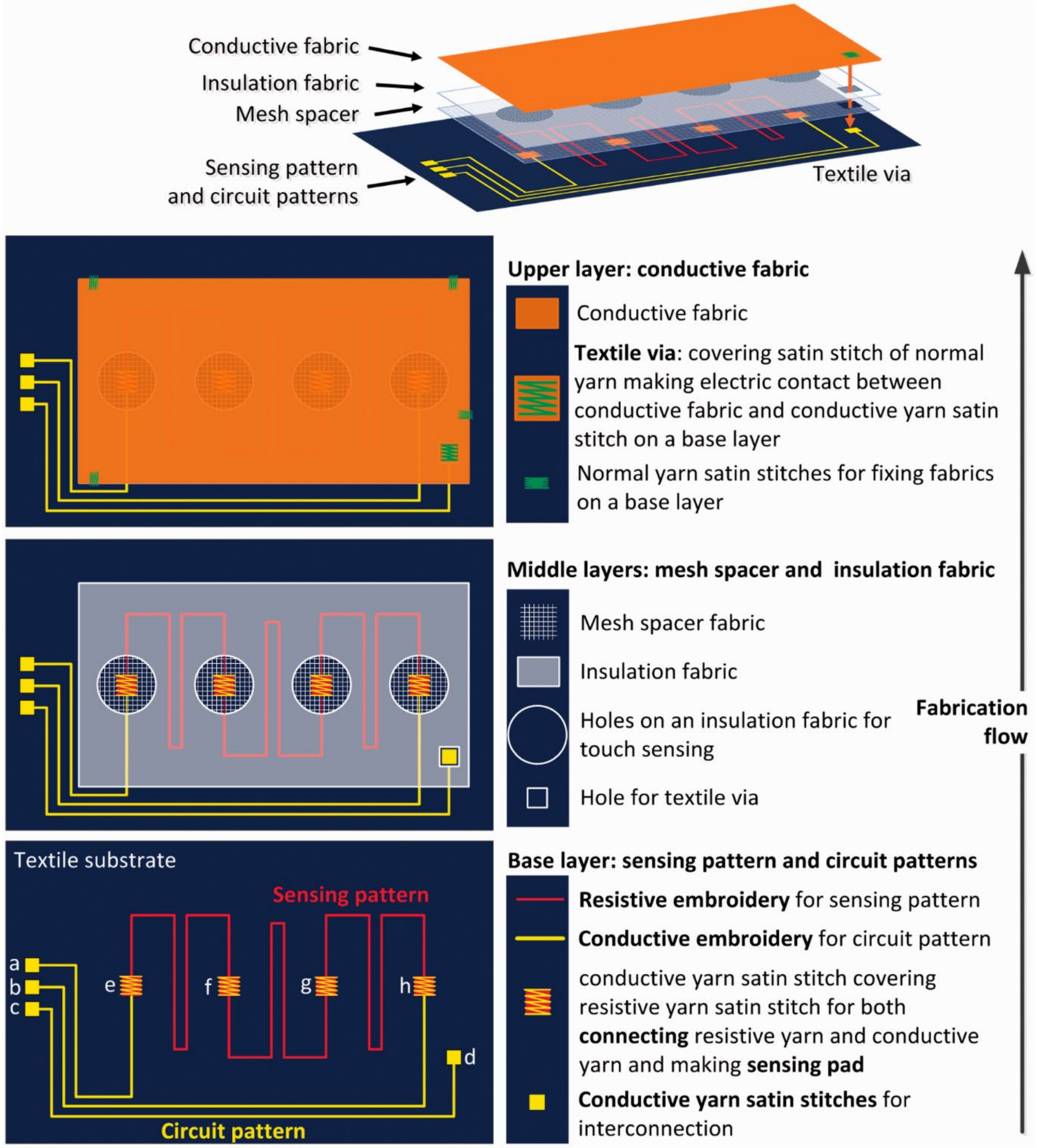


Figure 22 - Figure showing the layers in a stitched multilayered touch sensor (J. Roh, 2014)

It is important to acknowledge that many e-textile fabrication techniques still face limitations in terms of scalability, such as how many functional layers they can support, how reliably they can cross seams or garment folds, or how well they integrate with connectors. These constraints highlight a broader point, that is, for many aspects of e-textile circuit design, methods are still evolving, and consensus has yet to be reached. For example, **trace crossing, seam integration,** and **connector strategies** are areas where multiple approaches exist, but none have emerged as dominant or fully mature.

2.4 E-Textile Standards and Performance Indicators

2.4.1 E-Textile Standards

Manufacturing e-textile circuits, whether through weaving, knitting, stitching, or other methods, is currently limited by the lack of established standards to guide materials, fabrication processes, and performance benchmarks (Rotzler et al., 2021; Stanley et al., 2022). In the absence of such standards, fabrication remains largely dependent on trial-and-error methods, which may be suitable for prototyping, DIY, or small-scale production but fall short in achieving the repeatability, reliability, and quality control required for commercial-scale manufacturing.

Standards are crucial for ensuring interoperability, regulatory compliance, and consistent performance. They help define critical thresholds, such as acceptable resistance levels, mechanical durability, or washability, that fabrication methods must meet. However, before diving into specific standards currently in use or under development, it's important to clarify a key point: **a standard does not define or prescribe the full list of possible manufacturing methods** for e-textile production. While standards may reference specific methods (e.g., soldering) when establishing test methods or performance indicators, they do not dictate which fabrication techniques are available or appropriate across all applications. Instead, this responsibility falls to **design rule development** efforts, which explore, characterize, and curate the set of viable variables in different methods through iterative research and validation. Standards bodies then play a critical role by formalizing test methods and benchmarks for those techniques that have matured. As the field continues to evolve, developing and adopting process-specific standards, rooted in validated design rules, will be essential for moving beyond isolated prototypes and toward scalable, repeatable, and reliable e-textile production systems.

Although developing procedural standards for e-textiles is a complex undertaking, several organizations have initiated efforts to address this gap. The Interconnecting and Packaging and Components (IPC) organization has taken the lead in the electronics domain, while textile-focused organizations such as the American Association of Textile Chemists and Colorists (AATCC), the International Organization for Standardization (ISO), and the European Committee for Standardization (CEN) are contributing standards relevant to the textile aspects of e-textiles. In many cases, these bodies produce either full standards or technical reports and guidelines that inform practice. Table 2 summarizes some IPC standards and their potential relevance to e-textile EDA framework.

Table 2 - Some Relevant IPC E-Textile Standards and Their Relevance to EDA Design Rules

Standard	Title	Primary Purpose	EDA-Relevant Contribution	EDA Interface Type
IPC-8911	*Requirements for Conductive Yarns for E-textiles Applications*	Defines properties and performance criteria for conductive yarns (e.g., resistivity, durability)	Provides material property constraints for selecting thread types in routing and connectivity rules	**Material selection rules**
IPC-8921	*Requirements for Woven, Knitted, and Braided E-textiles Integrated with Conductive Yarns and Wires*	Establishes performance classes and test requirements for textile structures	Supports structural design constraints like minimum bend radius, fatigue limits, electrical performance expectations	**Substrate/Structure behavior modeling**
IPC-8953	*Design Standard for Embroidered E-textiles*	Specifies design guidelines for embroidery-based circuitry	Can be encoded as geometric and layout constraints (e.g., trace spacing, stitch type) for embroidered routing in EDA	**Geometric design rules**

IPC-8971	*Quality and Reliability Assessment of Coating and Encapsulation of Electronic Assemblies*	Provides guidelines for protecting e-textile assemblies	Informs environmental protection rules (e.g., coating thickness, compatibility with substrate)	**Post-processing/packaging rules**
IPC-8981	*Quality and Reliability of E-textiles Wearables*	Defines performance classes (General, Dedicated, High-Performance) and test methods	Provides overall performance thresholds (e.g., resistance, durability, washability) for circuit validation within categories	**System-level design validation**

AATCC and ASTM, for example, provide standards related to textile testing, AATCC with a focus on chemical and wet properties, and ASTM on mechanical and physical textile properties. While these standards do not directly address the needs of e-textiles, they offer valuable insights for material selection and durability assessment. Their joint publications, such as those on UV protection and moisture management, are not standards per se but serve as compilations of up-to-date technical procedures.

Still, textile standards alone cannot capture the full requirements of e-textile systems. For example, many textile standards, such as those from AATCC and ISO, do not include electrical performance indicators. Similarly, many electronics standards do not account for the flexibility, wearability, or structural complexity of textile substrates. Bridging this gap requires a more comprehensive understanding of how textile and electronic properties interact in integrated systems.

IPC has acknowledged this need and is currently developing a set of standards specifically for e-textiles (Rotzler et al., 2021). These include IPC-8911 (requirements for conductive yarns), IPC-8921 (requirements for textile structures with integrated conductors), IPC-8953 (embroidered e-textiles design standard), IPC-8971 (coating and encapsulation reliability), and IPC-8981 (quality and reliability of e-textile wearables). These standards represent an important first step in compiling terminology, classification systems, and baseline requirements from both the textile and electronics domains.

The standards that are presently available focus on the definition of terms, classifications, and requirements for testing. For example, IPC-8921 standards define a classification system and set qualification requirements for the electrical performance of woven, knitted, and braided e-textiles. Standardization of definitions is non-trivial in e-textiles because there is no overlap in some definitions; for others that overlap, they mean different things entirely. Case in point: the term "stitch." A stitch in PCB refers to connecting different copper layers to create a conductive path in a PCB through vias. A stitch in sewing means passing a threaded needle through the fabric to create loops to secure the fabric pieces together or for decorative purposes (as in the case of embroidery). Stitch in knitting means a loop of yarn formed by pulling a new loop through an existing loop using a knitting needle. While the terminology "stitch" is used in these contexts, it has to be explicitly stated in e-textile documentation.

Furthermore, the IPC-8981 standard has defined the structural characteristics important for the quality and reliability of different e-textile categories. The IPC-8981 standards categorized e-textiles into three major classifications: General E-textiles wearables, Dedicated Purpose E-textiles wearables (short and long term, e.g., sports is a long-term use), and High-Performance Harsh Environment E-textile wearables (short & long term, e.g., military applications is also a long-term use case). This classification framework reflects how **standards serve as a bridge to application objectives**, ensuring that performance expectations are tailored to use-case needs. In doing so, standards like IPC-8981 lay the groundwork for creating more **generalizable and enforceable design rules** that can be applied consistently within each category of e-textile applications. For each of these three categories, five testing procedures were established: mechanical, exposure, cleaning, and wearability & comfort tests. Some of these testing areas, particularly **mechanical durability** and **cleaning resilience**, could be **translated into EDA design rules**, especially where they affect circuit integrity or lifetime. Others, such as **exposure** and **wearability/comfort**, may exist outside the core circuit development process but are still critical to final product validation, depending on how the test methods are defined.

The IPC-8981 standard will establish test requirements for these categories of wearable e-textile products based on their functionality, non-electronic and electronics materials used in manufacturing, and expected length of use. The expected lifetime of an e-textile system intended for general usage will differ from that intended for a military application. For example, power conservation may be of utmost importance to a military e-textile system rather than aesthetics considerations. Similar distinctions among categories of e-textile wearables are what IPC-8981 is being developed for. Ultimately, these distinctions help illustrate how standards not only reinforce quality and reliability but also contribute to the development of structured, category-specific design rules, an essential step toward scaling up e-textile manufacturing with the support of EDA tools.

The IPC standards most related to our research are IPC-8971 and IPC-8952. IPC-8971 is the standardization of electrical requirements for printed electronics on e-textiles. The IPC-8971 standards outline general requirements for electrical testing of printed e-textile surfaces, and IPC-8952 presents standards for printed electronics on coated or treated textiles and e-textiles (IPC, 2023). These printed and e-textile standards also provide guidelines for electrical and mechanical test setups and techniques. Some previous standards identified the generic requirements for designing printed boards before and during the designing cycle. They help the designer to have an idea or expectations for some components, layout, and test design methods. These standards also discuss the electrical, mechanical, thermal, manufacturing, and costs of designing a circuit board and indicate how these features impact one another in terms of circuit performance. For example, in a digital circuit, the approach to digital power distribution design should be that the power and ground are designed first and not last, as is typically done with some analog circuits. Also, placing a ground close to power is encouraged to minimize the circuit's alternate current (AC) return path. For mechanical considerations, preference is given to the quantity of printed and laminated layers, thickness in the bend areas, line widths, and spacing for voltage isolation for printed circuit boards to withstand mechanical stress and strain.

While these standards are a step in the right direction for e-textile standardization, especially the IPC-8971 standards, the standardization process is still at the stage of broader guidelines for e-textile characterization. It does not extend to specific design rules that could be the basis for design specifications (Rotzler et al., 2021, p. 3). For example, in the IPC-2221 PCB standards, there is a specific range of values for electrical clearance for PCBs, while no specific electrical values were established for the e-textiles circuit. Table 3 shows two-level categories of the laid-out structure of IPC-2221 (PCBs), IPC-2223 (Flex-PCBs), and IPC-8952 (Printed e-textiles) standards. This comparison demonstrates that PCB standards do not translate directly to e-textile standards. Some new variables are being introduced as the circuit's boards expand from printed to flex circuit boards and e-textiles circuit boards. It is important to note that the latest publication of IPC standards on e-textiles as of the time of this writing contains the standard, Printed Electronics on Coated or Treated Textiles and E-Textiles (IPC-8952).

Compiling printed e-textiles standards may provide a starting point for identifying variables specific to e-textiles circuits in the standardization process, but many more fabrication methods and variables must be included to encompass the e-textiles circuit space. For instance, in Table 3, under the 'materials' category, there was an introduction to other material considerations for printed e-textile circuits. New variables like adhesives and seams were introduced for standardization.

Additionally, formed components were introduced in the 'electrical properties' category in addition to the electrical clearance and impedance control variables. Formed components are specific elements or structures within e-textile circuits intentionally shaped or molded to serve a particular purpose/function or meet design requirements. Examples are pads, connector housing, etc. All of these were not factored into the traditional PCB standards.

Table 3 - Comparison of Standards Categories Across Different Circuit Boards

PCB	**FLEX-PCB**	**PRINTED TCB**
I. GENERAL REQUIREMENTS	**I. GENERAL REQUIREMENTS**	**I. GENERAL REQUIREMENTS**
1. Information Hierarchy	1. Design Modeling	1. End-Product Performance Requirements
2. Design Considerations	2. Design Layout	2. Design Considerations
3. Schematic/Logic Design	3. Schematic	3. Schematic/Logic Diagram
4. Density Evaluation	4. Test Requirement Considerations	4. Parts List
5. Layout Evaluation		5. Test Requirement Considerations
		6. Layout Evaluation
II. MATERIALS	**II. MATERIALS**	**II. MATERIALS**
1. Material Selection	1. Material Selection	1. Material Selection

2. Dielectric Base Materials (Prepreg + Adhesives)	2. Dielectric Materials (Including Prepreg and Adhesives)	2. Flexibility
3. Laminate Materials	3. Conductive Materials (Surface Finishes)	3. Gap Bridging Applications
4. Conductive Materials	4. Organic Protective Coatings	4. Printing Over Seam Structures
5. Electronic Component Materials	5. Marking and Legend	5. Conductive Interfaces and Out-of-Plane Interconnects
6. Organic Protective Coatings		6. Via Hole Aspect Ratio/Material Deposit Aspect Ratio
7. Markings & Legends		7. Process Compatibility
		8. High-Aspect-Ratio Printing
		9. Materials Deposition Methods
		10. Dielectric Materials

		11. Adhesives
		12. Conductive Materials-Based Systems
		13. Coatings Over Printed Electronics
		14. Other Cover Materials
		15. Other Printed Materials
		16. Placed Components
		17. Marking and Legend
III. MECHANICAL/PHYSICAL PROPERTIES	**III. MECHANICAL/PHYSICAL PROPERTIES**	**III. MECHANICAL/PHYSICAL PROPERTIES**
1. Fabrication Considerations	1. Fabrication Requirements	1. Fabrication Requirements
2. Product/Printed Board Configuration	2. Product/Printed Board Configuration	2. Product/Printed Electronics e-textile Configuration
3. Assembly Requirements	3. Assembly Requirements	

4. Dimensioning Systems	4. Dimensioning	
5. Printed Board Thickness Tolerance		
6. Panelization		
7. Palletization		
IV. ELECTRICAL PROPERTIES	**IV. ELECTRICAL PROPERTIES**	**IV. ELECTRICAL PROPERTIES**
1. Electrical Considerations	1. Electrical Considerations	1. Electrical Considerations
2. Conductive Material Requirements	2. Impedance and Capacitance Control	2. Conductive Material Requirements
3. Electrical Clearance		3. Electrical Clearance
4. Impedance Controls		4. Impedance Controls
		5. Formed Components
V. THERMAL MANAGEMENT	**V. THERMAL MANAGEMENT**	**V. THERMAL MANAGEMENT**

1. Cooling Mechanisms		1. Cooling Mechanisms
2. Heat Dissipation Considerations		2. Heat Dissipation Considerations
3. Heat Transfer Techniques		
4. Thermal Design Reliability		
VI. COMPONENT AND ASSEMBLY ISSUES	**VI. COMPONENT AND ASSEMBLY ISSUES**	**VI. COMPONENT AND ASSEMBLY ISSUES**
1. General Placement Requirements	1. General Placement Requirements	1. Lands for Surface-Mount Components
2. General Attachment Requirements	2. Standard Surface Mount Requirements	2. Constraints on Mounting to Flexible Sections
3. Through-Hole Requirements	3. Lands for Surface Mounting	3. General Placement Requirements
4. Standard Surface Mount Requirements	4. Constraints on Mounting to Flexible Sections	4. General Attachment Requirements
5. Fine Pitch SMT (Peripherals)	5. Interfacial Connections	

6. Bare Die	6. Offset Lands	
7. Tape Automated Bonding		
8. Grid Array SMT		
9. No-Lead Devices		
10. Compliant Pin Design Guidelines		
VII. HOLES/INTERCONNECTIONS	**VII. HOLES/INTERCONNECTIONS**	**VII. HOLES/INTERCONNECTIONS**
1. General Requirements for Lands with Holes	1. General Requirements for Lands with Holes	
2. Holes	2. Holes	
3. Via Protection	3. Coverlay Access Openings	

VIII. GENERAL CIRCUIT FEATURE REQUIREMENTS	**VIII. GENERAL CIRCUIT FEATURE REQUIREMENTS**	**VIII. GENERAL CIRCUIT FEATURE REQUIREMENTS**
1. Conductor Characteristics	1. Conductor Characteristics	
2. Land Characteristics	2. Land Characteristics	
3. Large Conductive Areas	3. Large Conductive Areas	
IX. DOCUMENTATION	**IX. DOCUMENTATION**	**IX. DOCUMENTATION**
1. Special Tooling		1. Special Tooling
2. Layout		2. Layout
3. Deviation Requirements		3. Deviation Requirements
4. Phototool Considerations		4. Phototool Considerations
X. QUALITY ASSURANCE	**X. QUALITY ASSURANCE**	**X. QUALITY ASSURANCE**
1. Conformance Test Coupons		1. Material Quality Assurance
2. Material Quality Assurance		2. Statistical Process Control (SPC)

3. Conformance Evaluations		3. Build and Manufacturing Controls
4. Individual Coupon Design		4. Conformance Test Coupons
		5. Responsibility for Inspection
		6. Test Equipment and Inspection Facilities
		7. Preparation of Samples
		8. Standard Laboratory Conditions
		9. Tolerances
		10. Qualification Inspection
		11. Failures
		12. User Sampling Plan
		13. Noncompliance

		14. Reduction of Quality Conformance Testing
		15. Inspection Methodology
		16. Storage Conditions

The IPC-8971 standards used CAD/CAM drawings to inform the rules for routing in printed circuits on textiles, which does not necessarily translate equally to rules for stitched, woven, or knitted e-textile circuits due to the different fabrication methods of the conductive traces on the textile surface. The interaction of inks, stitches, or yarns on or in textiles is quite different. For example, a stitched trace on fabric has more unevenness than a printed trace. The knitting or weaving tensions also affect the electrical properties of knitted or woven yarn (Atalay et al., 2013; Koo, 2002; Ma & Gao, 2015). Svetlana et al. mentioned that the width of the embroidered pattern was smaller than the digital pattern **width**, while the **length** of the embroidered pattern was larger than the **digital pattern** (Svetlana & Milda, 2012). Svetlana et al. (2012) believes that studying the relationships between these changes can help an e-textile designer accommodate them and factor in the change percentage in designs. Hence, understanding the stitch properties that account for a functional and working circuit is essential.

Furthermore, for layout variables as a sub-category of manufacturing variables in circuit development, the characterization of the trace spacing for a TCB is not as detailed as that of a PCB. Some guidelines help design consideration for trace allowances in a PCB to avoid shorts, irrespective of the type of PCB, whether it is a general PCB or a PCB for a specific application.

Although the minimum allowance clearances for PCBs can depend on other factors like the manufacturing process and voltage levels, according to the IPC-2221 standard, minimum spacing for PCBs with voltages lower than 15v is ~0.1mm-0.2mm, the general rule of thumb is that trace spacing is thrice the width of the trace width, all things being equal (Jorgensen 2023). Details of some specific differences between TCB and PCB standardization can be found in Table 4. For every active component in an e-textile circuit, the following major parameters must be defined at the system specification stage before circuit development: component type and geometry/orientation, component material, nominal resistance, capacitance, and inductance (depending on which component is used), tolerance, power dissipation, and maximum voltage. The max/min/typical forward voltage for the component is different from the circuit voltage. The circuit's maximum voltage will depend on the spacing between adjacent conductors and the width/diameter of the trace. However, a consensus is that shorter component leads are necessary in an e-textile circuit to reduce impedance.

Table 4 - Major distinctions/similarities between Traditional PCB and TCB (E-Textile Circuit)

PCB	**TCB**
Known materials for etching (e.g. Copper)	No specific conductive thread (depends on the application)
Copper trace thickness is 0.035 mm.	None
Circuit board thickness = 0.8, 1.6, or 2.4mm	Fabric thickness is usually unspecified
Universal measurement unit	None

Boards laid out on a fixed grid – snap grid	Fixed grid for some kinds of knitting/weaving but no fixed grid for stitching.
Minimum spacing between 240 volt tracks and isolated signal tracks – 8mm	None
Every track has its resistance. Narrower track = higher resistance	Not necessarily the same for conductive threads. Sometimes, resistance depends on the material the thread is made of.
Pad-to-hole ratio – minimum of (1.8x hole or 0.5mm larger)	None
Vias to hole ratio = 0.5 – 0.7mm	None (even though useful for a multilayer circuit)
Clearance for pads and holes = 15 thou or 8-10 for dense layouts	None
There are equations and charts that guide the electrical properties of each track. The general rule of thumb is that thicker tracks are preferable.	None
Usually on a rectangular shape board and usually smaller sizes	Irregular shapes and larger sizes across the body silhouette
Short routing is encouraged for both. It decreases resistance, capacitance, and inductance.	
Recommended angle for routing = 45$^{o.}$ Avoid 90^{0} or more.	None

Avoiding sharp corners is recommended for PCB	Getting precise rounded corners in TCB can be tricky, especially stitching.
Perfected serpentine track corners	Serpentine tracks are not yet perfected.
Through-hole component legs to connect top and bottom tracks	
The substrate is usually Fiberglass with known material properties. The dielectric constant value of 3.9-4.8 (Sometimes, Teflon material is used)	No standardized fabric material properties are known for a textile circuit substrate.
Netlists (in Gerber/drill/pick and place file formats)	The closest we have are layers of dxf/pdf files in AI/CLO3D

Apart from the standardization of the manufacturing parameters, there is also a development in the standardization of the performance indicators of e-textiles. A case in point is that of the washability of e-textiles. Although the existing standards for washability of e-textiles are very sparse, the most common standards used are from the traditional textile industry, e.g., ISO-6330 (Rotzler et al., 2021; Rotzler & Schneider-Ramelow, 2021). These standards define wash test methods that can translate to e-textiles but do not include metrics or methods for measuring electrical properties post-wash. The industry has made efforts to develop testing conditions that can standardize the washing process and post-wash assessment of e-textiles. Rotzler et al. (2022) classified the current vast washability test practices used in the e-textile industry in the absence of specific e-textile standards into four major categories - (1) wash testing according to the ISO-6330 standard, (2) wash testing according to other standards, (3) wash testing under household conditions, and (4) washing testing with alternative methods. Rotzler went further to mention that there is a lack of compliance in following guidelines in the ISO-6330 standards because the standards are specifically for textiles and not e-textiles, hence there is a need to develop washing standards for e-textiles. When such washing standards are established for e-textiles, design rules can be set by placing constraints on trace spacing, material compatibility, and joining techniques that can survive a specified number of washing cycles for the different classification of e-textiles as specified by IPC.

2.4.2 Performance Indicators

Conductivity, durability, and washability consistently emerge as the top performance indicators in the characterization of e-textiles (Molla, 2020). Among these, conductivity stands out as the fundamental, baseline metric of whether an e-textile circuit is functioning as intended. In the context of EDA systems, where the goal is to produce circuits that perform reliably according to design inputs, conductivity becomes the metric for validating whether the circuit works, whether the electrical connections are intact, whether signal paths remain continuous, and whether resistance values are within acceptable limits.

These metrics are evaluated to ensure that the textile-integrated circuit remains electrically functional even after exposure to physical stress, bending, abrasion, or laundering. Unlike traditional textiles, where durability might be quantified through metrics such as tear strength, pilling resistance, or colorfastness, performance in e-textiles is primarily judged by the circuit’s ability to maintain its electrical function. Across nearly all of these performance tests, the key indicators of success are electrical metrics, most commonly changes in resistance, as well as the presence of opens or shorts. Whether assessing mechanical stress, washing cycles, or environmental exposure, researchers typically measure whether the circuit still "works" by monitoring if resistance values remain within acceptable bounds or if sudden failures (e.g., open circuits or short circuits) occur.

2.4.2.1 Conductivity

Conductivity is a core electrical performance indicator used to evaluate how effectively a circuit allows the movement of electrical charge. It is inversely related to resistivity and is typically assessed by measuring **electrical resistance** across different points of a circuit. In e-textile systems, **conductivity measurements serve as a critical method for validating circuit performance**, confirming that reliable electrical connections have been formed, that there are no unintended shorts or open circuits, and that the observed resistance levels align with design predictions. In some cases, **voltage levels** at specific nodes may also be measured to verify correct circuit function. These measurements directly support the objectives of **Electronic Design Automation (EDA)** tools, which aim to generate circuits that perform according to defined electrical specifications.

The conductivity of an e-textile circuit depends heavily on both the **material properties** of the conductors and the **quality of interconnects**. Conductive threads, such as silver- or copper-coated fibers, vary in their inherent resistance. Although silver is more conductive, copper is sometimes favored in PCB applications for cost-efficiency. In e-textiles, however, silver-coated threads are more commonly used due to compatibility with textile processes. Still, a **fully metallic copper fiber** will typically exhibit lower resistance than a **silver-coated non-conductive core**, demonstrating the importance of material composition as a design rule input.

Designers often apply fabrication-specific strategies to optimize conductivity. For example, in **weaving**, conductivity may be improved by increasing the **density of conductive yarns, modifying the weave structure**, or **enhancing yarn composition** (Atwa et al., 2015). In **stitching or embroidery**, resistance can be significantly affected by how a thread is routed through a sewing machine. Passing conductive thread through both the needle and bobbin, effectively doubling the conductive mass, has been shown to reduce resistance (Ruppert-Stroescu & Balasubramanian, 2018). These types of layout-driven strategies are essential for EDA rule development, as they link fabrication parameters to performance outcomes.

A major challenge in using resistance as a performance indicator is that **e-textile circuits are subject to mechanical, chemical, and environmental degradation**, which can alter their conductivity over time. For instance, uninsulated conductive threads may **oxidize**, leading to increased resistance. Physical stress from bending, stretching, or washing can also impact circuit performance. These concerns reinforce the need for **post-fabrication validation** of conductivity and the eventual integration of **lifetime prediction models** into EDA tools.

Measurement itself presents challenges: **inconsistent surface topology** in textiles can make it difficult to establish reliable contact with probes. As Posch & Fitzpatrick (2021) and Rotzler & Schneider-Ramelow (2021) have noted, this variability often necessitates **averaging multiple resistance readings**, a practice common across literature (Molla, 2020). Moreover, resistance values provided by thread manufacturers typically represent **unfabricated thread**, which may diverge significantly from actual performance after integration through weaving, stitching, or printing. This underlines the importance of **fabrication-aware material characterization** within EDA environments.

Numerous factors influence stitched circuit conductivity: **stitch density, stitch length, thread tension, fabric type, mechanical load, and contact resistance**. Molla et al. observed that increasing a stitch count improved overall conductivity. Petersen et al. (2011) further studied how **mechanical deformation** and **aging** affect stitched resistors on knitted, polypyrrole-coated fabric. By applying different stitch lengths (1–4 mm) and weights (cylindrical and parallel bar), they found that fabric resistivity, rather than surface resistivity, offered more reliable insight into performance degradation. Resistance increased over time, but stitch lengths between 1.5 mm–2 mm combined with cylindrical weights yielded the most stable and low-resistance configurations. High stitch density and tension were also associated with improved contact quality.

In summary, **conductivity testing serves as a foundational performance verification mechanism** for e-textile circuits. It is one of the few measurable outputs that can be used to **confirm whether a circuit produced through an EDA system functions as intended**. Integrating predictive models for conductivity degradation, contact resistance, and the impact of other fabrication parameters involved with factors such as stitching, fabric formation (weaving, knitting) or applied processes such as printing into EDA tools can help close the loop between design and performance, transforming today's trial-and-error practices into **data-driven, rule-based design processes**.

2.4.2.2 Durability

Durability in e-textiles refers to the ability of a textile-integrated circuit to maintain its performance when subjected to repeated mechanical or chemical stress. The **metrics** commonly used to evaluate durability include the **failure rate** of stitched or printed traces, the **time to failure**, **changes in electrical resistance**, **mechanical properties** like **tensile strength**, and the

structural integrity of interconnect points such as solder joints. These metrics reflect how well the e-textile can endure real-world use, including bending, abrasion, compression, oxidation, and laundering, without compromising electrical functionality.

The stresses that e-textiles undergo can be broadly divided into **mechanical** and **chemical** categories. Mechanical stresses arise from forces that cause deformation, such as stretching, folding, or twisting during wear or movement. Chemical stresses result from exposure to substances such as detergents, sweat, or moisture, which can degrade conductive materials or textile substrates. Durability tests are designed to simulate these conditions and quantify their impact using appropriate evaluation methods. For example, **mechanical durability** is often assessed using an Instron machine or flex-and-fold devices to apply tension or cyclic loading to stitched traces while recording **changes in resistance** or **physical failure**. A tumble dryer can be used to simulate stochastic wear and tear conditions, capturing both **physical** and **electrical degradation** over repeated cycles.

In one study, Berglund et al. (2015) developed a durability testing method using a tumble test to assess stitched e-textile circuits. Molla et al. expanded on this by evaluating **400 stitched LED traces** under similar conditions. They found that **42.5% of these circuits failed** by the end of the test, and the most frequent **point of failure** was the solder joint connecting the LED to the textile. This study used both **failure rate** and **time to failure** as core durability metrics and demonstrated that **perpendicular trace orientations** performed better than parallel ones. It also revealed that most failures occurred within the **first 90 minutes** of testing, highlighting **early fatigue** as a critical issue in certain configurations.

Another aspect of durability relates to the performance of **soldered joints** under stress. Here, it is important to distinguish between **solderability** and **durability**. Solderability describes how well a component initially bonds to a textile using solder material to form an electrical connection. **Durability**, on the other hand, measures **how long that connection remains reliable** after repeated mechanical or chemical stresses. A connection that appears functional at the point of assembly may degrade over time due to **poor solder volume**, **incorrect temperature profiles**, or the **mechanical demands of the application**. Molla (2020) emphasized that **component size** plays a significant role in this process, especially for miniature components, where the margin for error in applying solder is narrow. Optimizing **soldering parameters** is therefore essential not only for achieving initial functionality but also for maintaining **circuit performance over time**. Durability metrics are fundamental to understanding **long-term reliability** in e-textiles and are critical to informing **design rules**. They also help identify which **fabrication parameters**, such as **stitch type**, **trace orientation**, or **interconnect method**, are most influential in ensuring that circuits continue to function as predicted throughout their intended lifespan.

2.4.2.3 Washability

Washability refers to how well an e-textile circuit retains its performance and structural integrity after exposure to laundering. The **metrics** commonly used to evaluate washability include **change in electrical resistance**, **presence of opens or shorts**, **mechanical integrity of solder joints**, **visual degradation** such as fraying or discoloration, and the **percentage of functional circuits** after a defined number of wash cycles. These metrics help quantify the effects of chemical and mechanical stresses during washing and drying processes.

Degradation in washability tests typically arises from two main sources: **chemical stresses** and **mechanical stresses**. Chemical stresses are due to interactions with water, detergents, or environmental moisture, leading to **oxidation** of conductive materials. This is especially critical because many conductive yarns used in e-textiles are not insulated, leaving them vulnerable to oxidation. In contrast, mechanical stresses are physical forces such as agitation, tumbling, or centrifugal force that occur during washing and drying cycles, which can cause breakage or delamination in circuit traces or interconnects (Rotzler & Schneider-Ramelow, 2021).

Molla et al. conducted a study to evaluate how wash cycles influence **circuit functionality** in stitched e-textiles. After 17 hours of machine washing and drying, they tracked **failure points** and **resistance changes**. The most frequent **point of failure** was at the interface between the conductive trace and the solder joint, distinct from the failures observed in durability testing under tumble conditions, where failures occurred between the **trace** and the **component lead**. These findings suggest that **mechanical agitation in tumble tests exerts higher stress** on solder joints compared to standard washing processes.

A notable limitation in Molla's study was the **unreliability of resistance readings** across wash cycles. These inconsistencies highlight a challenge in washability testing, ensuring **repeatable electrical measurements**. Inaccurate or unstable readings may stem from **contact variability**, especially when test probes interface with soft, uneven textile surfaces. Linz (2011) addressed this challenge by showing that **adhesive bonding techniques** for attaching PCBs to embroidered traces yield more stable and reliable electrical contacts compared to mechanically drilled contact pads.

Another shortcoming in typical wash testing is the lack of control over **force directionality** during machine cycles, limiting insight into how different types of stress (e.g., lateral vs. vertical force) impact e-textile reliability. To overcome this, researchers sometimes supplement washability tests with **mechanical load testing** using instruments like an Instron machine, which enables controlled application of directional force and quantification of **tensile failure thresholds**.

Ultimately, reliable washability evaluation must account for the four parameters of the **Sinner's Circle: time**, **temperature**, **mechanical action**, and **chemical action** (Rotzler et al. 2021, Waschmittel 2017). Rotzler et al. (2021) emphasize that only by controlling or monitoring all four of these factors can one assess washability in a repeatable and meaningful way. Together, these **metrics** define the ability of an e-textile circuit to survive laundering without loss of electrical or mechanical function, an essential consideration for real-world wearable electronics.

2.4.2.4 Flexibility and Bendability

Flexibility and **bendability** are key **performance indicators** that assess an e-textile circuit's ability to withstand bending, folding, or flexing without compromising its **structural integrity** or **electrical functionality**. While related to **durability**, these metrics differ in scope: **durability** captures overall robustness over time and under various stresses, while **flexibility** and **bendability** focus on the immediate and repeated ability of a circuit to conform to shape changes common in textiles, especially during use.

A range of **quantitative parameters** are used to characterize these metrics. The most common include **bending cycles**, **bending angles**, **bending radius**, and **flexural strength**. Among these, the **bending radius** is particularly critical. It defines the minimum radius to which a circuit can be bent without failure. For example, **conventional electronics** such as flexible multichip modules typically allow a bending radius of ~50 cm (Post et al., 2000), whereas textiles, due to natural draping and folding behaviors, often undergo **bending radii as small as 10 mm**, particularly around body joints (Ivo, 2006).

These differences highlight why measuring **flexibility metrics** is essential for designing e-textiles that maintain circuit performance under normal wear conditions. Understanding the relationship between component layout and mechanical deformation helps guide choices in **component type**, **spacing**, and **placement strategy**. For instance, Locher et al. proposed that when using components in a **quadratic grid layout**, the **grid spacing**, the distance between two adjacent components, should be at least **twice the diagonal width of the component**. This layout improves the **foldability and drapability** of the e-textile while reducing strain on interconnects (Ivo, 2006).

Flexibility characterization also informs decisions in material selection and circuit design. For example, Moradi et al. (2018) emphasized the use of **bending radius** as a primary metric for comparing flexibility performance across different substrate types and conductor configurations. These insights help bridge the gap between electronics and textiles, making it possible to integrate circuits into garments without sacrificing comfort or reliability.

Ultimately, **flexibility** and **bendability** metrics are essential for ensuring that e-textile circuits behave as predictably and safely as possible when integrated into everyday wearable applications. They guide not only the design of the circuit itself but also the choice of conductive materials, placement techniques, and garment construction.

2.4.2.5 Repeatability and Reliability

Repeatability and reliability are core performance indicators that evaluate how consistently a fabrication method or circuit design can be reproduced with similar outcomes, and how dependably it performs over time. In the context of e-textiles, achieving repeatability means the same fabrication technique yields consistent electrical and mechanical results across multiple iterations. Reliability, on the other hand, reflects the long-term dependability of the circuit's functionality under real-world conditions.

These metrics are critical indicators of how scalable an e-textile technology is, from DIY prototyping to commercial manufacturing (Venturi & Taylor, 2022). It is not sufficient for a circuit to work once; the goal is for it to work repeatedly, using the same materials and processes, and to retain that functionality through wear, wash, and time.

Despite their importance, there is limited dedicated research on **quantifying** these metrics in e-textile systems. However, parallels can be drawn from related domains such as additive manufacturing and 3D printing, which also focus on layered material construction. These industries have developed frameworks for ensuring repeatability and reliability, such as statistical process control and design of experiments, which are increasingly relevant for e-textile production.

In stitched and embroidered e-textiles, **electrical resistance** and **contact reliability** have emerged as the two major sources of unreliability (Molla, 2020; J. S. Roh, 2017). For instance, Ahn & Kim (2022) emphasized the use of **statistical averaging** and repeated measurements to account for variability in resistance readings across swatches. Gowrishankar et al. (2013) employed this approach by taking resistance measurements at consistent intervals, every 4 cm, across embroidered stitches to assess reliability in stitched resistors. Similarly, Molla (2020) fabricated hundreds of stitched swatches to study repeatability, adjusting parameters like **stencil thickness** and **pad area ratios** to improve joint consistency. Nonetheless, variability in **resistance values** persisted, suggesting a strong need for standardized methods to measure and evaluate these metrics. Studies have also highlighted **unreliability in connection joints** as a persistent challenge (Lehn et al., 2004; Linz et al., 2006; J. Roh, 2014; J. S. Roh, 2017; Servati et al., 2017). Whether due to inconsistent soldering, misalignment of pads, or environmental degradation, these points of failure critically impact both repeatability and reliability.

Overall, formalizing the measurement of repeatability and reliability metrics, through repeat trials, statistical evaluation, and joint quality analysis, is vital for validating e-textile performance and building confidence in manufacturing processes. Doing so will not only support the development of design rules within EDA frameworks but also help bridge the gap between lab-scale innovations and scalable, user-ready products.

2.5 Circuit Testing

While performance indicators give insight into how e-textile circuits hold up under different conditions, they don’t always confirm whether the circuit functions as designed. Conductivity as a performance indicator check can reveal basic failures like opens or shorts, but verifying circuit behavior, such as correct voltage at different points, requires targeted electrical testing. Circuit testing in PCBs checks that the designed PCB works as it should. Circuit testing can be electrical, mechanical, or optical testing. Electrical testing is having the PCB checked for electrical continuity or shorts. The electrical testing for PCBs is done automatically using flying probes or beds of nails to test for multiple connection points. Flying probes and beds of nails are two common test methods used in the electronics industry and have been adopted in the e-textiles manufacturing process (Chattopadhyay 2019). **Flying probes and beds of nails** are non-invasive testing techniques of e-textile prototypes using probes or beds of nails to make electrical contact at specific points in a circuit board, and they can be done manually or automatically (Figure 23). However, using traditional probes used in the electronics industry might not be the optimal solution for e-textiles because continuous puncture of nails in e-textiles can potentially damage the fabric's structure and disrupt the electronic connection of the e-textiles circuit (Molla, 2020).

Additionally, it is important to note that resistance in e-textiles can vary each time a contact is established, adding to the complexity of the electrical resistance measurement process. IPC-8952 and IPC-8971 standards recommend using a rounded probe tip instead of a pinpoint probe to avoid damage to the e-textile circuit, but the downside is a lower contact point with a rounded probe tip. As specified in IPC-8952 standards for testing printed e-textiles, other testing methods include functional and in-circuit testing using an automated optical inspection method. The functional test uses a computer simulation to check through a circuit's connectors or test points. Like the functional test, the automated optical inspection method uses a camera to detect physical faults at different manufacturing stages. The latter two methods are limited to detecting physical faults in the circuits.

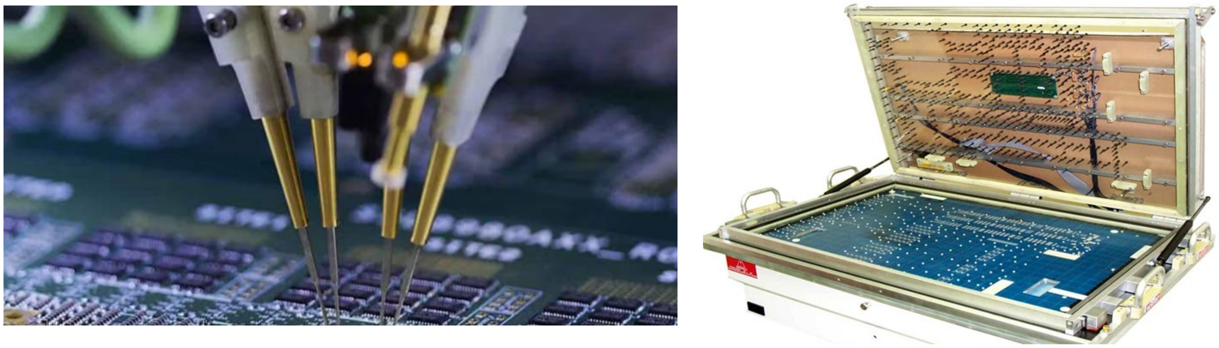


Figure 23 - left: Flying probe (Taisha Chattopadhyay 2019), right: beds of nails (Editorial Team 2020)

Electrical testing for PCBs occurs at multiple stages of manufacturing to ensure circuit integrity and alignment with design expectations. One key step involves verifying all nets, across board layers, by making contact with each pad to ensure electrical continuity. Adjacent nets are also tested for isolation to prevent unintended connections. These tests confirm that the circuit layout has been accurately replicated during fabrication. Importantly, the machine compares the measured electrical properties to the predicted values from the design, which is exactly what design rules aim to optimize: increasing the likelihood that real-world measurements align with design intent. In addition to electrical testing, optical inspection is used to detect physical defects, and mechanical stress testing is conducted to verify the structural integrity of the PCB. While this testing is a procedural method for industry-standard PCBs, there are no prescribed ways to test TCB circuits. State-of-the-art testing of e-textile circuit prototypes uses a digital multimeter and probes or alligator clips to check for shorts and opens in the e-textile circuit. Testing circuits in e-textiles is non-trivial because repeated testing is required at every stage of the development of the product, including after the product is fully developed during manufacturing.

Additional challenges exist in testing layers in e-textile circuits that have been fully insulated as part of the production process. To mitigate this challenge, Molla et al. mentioned that insulation of traces should be done when traces have been adequately tested. However, some insulation methods (like couching or embroidered insulation) risk damaging the underlying circuit, and thus necessitate testing after insulation. Molla et al. outlined some guidelines for quality assessment, including testing, troubleshooting, and reworking the stitched e-textile circuit. These testing guidelines were carried out at every stage of e-textile production. The guidelines included: (i) visual test - visual inspection of the traces, joints, and components for any form of disconnection, (ii) digital multimeter testing of the traces and joints - establishing that the voltage difference between power and ground is the expected value, any other value meant a faulty connection in the circuit, (iii) isolating each completed sensor component to test with a microcontroller test rig, and (iv) post-production assessment of the functionality of the full garment. These guidelines are specific to his study and might not translate across all e-textile circuits. Standards for testing e-textiles are still very much in the infancy stage. Overall, there are no standardized ways to test e-textile circuits or characterize and evaluate fabrication parameters. Stanley et al. (2022) mentioned that the lack of standards for manufacturing methods and materials is one of the major factors inhibiting the commercialization of e-textiles. Therefore, there is a need to start the collation process of manufacturing design rules for testing TCBs, which can further be expanded upon to develop a future EDA tool for TCB design manufacturing.

2.6 Electronic Design Automation

Electronic Design Automation (EDA) is a critical component of modern electronic design, including e-textile design. It encompasses a wide range of tools and software algorithms that automate various stages of the design process, from schematic creation to layout, verification, manufacturing preparation, support for industry adoption and standardization. The different elements of EDA are interconnected and collectively support efficient, scalable design. In this dissertation, the focus will be on one essential aspect of EDA: the development and application of **design rules** as they pertain specifically to e-textile circuit design. Design rules can significantly improve the manufacturability and performance of stitched woven circuits, just like traditional PCB design. Design rules optimization through artificial intelligence and neural network technology have been used to optimize automatic circuit layout in traditional PCBs. This optimization has led to the development of auto-routing in PCBs (Jones, 2004). The closest we have to auto routing in TCB was the work done by Hamdan et al. that converts an artist's sketch into an embroidered e-textile circuit (Al-Huda Hamdan et al., 2018). Hamdan et al. used an end-to-end developmental workflow to convert artist sketches to an embroidered e-textile circuit. Some of the routing and component placement fabrication parameters were evaluated for the e-textile design. This automation speeds up the process, but custom components were used, which do not translate to design rules and guidelines that can guide any end-to-end design process for stitched e-textile.

Although this was a significant landmark in the automation of stitched e-textile circuits, the reproducibility of the process was limited. One major setback was that the system does not offer auto-routing and rule checks for the fabric circuits. Other research that has developed a type of EDA tool has focused on software tools designed to control the embroidery process and tools used to develop the electronic circuit. Using existing PCB design tools, Eichinger et al. created custom software to convert a 3D CAD circuit layout to an embroidered circuit (Eichinger et al., 2007).

Although a capacitive sensing circuit was stitched successfully, the approach bypassed the understanding of textile fabrication parameters like stitch density, length, and type. The focus was more on using regular PCB design tools than understanding how to adapt them to textile manufacturing.

Locher et al. conducted a study that adapted EDA tools for PCBs to design rules for auto-routing and component placement in woven e-textiles (Locher et al., 2004). The fabrics and the conductive copper wire were first characterized to understand their electrical and mechanical properties. Afterward, the substrate area on the fabric to route the circuit was evaluated based on textile-specific routing and component placement constraints. One component placement rule established for this woven e-textile to ensure a simultaneously functional and drapey e-textile circuit was to place components in a quadratic grid on the textile. Two routing rules established were that a textile layout must be entirely perpendicular as determined by the fabric structure, and the high resistance of thin copper wires must be considered. Locher et al. conducted several weaving experiments to find different routing methods in fabric for optimal sensor component placement (Locher et al., 2004), understanding electronic connections through interlacing weaving structure in 1D to incorporate the electronics at the fiber level. After that, Locher embedded electronics in 2D and 3D between layers to improve conformability on the body and connectivity in the electronic circuit route. Locher later implemented these rules as temperature sensors and wireless connections in a woven textile. Although Locher's approach was used for weaving techniques using wires and not a conductive thread for routing, the insights from adapting traditional PCB EDA tools implemented in Locher's approach can be used to characterize stitched e-textiles in a woven textile.

In a more recent study, Knowles (2023) explored the use of digital strategies to advance e-textile design, with a particular emphasis on integrating 3D garment simulation as a predictive tool for evaluating performance. The study aimed to digitally link textile design decisions, such as material selection and pattern dimensions, to electrical performance indicators like resistance and signal-to-noise ratio. In doing so, it shifted the focus toward manufacturing by defining foundational design rules for key textile processes (e.g., knitting, weaving, embroidery) and embedding these constraints within CAD-CAM environments. This approach helps designers understand how their choices interact with the limitations of industrial manufacturing tools and how these choices may impact final performance outcomes.

Additionally, Knowles proposed a process flow for e-textile system design by integrating best practices from both the textile and electronics industries. Through engagement with academic and industry stakeholders, the study identified critical gaps in current digital tools and infrastructure and offered a transdisciplinary framework along with a roadmap to support the development of a cohesive digital ecosystem for e-textile manufacturing.

Our study builds on and extends this work in several major ways. While Knowles focused primarily on CAD-CAM integration and predictive simulation, our research shifts the focus to the system-level organization and data structures required to support repeatable and standardized e-textile manufacturing. Unlike predictive simulation, which falls under the domain of application-specific objectives, or the more downstream CAD-CAM integration, our work operates at an intermediate layer. It goes deeper into defining the scope, interdependencies, and logic of design rules, and demonstrates how these rules can be structured and applied in practice to guide fabrication decisions. Our work introduces a modular design framework for EDA in e-textiles, enabling real-time decision support and integration of multiple data sources (from both textiles and electronics). Finally, where Knowles identifies general gaps in infrastructure, our study characterizes specific fabrication variables and their interdependencies, laying the groundwork for data-informed design rules that improve communication between designers and manufacturers and support future standardization.

2.7 Summary

Chapter 2 provides a comprehensive review of variables from relevant literature to establish the context for this research as summarized in Table 5. It explores various manufacturing methods for e-textiles, current practices in circuit development, and key performance considerations. The chapter also addresses challenges in standardization, reviews existing standards applicable to both textiles and electronics, and examines the role of EDA in streamlining circuit design. Finally, it draws parallels with conventional PCB manufacturing processes to highlight opportunities and gaps in developing scalable, rule-based approaches for e-textile circuit production.

Table 5 - Summary of variables observed in the literature review

#	Variable	Method	Category	Impact / Notes	Reference(s)
1	Trace width	All	DR	Affects traces, joint strength and reliability	Molla et al., 2020
2	Pad size / diameter	All	DR	Determines contact area and mechanical strength	SMT practices,

					Michal et al., 2019
3	Lead geometry types	All	DR / AO	Influences mechanical stress and solderability	-
4	Thermal profile (temperature, dwell time)	Soldering	DR / S	Affects joint quality and textile compatibility	Molla, 2020
5	Joint resistance threshold (<1Ω)	All	DR / S	Used as pass/fail criteria for electrical connection	Michal et al., 2019
6	Skin contact safety / toxicity	Soldering	S / AO	Toxicity of exposed joints	Molla, 2020
7	Weld energy input (current, ultrasonic amplitude)	Welding	DR	Governs melting behavior and weld strength	Slade & Winterhalter, 2015
9	Material compatibility (e.g., thermoplastics)	Welding	AO	Only viable on compatible substrates	Slade & Winterhalter, 2015
10	Insulation removal via melting	Welding	DR	Enables contact during ultrasonic welding	Slade & Winterhalter, 2015
12	Adhesive type (conductive vs. non-conductive)	Adhesive Bonding	DR	Determines if joint is electrical or mechanical	Stanley et al., 2022

13	Adhesive conductivity types (ICA vs. ACA)	Adhesive Bonding	DR	Affects directionality of conduction	Stanley et al., 2022
14	Thermal stability of adhesive	Adhesive Bonding	AO	Limits use in high-temp environments	Molla, 2020
15	Component size / weight limitations	Adhesive Bonding	AO	Adhesives best for lightweight components	Molla, 2020
16	Bond strength under stress	Adhesive Bonding	DR / S	Affects mechanical reliability	Scheulen et al., 2013; Simegnaw et al., 2021
17	Stitch type (e.g., zigzag, cover stitch)	Stitching / Embroidery	DR	Impacts electrical behavior and stretch response	Molla, 2020; Gioberto et al., 2016
18	Stitch geometry / orientation	Stitching / Embroidery	DR / AO	Affects deformation and signal response	Bekampien & Domskien, 2014
19	Stitch length	Stitching / Embroidery	DR	Affects resistance and mechanical durability	Warrior et al., 1999; Simegnaw et al., 2021
20	Stitch density	Stitching / Embroidery	DR	Determines coverage and signal stability	Sanchez et al., 2021

21	Stitch tension	Stitching / Embroidery	DR	Affects thread behavior and signal reliability	Warrior et al., 1999
22	Thread type (material, conductivity)	Stitching / Embroidery	DR / S	Affects resistance, conductivity	Dupler & Dunne, 2019
23	Fabric substrate type	Stitching / Embroidery	DR / AO / S	Influences circuit behavior and integration	Gioberto et al., 2016
24	Sensor placement (e.g., joints, folds)	Stitching / Embroidery	AO	Placement affects signal response and stability	Gioberto et al., 2016
25	Ink type (silver, carbon, etc.)	Printing, Lamination	DR	Determines conductivity, adhesion, and durability	Dong et al., 2020
26	Substrate compatibility	Printing, Lamination	AO	Defines printability and adhesion quality	Dong et al., 2020
27	Curing conditions (temperature, time)	Printing	DR	Critical for ink performance and adhesion	Dong et al., 2020
28	Trace spacing	All	DR	Determines resolution, electrical properties	Dong et al., 2020

30	Yarn placement (warp/weft)	Weaving	DR	Placement affects continuity and routing	Pouta, Jussi Mikkonen, 2015
31	Weave pattern (e.g., twill, plain)	Weaving	DR	Determines flexibility and electrical path	-
32	Yarn type	Knitting, Weaving	DR / AO	Affects stretch, resistance, and comfort	Gioberto et al., 2016, Pouta, Jussi Mikkonen, 2015
33	Knit structure (e.g., weft, warp knit)	Knitting	DR / AO	Affects mechanical/electrical properties	-
34	Conductive path routing through loops	Knitting	DR	Determines signal continuity and flexibility	-

******* DR - Design Rule, AO - Application Objective, S – Standard***

MD is under DR, where not mentioned explicitly.

3. Research Through Design of the BiliOnesie: A case Study Designer-Researcher Approach to Discovering Defining E-Textile Variables

*** Acknowledgment – The work presented in this chapter is the result of a collaborative effort, and I gratefully acknowledge the contributions of Heidi Woelfle, Tyne Andrews, and Dr. Lucy Dunne. Heidi and Lucy contributed to the design and prototyping of the first and second prototype. Tyne and Lucy contributed to patternmaking for the second prototype. I conducted component and material analysis, and completed the circuit design for the first prototype, and Lucy completed the circuit design for the second prototype. Their expertise, insights, and feedback were invaluable throughout the design, development, and reflection processes that shaped this research. The meta-reflection and analysis of the process is my own. The ideas and outcomes from this research reflect a shared commitment to advancing understanding in the e-textile design space.*

3.1 Introduction

This chapter outlines the practice-based research process used in the development of a phototherapy garment to treat neonatal jaundice, referred to as the *BiliOnesie*, through two iterative prototyping cycles. In addition to treating prototypes as endpoints in a conventional product development process, this research-through-design phase positions garment creation as a central methodological approach for generating insights into scalable and manufacturable e-textile circuit designs. The garment functions as a living laboratory to explore key variables, design constraints, and opportunities that can inform the design rules proposed in later chapters. As with the prior chapter, the research questions this experience pursued were:

1. What are the defining design variables that experts consider when developing effective TCBs?
2. What performance indicators are used to characterize TCB performance?
3. How do design variables and performance indicators relate to each other in TCB design?

Similarly, as with the prior chapter, TCB design and fabrication insights are bolded within the text and synthesized in the final section of the chapter.

Framed as research-through-design (RtD), this process emphasizes how iterative cycles of making, testing, and redesigning can yield critical insights into circuit layout, component behavior, garment integration, and fabrication feasibility. Each prototype served not as a final deliverable, but as a knowledge-generating probe embedded within the process of developing the broader TCB EDA framework proposed in this dissertation. By reflecting on material behavior, construction limitations, and performance outcomes, the practice-based exploration directly informed the development of structured, scalable design rules for textile circuits. The evolution from Prototype 1 to Prototype 2 highlights how key trade-offs, such as those between manufacturability, electrical robustness, and wearability, were progressively identified, negotiated, and resolved through hands-on experimentation. Further, the development and prototyping process for this application example serves to illustrate some of the central challenges of e-textile product development that motivate this research more generally.

3.2 Methodological Overview

We adopted a research-through -design (RtD) framework, grounded in iterative prototyping, physical making, and reflective practice, as a means of generating situated knowledge in a complex, emerging field (Toeters, 2013; Bye et al., 2010). RtD is particularly well-suited to design research in e-textiles because it enables the designer-researcher to uncover tacit knowledge and system-level interdependencies that may not emerge through traditional empirical or theoretical inquiry alone. By anchoring the study in the real-world development of a functional neonatal phototherapy garment, this method supports engagement with the practical constraints, material behaviors, and cross-disciplinary interactions that shape the design space.

RtD has been previously applied in e-textile research to explore issues such as garment-user interaction, material integration, and iterative co-design (Zimmerman et. al. 2007, Halperin et. al. 2024). In our study, the method not only enabled a recursive loop between making, testing, and theorizing, a functional prototype, but also helped create a deeper understanding of how fabrication parameters, material properties, and application-specific constraints interact in ways that can inform the structure of design rules for EDA systems.

3.3 Defining Design Objectives

The design goals for BiliOnesie were driven by both functional and clinical requirements. The BiliOnesie is a wearable system designed to deliver targeted phototherapy for treating neonatal jaundice. Phototherapy for neonatal jaundice demands light exposure of the skin surface at a wavelength between 425–475 nm, with peak efficacy around 455 nm, ideally at a minimum irradiance of 30 μW/cm² and a maximum irradiance of 50 μW/cm². Additional requirements emerged from healthcare constraints, including maximizing the amount of the skin exposed to illumination (excluding the face for eye protection), infant physical comfort, and safety with respect to electrical insulation.

These requirements were translated into specific objectives for the e-textile system and shaped every aspect of the design process, from material selection to circuit topology, LED and solder joint encapsulation, and garment construction. These major requirements included the following:

- Maximize light exposure to the infant body while avoiding the face. That is, ensure broad surface coverage of light, particularly in areas prone to folding (e.g., limbs, joints, underarm).
- Ensure softness, breathability, and electrical safety through insulation and circuit stability for newborn skin.
- Maintain irradiance values in the clinically effective range (target:30-50 µW/cm^2).
- Integrate a safe and reliable textile-based electronic circuit that supports manufacturability and performance.

3.4 Design and Fabrication Process

The prototyping process was structured to evaluate how design decisions, such as trace spacing, component placement, stitch type, and thread materials, affect system functionality, manufacturability, and potential standardization. The key fabrication stages involved a series of deliberate design and engineering investigations that informed design decisions to ensure both functionality and manufacturability. The design was implemented in two prototypes:

3.4.1 First Prototype: Establishing Baseline Construction

3.4.1.1 Electrical Design and Components

Figure 24 - (left) First prototype (right) test setup of the BiliOnesie garment

In the initial prototype (Figure 24), the process began **with material and fabrication process selection**. Because stitched methods are a lab focus and because we hypothesized that they might facilitate more flexible, breathable e-textile circuits, stitched fabrication was chosen from the outset. The process of making that decision highlighted the challenges that e-textile designers face in understanding the benefits and drawbacks of different fabrication methods, and the ways in which decisions (and revisions of those decisions) about fabrication methods can constrain, interrupt, and extend development processes.

Selection of a base fabric was the next decision: a cotton-Spandex knit was chosen due to its inherent flexibility, softness, and overall comfort for infant wear. However, beyond these usercentered qualities, the fabric was also selected for its mechanical properties, specifically, its ability to stretch effectively in the vertical (longitudinal) direction. This vertical stretch was critical for the BiliOnesie application, as it allowed the conductive traces to elongate along the same axis as the body, accommodating both infant movement and the serpentine routing paths of the circuit. Aligning the serpentine traces with the fabric's primary stretch direction helped to reduce mechanical strain on the traces during normal wear and use. Additionally, this alignment contributed to the overall durability of the textile circuit, as it minimized the likelihood of delamination, breakage, or resistance drift during repeated stretching and relaxation cycles involved in both fabrication and use.

Given the sensitivity of infant skin to elevated temperatures, **heat management** was a critical design consideration in the development of the BiliOnesie. To minimize thermal risk, only low-power components were selected in order to reduce heat generation at the source. Passive cooling strategies, such as breathable fabric and breathable encapsulants for joint areas were chosen to allow heat to dissipate away from the infant's body, ensuring both safety and comfort.

For the **conductive traces**, silver-coated Vectran (Liberator 10) thread was selected due to its excellent **durability**, **solderability** and **electrical conductivity**. A previously made initial onesie pattern was used to define the pattern shapes for the first prototype. Next, in the **circuit layout** stage, a parallel circuit design was selected, to simplify the circuit layout on the body. LEDs were placed over the pattern pieces in a grid formation (Figure 25), and **serpentine rows of 2 parallel stitched traces** (power and ground) were carefully routed to cover the body using the pattern shapes as a guide, accounting for **seam crossings** where needed so that the circuit could pass from one pattern piece to the next across a seam. The **2 mm spacing** between the stitched power and ground traces was designed based on the LED package size and proved effective for this footprint. The stitching layout design was then translated for automated stitching by manually drawing it, with the PS-300B pattern stitching software (Figure 26).

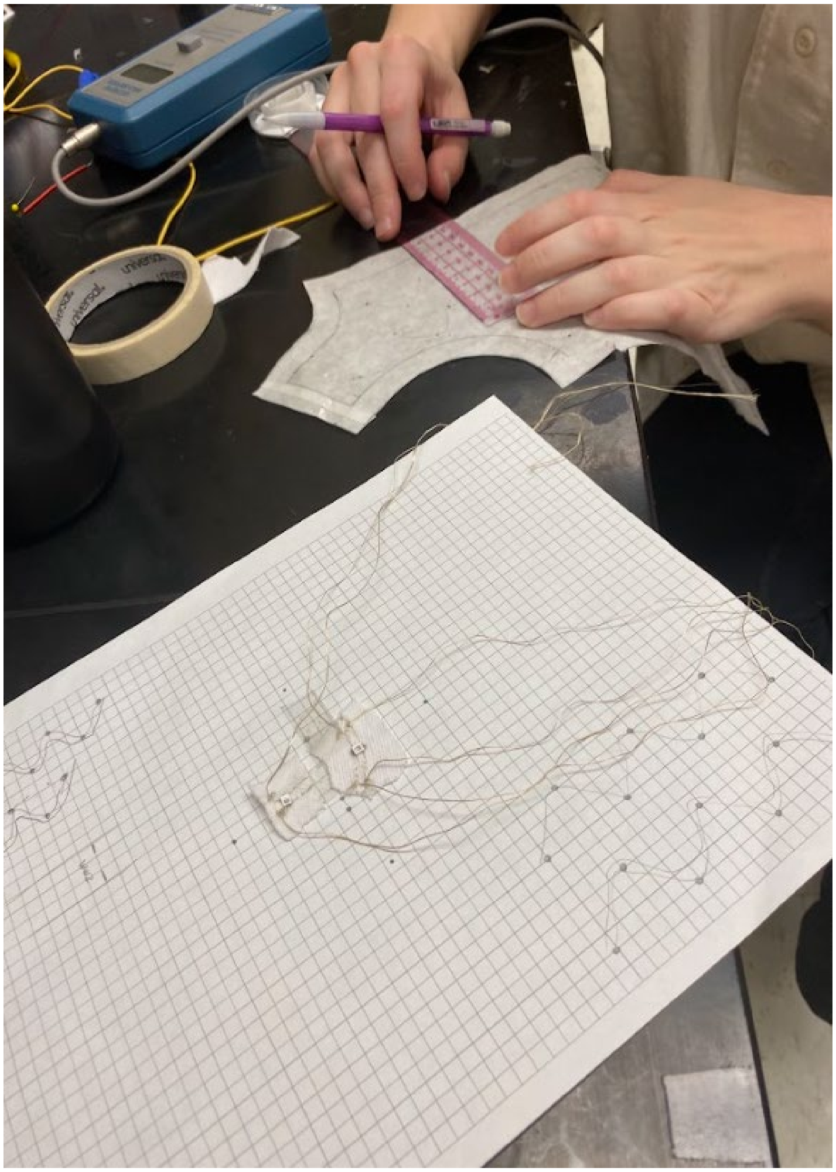


Figure 25 - In-process calculation of the serpentine routing trace on a grid overlaid on the onesie pattern

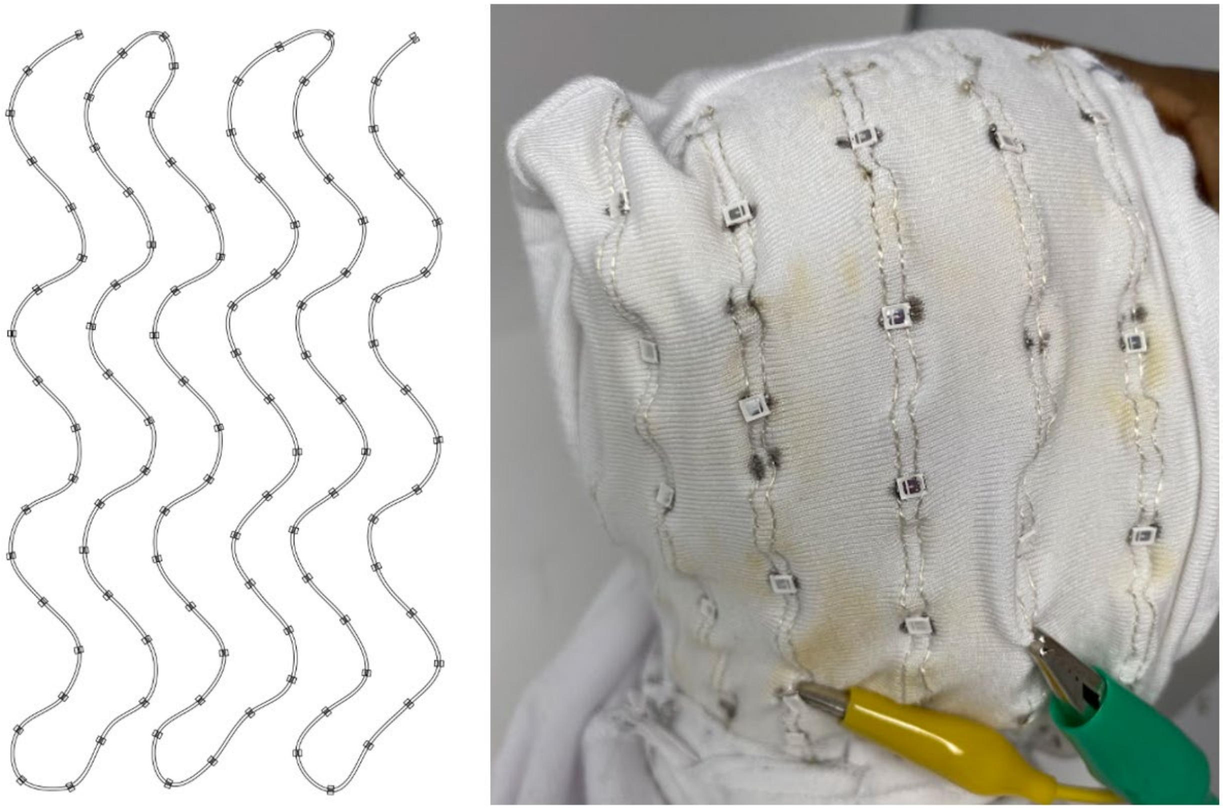


Figure 26 - (left) Serpentine rows layout of 2 parallel stitched traces (power and ground) (right) soldered, stitched traces on the hoodie pattern piece

3.4.1.2 Assembly and Encapsulation

Traces were sewn using a PS-300B pattern stitching machine, and manual seam crossings were stitched by hand to connect across different garment panels. Everlight SMD LEDs were soldered individually between the pre-stitched power and ground traces. For insulation, a three-layer construction was used, with an added fabric layer serving as an **insulator** to protect the skin and circuit.

3.4.1.3 Resulting Prototype

The resulting prototype was tested by applying voltage to the circuit and gradually increasing that voltage. About a quarter of the 162 LEDs (Figure 27) were successfully illuminated, but before the supply voltage could be increased high enough to illuminate all of the LEDs, the current reached a level that burned out some of the LEDs. For the LEDs that could be illuminated, we used a bilimeter measurement device to measure the garment's irradiance output (Figure 28 below).

Figure 27 - LEDs powered by a single power source before the supply voltage was high enough to illuminate all of them

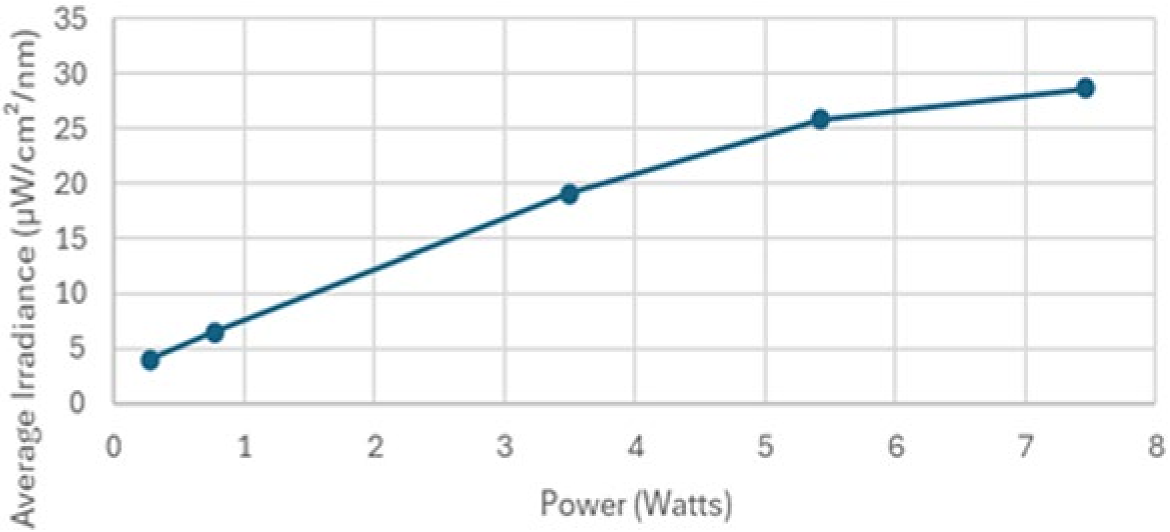


Figure 28 - Average irradiance readings at different supplied power levels

3.4.1.4 Reflections and Insights

This phase revealed the benefits of parallel layouts for maintaining functionality **when individual LEDs fail -- the remaining LEDs were still functional.** However, it also exposed the limitations of an incomplete circuit design process: as **resistor-integrated SMD LEDs were not readily available**, only about a quarter of 162 LEDs could be illuminated simultaneously on the garment surface before the current exceeded the limits of individual LEDs (see Figure 27 above). Therefore, the circuit design was not capable of providing the desired illumination. Because of the perceived simplicity of the parallel-LED circuit, we did not use a circuit schematic or simulation software in the design process, which might have caught some of those design variables. Furthermore, circuit design software would still not have facilitated translation of the design to the Brother PS-300B pattern stitching machine. The need for a more complex but more effective circuit design was identified. Here, a TCB-specific EDA system might have enabled us to design (and possibly simulate) the circuit in the traditional way, and then translate the circuit design for fabrication directly, while assisting with the design decisions around trace spacing and layout. Gerber files generated by such a system would need to interface with systems like the PS-300B stitching software and/or with the machine directly.

Another challenge that was illuminated in this prototype was that of circuit assembly and multi-panel garment design: **soldering** LEDs to the garment's surface was a big bottleneck, and **seam crossings** increased assembly time and introduced points of **electrical vulnerability**. We experimented with a hot-air gun for reflowing, which worked but was time-consuming and had issues with **scorching** the base fabric (Figure 29). The need for **simplified routing** and **soldering efficiency** emerged. A TCB EDA system could have helped us navigate the thermal requirements for substrate fabrics given specific soldering processes, to avoid scorch risks. A more-developed approach to soldered processes for TCB would similarly help in avoiding the unpredictability of solder joints resulting from trial-and-error fabrication processes.

Figure 29 - Scorched fabric substrate

Finally, the garment design (based on an infant sleeper onesie) was too big for the newborn mannequin we used as shown in Figure 24 above, and we observed quite a bit of **folding and buckling** of the fabric. Buckling of the fabric meant that LEDs were subject to more bending stresses and ended up shining in different directions, rather than directly onto the skin, and that there was an increased risk of shorting due to the power and ground traces coming in contact as the insulation layer buckled away from the circuit layer. This led to two insights: the need for a **better-fitting** onesie that held LEDs closely to the skin and the need for more **durable encapsulation** to ensure safety of the circuit and durability of the components. Garment fit is an application-specific requirement but could be informed by better 3D simulation tools. **Encapsulation methods** are potentially more generalizable -- but are currently an example of e-textile processes that remain in the method development stage, and therefore are difficult to standardize, automate, or model.

Figure 30 - Final constructed garment of the first BiliOnesie prototype

3.4.2 Second Prototype: Toward Scalable Manufacturing

In the second iteration, the focus shifted toward scalability and mass-manufacturing potential, while improving the device performance. We revised the **garment pattern** and **circuit layout**, optimized the LED and fabric choices for illuminance and manufacturability, and explored alternative methods for fabricating the LED circuit for better durability and efficiency.

3.4.2.1 Characterizing Illuminance/Fabric Relationships

Because of the necessity of circuit redesign, the first question we needed to answer was exactly how many LEDs we needed to achieve the target illumination range. Similarly, the challenge of fabric scorching during soldering presented an additional obstacle that necessitated exploring alternative fabrics. As these factors affect each other, in order to assess the functionality and performance of the prototypes, we measured the **irradiance of 3 candidate LEDs under various conditions** (e.g., with different fabrics, encapsulation strategies, and LED spacings). The aim was to determine the **minimum number of LEDs** required to meet clinical irradiance thresholds while ensuring mechanical and electrical reliability as well as manufacturability and solderability. More details about fabric characterization and garment construction were published in (Adeleke et al. 2024, Woelfle et al. 2025).

3.4.2.2 Revisions to garment pattern

The illuminance test results indicated that the polyester-spandex fabric was the most effective in blocking excess LED light, helping us achieve our target irradiance levels of 30–50 µW/cm². However, we ultimately opted for cotton because the polyester fabric was discontinued and **no longer available**. We selected a cotton fabric that closely matched the weight of the original polyester, which helped preserve similar optical performance. While not identical in light-blocking capability, cotton proved sufficiently effective and offered additional benefits such as increased breathability, making it a worthwhile trade-off.

Given that information, we were able to revise the garment pattern. The pattern revision addressed two issues: the need for better fit, and the need for fewer seam crossings. We revised the pattern to reduce its overall size to fit a newborn's dimensions, to curve around a newborn's fetal "scrunch" body position, and to merge pattern pieces wherever we could so that traces could pass around the body with as few seam crossings as possible. The pattern revision was tested on the mannequin to validate the fit.

Also, we improved the garment pattern making in the second prototype phase by making a custom pattern driven by the need to accommodate both functional and electrical design constraints. The first prototype used a traditional sleeper onesie shape, which typically has front snaps/zippers and/or inseam openings for donning and doffing. However, these garment openings posed risks for this application, either by requiring conductive traces to cross garment openings or placing mechanical stress on the circuit paths. Further, the tight fit of the narrowest part of the garment, the sleeves, posed a donning challenge when the infant's arm needed to be inserted into a closed sleeve. To address this, the new design incorporated an opening at the overarm, shoulder, and neck area, allowing the garment to open completely to the underarm level for easier garment donning and doffing without pulling on or bending the circuit-integrated areas. This opening strategy also kept electrical paths away from high-stress closure points and eliminated the need for traces to cross garment openings. Additionally, the garment pattern was simplified in the second prototype from a multi-piece structure to just two major pattern pieces, significantly reducing seam crossings. This minimized the need for traces to pass over seams, which in turn improved the mechanical durability, electrical reliability, and manufacturing efficiency of the final e-textile system.

These steps again likely fall outside of the domain of traditional EDA system design -- the closest analogy would be the definition of a PCB shape. This is typically a much simpler shape than most garment patterns. A full-spectrum EDA system for TCBs might consider **interfacing effectively with garment patternmaking and simulation software,** such that the pattern outlines (and any internals that must be accounted for) are passed to the circuit routing module prior to trace layout.

Figure 31 - Second BiliOnesie prototype on mannequin

3.4.2.3 Revisions to Circuit Layout

The illuminance test results showed us that we would need an **optimal spacing** of 3 cm on the garment surface. While a parallel circuit design had significant advantages in terms of number of LEDs that could be supported (if LED-integrated resistors were available), trace layout, fault-tolerance, and the resulting circuit would need to be powered at a very high (>2A) current, posing an electrical hazard. Ultimately, however, the unavailability of resistor-integrated components presented an insurmountable challenge, and we pivoted to a combination series-parallel circuit design.

The revised garment pattern and the target LED spacing provided the first inputs to the circuit design (note that this is reversed from most processes, where it is assumed that the circuit design comes first, followed by the garment design, followed by an integration of the two). Comparing the target spacing with the available real estate on the garment surface yielded a requirement of over 400 LEDs. The power requirements for a series/parallel circuit of this size were too high for our application. To reduce the number of LEDs required to a level that could be supported by mains power (120V), we had to reduce the number of LEDs to 120, which meant a spacing of approximately 4cm. This is above the target but was a necessary design compromise.

The circuit was then laid out over the garment surface such that the parallel branches of the circuit would contain similar numbers of LEDs, and such that we could minimize the number of traces that needed to pass through narrow areas on the pattern, like the toe, armpit, and nape of the neck. Seam crossings were minimized to 4, and the resulting circuit required 6 trace crossings to allow parallel branches to pass over each other.

This layout process, integrated with a **circuit design module**, is the core domain of an EDA system. Ensuring that component lands are the right dimension, that trace layouts sit within pattern pieces with adequate spacing for seams, and that traces are separated sufficiently to prevent shorts is core to what design automation facilitates. Similarly, the ability to dynamically edit the circuit design and the layout would have significantly streamlined the development process.

3.4.2.4 Exploring Alternative Soldering Approaches

While developing the samples used to test irradiance/fabric relationships, we tested a **heat press approach** used by Molla (2020), using a flat press to reflow solder paste and attach SMD components. This was not reliably effective for us. With so many LEDs (with reverse gullwing lead type) to attach, the flat press process generated inconsistent solder joints and was prone to **scorching the fabric**, indicating a mismatch in thermal compatibility.

3.4.2.5 Reassessing Circuit Assembly

Based on these outcomes, we returned to **targeted manual soldering** but optimized the workflow, expanding it to include a novel insulating and strain-relief approach:

- Threads were cut and tinned in advance, allowing faster cleaner soldering at each connection.
- A **custom clear acrylic** (nail-polish grade) was used for **encapsulating LED solder joints**, reducing the need for multiple fabric layers and allowing for visual inspection of LED operation.

These changes reduced the garment layers from **three to two**, improving comfort and breathability while preserving circuit protection.

In parallel, we explored **plastisol screen printing** as a potential encapsulation and circuit insulation method for the conductive traces, reducing layering and offering a thinner, more flexible finish in the garment but stiffer, wider traces due to the plastisol applied on the traces.

3.5 Results & Reflections

3.5.1 Synthesis of Variables Identified

The **BiliOnesie case study** illustrates that design variables in e-textile systems do not emerge in isolation, but rather as **situated and interdependent**, shaped by the constraints, functional requirements, and fabrication methods embedded in the design process. Through this case study, two **distinct categories of variables** were identified:

1. **Generalizable Variables**: These are variables that transcend the BiliOnesie application and apply across a broad range of e-textile systems as discussed in *section 3.5.1.1.* A subset of these includes **method–material variable relationships**, which, in this case, stemmed from the decision to use **stitching on knit substrates**. While these variables are influenced by specific fabrication choices, common design logic that is applicable to multiple contexts can be extracted from them. This set of variables was emphasized in the development of the EDA framework discussed in Chapter 5.
2. **Application-Specific Variables**: These are tied to the **unique functional requirements** of a particular application, in this instance, **phototherapy for neonatal jaundice**. Examples include therapeutic light dosage, irradiance thresholds, and infant safety criteria. Other application-specific variables are discussed in *section 3.5.1.2.* While essential for the BiliOnesie, these variables may not be relevant to other e-textile applications and are

thus considered **outside the core scope** of a generalizable EDA framework. However, identifying them allows designers and researchers to **distinguish between general design rules** and **context-specific adaptations**.

This distinction is critical: it enables a clearer understanding of which variables contribute to the **underlying architecture of an EDA framework**, and which are **situational extensions** driven by application demands. As such, the case study serves as a model for **disentangling framework-wide rules from application-driven constraints**, helping guide future researchers and designers in recognizing what should be encoded into general design logic and what remains contextual.

Additionally, this case study demonstrates how **reflective practice** was employed as an investigative strategy to support the structuring of the EDA decision model. Variables did not simply appear as static inputs; rather, they emerged through **design constraints, failure events, iterative problem-solving, method development, and tacit garment-making expertise**. Each design decision was not only a technical solution but also an **analytical lens**, exposing deeper interdependencies between **materials, fabrication processes, and application-specific performance goals**.

3.5.1.1 Generalizable Design Variables

These generalizable variables (Table 6) emerged early in the BiliOnesie project and represent foundational decisions that informed subsequent choices in the design path.

Table 6- Generalizable Variables

Variable	**Emergence in BiliOnesie**	**Justification for Generalizability**
Substrate Type	Stretch knit imposed handling and stability challenges	Influences process compatibility and trace properties
Manufacturing Method	Stitching method was used for circuit integration	Many other variable categories are dependent on this decision point; defines relevant trace techniques and integration constraints
Traces	Silver-coated nylon thread selected for conductivity, solderability, and sewability	Determines electrical resistance, mechanical resilience, trace geometry, and joint interconnectivity options
Component	LEDs were used for therapeutic light delivery	Influences pad design, lead type, soldering method, and placement constraints
Layers	Single conductive layer with overlaid insulation	Impacts routing logic, layout complexity, and mechanical thickness

As will be described in Chapter 5, these variables were incorporated into the EDA framework as primary logic gates, nodes from which context-specific decision rules branch.

3.5.1.1.1 Sub-Variables Derived from Method–Material Combinations

Because the integration method was **stitching** and the substrate was a **knit fabric**, many variables and their interdependencies were **method dependent**. These inform some **design rule paths** and influence method-specific downstream decisions (Table 7).

Table 7- Sub-variables from Method–Material Combinations

Variable	**Method-Specific Challenge**	**Design Response**
Trace Type	Stitch needed to stretch with fabric while maintaining shape	Chose serpentine-lockstitch to balance flexibility with trace consistency
Trace Spacing	Tight spacing caused puckering; loose spacing caused detachment	Optimized within 2–3 mm range based on material behavior
Trace Handling	Conductive thread (silver-coated nylon) frayed easily	Applied heat sealing or fray-check to cut ends
Substrate Construction	Rib knit required special handling due to curl and distortion	Informed stitch type and trace orientation choices
Substrate Fiber Content	Cotton-Spandex required balancing stretch and heat resistance	Chosen for comfort, durability, and thermal compatibility during soldering or encapsulation

These sub-variables enable granular **logic** that makes an EDA system method and material-aware.

3.5.1.2 Application-Specific Variables: Neonatal Phototherapy

The therapeutic use case of the BiliOnesie introduced **unique constraints** that are not broadly applicable but are crucial in demonstrating the need for **application-aware branches** in the EDA tool (Table 8).

Table 8- Application-specific variables

Variable	**Constraint**	**Impact on Design Decisions**
Light Wavelength (470 nm)	Must match bilirubin absorption peak	Dictated LED selection and placement strategy
Uniform Light Distribution	Even exposure required for therapeutic efficacy	Informed zone-based circuit layout and LED arrangement
Number of LEDs	Must be sufficient to meet irradiance target (30–50 µW/cm²) across the treatment area	Drove the circuit layout strategy, including LED spacing, trace layout, and power requirements.
Circuit Architecture	Must support uniform power distribution	Required modular, multi-branch circuit topology to evenly distribute current across zones.
Heat Dissipation	Infant skin is sensitive to heat	Required low-power components, passive cooling, and breathable encapsulants

Variable	Constraint	Impact on Design Decisions
Skin Contact Safety	Leads must not be exposed on the inside of garment	Demanded full encapsulation and electrical isolation testing
Body Size	Neonates grow rapidly and move frequently	Affected lead routing, stretch zones, and seam placement
Garment Pattern	Easy donning/doffing without damaging circuitry	Led to a modular pattern strategy that minimized stress on electrical paths

While not part of the core EDA framework, the application-specific variables observed in the BiliOnesie case validated the need for **modular, application-aware layers** within the broader e-textile design ecosystem.

3.5.2 BiliOnesie-Informed Design Rule Examples

The BiliOnesie case study contributed to both the structural logic and content of the EDA framework. It clarified how parent variables can function as decision nodes, how specific method–material pairings influence the behavior of dependent variables, and how design rules must flexibly respond to both contextual and technical constraints.

Although a full experimental characterization is presented in a later chapter, it is useful at this stage to project forward and outline the types of design rules likely required to meet the system-level objectives of an EDA framework. Even in the absence of detailed performance data, constraints and tradeoffs based on established material properties and circuit behavior can be anticipated. As the project evolves, these preliminary heuristics are refined and formalized through empirical data, revealing how design rules may vary depending on material-process interactions.

3.5.2.1 Method + Substrate + Tracing Rule Path (Stitching on Knit)

These are example design rules extracted from the design process:

Rule 1

IF integration_method = stitching AND substrate_type = knit THEN recommended_stitch_type = serpentine straight stitch

Rationale: Accommodates stretch and reduces thread breakage in directional knits.

Rule 2

IF stitch_type = lockstitch AND thread_type = silver_plated_nylon THEN stitch_spacing = 1.5–2.5 mm

Rationale: Prevents puckering and detachment by balancing electrical and mechanical stability.

Rule 3

IF substrate_type = knit AND stitch_type = lockstitch AND lead_type = Leadless AND integration_method = soldering THEN stitch_length ≥ 2 mm

Rationale: Ensures sufficient area for durable electrical contact.

Rule 4

IF substrate_type = knit AND stitch_type = lockstitch AND lead_type = Inverted Gull-wing AND integration_method = soldering THEN stitch_length ≥ 3 mm

Rationale: Ensures sufficient area for durable electrical contact.

Rule 5

IF thread_type = silver_plated_nylon THEN pre-processing = apply fray-check OR heat-seal cut ends

Rationale: Minimizes failure due to thread fraying during fabrication.

3.5.3 Summary

While the literature review in the previous chapter identified key variables, such as trace width, stitch type, stitch pitch, lead configuration, LED footprint, and joining methods, the iterative development of the BiliOnesie provided practical validation, surfaced unexpected challenges, and revealed new variables not previously considered. It also served as a critical step in disambiguating generalizable variables from application-specific variables, an intellectual distinction that many experts in the space struggle with that is vital to the development of universal EDA systems.

In some cases, literature-based recommendations did not translate well into practice. For instance, Molla et al. (2020) suggested reflow soldering as a viable method for attaching surface-mount LEDs to conductive fabrics. However, this approach proved unreliable due to the thermal sensitivity of the fabric and poor adhesion on stitched traces on a knit fabric. This highlighted the disconnect between theoretical feasibility and real-world constraints. As a result, a manual precise targeted soldering technique was used, leading to the definition of new design parameters such as soldering temperature, strain relief strategies, and lead design. Similarly, while general guidelines for trace width and spacing were presented in prior research, prototyping showed that these values must be contextually adapted to account for fabric stretch behavior, stitch orientation, and material properties. For example, aligning traces along the warp direction of the cotton-Spandex knit offered more stable elongation and reduced deformation, critical factors in the performance of serpentine routing patterns and stitch pitch design.

These real-world insights directly informed the data modeling process. The two BiliOnesie prototypes served as testbeds for mapping variable relationships and decision paths, which now populate the logic of the EDA framework (see Chapter 5). Rather than a purely theoretical construct, the resulting framework embeds practitioner knowledge to support traceable, logic-based design decisions.

In addition, the RtD process extended beyond the scope of the literature review by addressing the full spectrum of early-stage e-textile design, including concept development, textile and garment selection, circuit integration, and iterative testing. This broader lens was essential for identifying system-level dependencies and revealing where new design rules are needed. However, the study explicitly stops short of addressing mass manufacturing. While it identifies areas where production challenges will likely emerge, such as immature fabrication techniques or inconsistent methods, it does not attempt to resolve them. Instead, it highlights the need for future research and standardization efforts to support scalable, EDA-integrated workflows.

The BiliOnesie functioned not only as a wearable prototype but also as a design probe, exposing the intricate, interdependent nature of variables within e-textile systems. Its development showed that design is not a linear process, but one shaped by branching constraints informed by material behavior, fabrication limits, and functional goals. Ultimately, through iterative testing, reflective practice, and hands-on engagement, the BiliOnesie case contributed both a functional product and a foundational design intelligence system, one that equips future designers to navigate the complex, interrelated decisions involved in e-textile development.

4. Investigating and Formalizing Expert Knowledge

4.1 Introduction

This chapter presents the qualitative interview methodology used to investigate expert knowledge of critical variables, recurring challenges, and current practices in e-textile design and manufacturing, as well as the results of that investigation. Drawing on expert interviews using grounded theory analysis, the study aimed to identify what experts perceive as the key factors influencing TCB development. In this interview phase, we explored the key design variables, input relationships, and performance indicators that experts consider when developing effective TCBs. Rather than analyzing each variable in depth, the focus was on capturing a wide range of considerations to map the broader landscape of factors influencing design. By emphasizing breadth over depth, we were able to identify patterns and dependencies that occur across different domains and practices. Structuring this information helps illuminate the interdependencies among design variables and reveals the underlying logic that governs textile circuit behavior.

This study contributes to the development of a system-level EDA framework by using direct interaction with experts to identify what they perceive as foundational design variables, relevant performance indicators, and current industry limitations. These insights, integrated with those collected from the literature review and the RtD experience, serve as the basis for formalizing variable relationships in the next phase of the framework development.

4.2 Research Objectives

As with the prior two phases, this phase addressed three core questions:

1. What are the defining design variables that experts consider when developing effective TCBs?
2. What performance indicators are used to characterize TCB performance?
3. How do design variables and performance indicators relate to each other in TCB design?

4.3 Research Methodology

4.3.1 Expert Interviews

Twelve semi-structured interviews were conducted with 12 experts from both academia and industry, including designers, researchers, engineers, and technologists working across various domains within the e-textiles field. There were no restrictions based on age. Participants were selected based on their extensive experience developing and testing functional electronic-textile systems, with a minimum of five years of experience in e-textile circuit design. Participants, recruited via targeted recruitment and snowball sampling, brought diverse disciplinary backgrounds and offered access to tacit knowledge often missing from the published record. Detailed characteristics of participants are summarized in Table 9.

Table 9- Summary of Participants Characteristics/Experience

ID	Country	Primary Role	Years of Experience	Technical Specifications	Professional Background
P1	Belgium	E-textile Researcher	9	Lamination, weaving, sewing	Academia and industry

ID	Country	Primary Role	Years of Experience	Technical Specifications	Professional Background
P2	Canada	Textile Engineer	10	Embroidery, weaving, stitching, knitting	Industry, Manufacturing
P3	USA	E-textile Engineer	10	Embroidery, stitching, printing	Industry, Manufacturing
P4	Canada	Electrical Engineer	12	Fiber optics, polymer fiber extrusions, standardization	Industry
P5	Malaysia	PCB & E-textile Researcher	25	PCB assembly, printing, manufacturing	Industry
P6	USA	E-textile Researcher	10	Stitching, printing	Industry
P7	Germany	E-textile Researcher	5	Embroidery, knitting, lamination	Academia and industry
P8	USA	E-textile Engineer	5	Materials Engineering	Industry

ID	Country	Primary Role	Years of Experience	Technical Specifications	Professional Background
P9	Canada	E-textile Engineer	10	Stitching	Industry, manufacturing
P10	USA	E-textile consultant and engineer	10	Embroidery, circuit board stitching, consulting	Industry
P11	France	E-textile Researcher	>25	Weaving, standardization	Academia and industry experience
P12	Germany	E-textile Researcher	15	Embroidery, standardization	Industry

The interviews were designed to elicit in-depth insights into participants' experiences with e-textile circuit design and manufacturing methods. The semi-structured format allowed participants to share their expertise and personal perspectives freely, particularly regarding their interaction with fabrication processes such as weaving, embroidery, lamination, and printing. Interview questions were informed by prior literature and existing standards, ensuring relevance while allowing for exploration of underrepresented areas in the field. While a core set of interview questions (see Table 10) served as a guiding framework, the conversation remained flexible and participant-led, following the emergent design approach outlined by Creswell et al. (2018). This approach enabled the interviewer to adapt questions based on the interviewee's responses while maintaining alignment with the study's central themes.

Each interview lasted approximately one hour and was conducted via Zoom. Interview duration was flexible, with additional time permitted based on participant availability and interest. The interview guide (Table 10) was structured into three sections: (1) demographic information, (2) experiences with failure or challenges in e-textile manufacturing, and (3) perspectives on key variables and relationships that should be considered when developing design rules for e-textile circuits. The emphasis was on identifying the variables and interdependencies that participants believe are critical for informing a systematic, rules-based approach to design. Participants were offered a $30 Amazon gift card in appreciation of their time.

Table 10- Interview question guide

Category	Questions
Experts' details	Name, years of experience, and general introduction.
Discussion on failures experts might have encountered during their interaction with e-textiles.	Can you describe some of your experiences working with e-textile circuits and the kinds of failures you have encountered? What are some of the ways you identify and diagnose these failure points? What steps did you take to troubleshoot these circuit failures? Were there some recurrent failures or failure patterns in the circuit? If yes, can you expand on these?

	Can these failure points of designing e-textiles be grouped or classified into categories? What were some of the challenges you encountered during the troubleshooting processes of the failures? Are the failures more electrical or mechanical? If a preventive measure is possible to identify some of these failure points, what part of the manufacturing process do you think should be the main focus? What valuable lessons have you learned from the past that you still find useful in your current interaction with e-textiles? How will you describe some lessons you have learned in troubleshooting failure points in e-textile circuits?
Discussion understanding variables/relationships through an example walk through.	Can you walk me through an example e-textile product development process? What are some of the factors/variables you have found to be important to the performance of e-textile circuits?

	Can you share any experiences or case studies where you used an innovative method to improve the performance/outcome of an e-textile circuit? Some innovative methods that you developed yourself, if any? Suppose we were to develop electronic design automation software for TCB like we have in traditional PCBs. What variables would you want to be included in the software to help your design process? What part of the e-textile design process do you often find yourself redesigning?

4.3.2 Coding and Analysis of Expert Interview Data

The expert interview transcripts were analyzed using grounded theory, a qualitative method that allows theory to emerge from the data rather than being imposed by pre-existing frameworks. This approach was particularly suited to the exploratory nature of this study, which aimed to identify and understand key variables, challenges, and relationships relevant to the design of TCBs. Twelve expert interviews were transcribed and analyzed. The analysis was conducted using **Dedoose**, a qualitative coding tool. The coding process followed a systematic, multi-stage grounded theory approach (Figure 32):

- **Familiarization**: Each transcript was read and annotated multiple times to build a deep understanding of the data and to identify preliminary themes.
- **Open Coding**: Concepts such as design variables, manufacturing methods, and failure modes were identified line by line. Failure modes were particularly significant, as experts

often revealed critical variables indirectly through descriptions of what went wrong or what caused a system to fail. Framing these insights explicitly as "failure modes" allowed us to extract and define underlying variables more clearly.

- **Axial Coding**: Related open codes were grouped into broader categories to uncover meaningful patterns and relationships across participant responses.
- **Selective Coding**: The analysis then focused on connecting key categories, specifically how design variables relate to failure modes and performance indicators relevant to TCB design.
- **Framework Mapping**: Afterwards, this inductive process allowed variables and themes to emerge organically, we further organized the findings using the Six Ms framework (Man, Machine, Material, Method, Measurement, and Mother Nature/Environment). This final step served to contextualize the identified variables within a broader socio-technical manufacturing ecosystem.

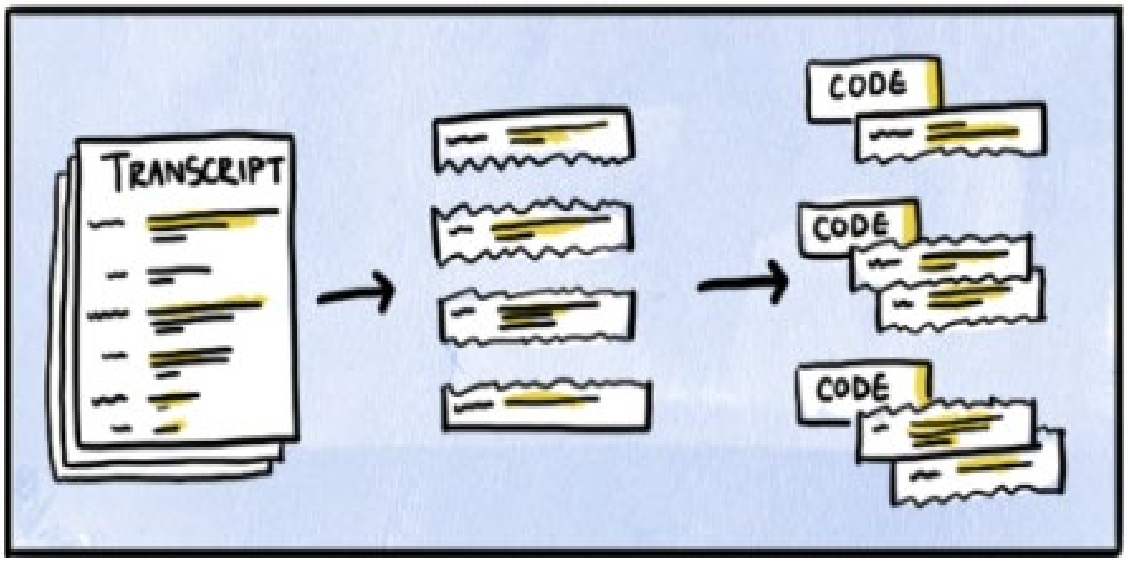


Figure 32 - Inductive coding process (Delve 2023)

4.4 Results

Analysis of the interview data revealed several recurring themes that highlight the most pressing needs and constraints necessary to inform the structure and features of an EDA framework tailored for e-textile circuit design. These themes reflect technical, systemic, and usability challenges that, if unaddressed, could significantly impede the ability to create scalable, repeatable, and manufacturable e-textile systems. Each theme below represents a core insight derived from expert interviews and grounded theory analysis.

4.4.1 Focus on Interconnects/Joint Areas: A Primary Pain Point

Interconnects, defined as the physical and electrical junctions linking components to traces, emerged as the **most persistent challenge** in e-textile circuit design. Across multiple expert interviews, interconnects were described as **highly failure-prone, unpredictable, and difficult to standardize**, particularly due to the dynamic, flexible nature of textile substrates.

Experts consistently reported that interconnects are **not just passive conductors**, but active zones where multiple stressors, mechanical, electrical, and environmental, converge. These stressors degrade performance over time and introduce variability that complicates repeatability, simulation, and manufacturability. Several common challenges were identified:

- **Mechanical Stress**: Interconnects are especially vulnerable to stress from bending, stretching, compression, and laundering. These mechanical forces often initiate fatigue and lead to eventual failure.

- **Material and Geometric Variability**: The **conductivity and durability of interconnects vary widely** depending on the type of conductive thread or ink used, the stitch, weave, or knit geometry, and the compatibility between materials. This variability makes predictive modeling difficult.
- **Rigid–Soft Interfaces**: One of the most commonly cited issues was the difficulty of **joining soft conductive elements to rigid components** (e.g., microcontrollers, LEDs, or batteries). As Participant 10 noted, "*the mechanical connection between a hard thing and a soft thing is tricky*," and often becomes the weak link in an otherwise functional circuit.
- **Lifecycle and Wear Concerns**: Beyond initial assembly, interconnects must remain stable over the lifetime of the product, which includes bending during use and exposure to moisture or washing cycles. Participant 6 emphasized the challenge of not only forming a strong electrical connection but maintaining that integrity *throughout wear and the lifecycle of the product.*

Because of these challenges, interconnects are often seen as **the limiting factor** in the scalability and reliability of e-textile circuits. Participant 7 stated bluntly: "*There is often a problematic point for e-textiles*," adding that their research group is actively focusing on improving interconnection reliability. Participant 5 echoed this need by describing the difficulty of simulating interconnect behavior, particularly across layers in more complex architectures: "*You have a via to do the interconnection... but for e-textile, you want to do a simulation, especially on the functional test.*"

Critically, simulation support for interconnects remains underdeveloped. As Participant 7 noted, "*I'm not sure if this is achievable in the near future, to have really predictive simulations of how the interconnections will behave.*" This statement reflects a broader sentiment across the participant group: that interconnects represent a high-risk design element that lacks sufficient support across current tools and standards.

To address this, future EDA frameworks must treat interconnects not as secondary or downstream considerations, but as primary design challenges requiring dedicated modeling, rule definition, and validation. However, doing so effectively requires coordinated progress across four interconnected domains:

Method Development and Convergence:

At the most fundamental level, there is still no consensus around how to reliably make interconnects in e-textiles. Stitching, lamination, adhesive bonding, soldering, and conductive inks all offer different advantages and limitations depending on the materials, use case, and fabrication environment. Variability in mechanical strain, contact stability, and aging behavior further complicate the picture. As such, the development of consistent, repeatable joining methods is a prerequisite for building trust in e-textile systems. This includes refining joint geometries, establishing best practices for hybrid joints (e.g., stitched + soldered), and exploring reinforcement strategies to reduce mechanical failure. These efforts are currently housed in prototyping labs and research projects and need greater convergence before standardization or automation can be meaningfully applied. Given the variability that experts reported in material combinations and application-specific requirements, it is likely that a “library” of interconnect and strain-relief methods may be needed, along with corresponding rules to guide the appropriate selection among these methods.

Standardization and Testing:

Once methods are established, the next challenge lies in defining how to test joints and what constitutes acceptable performance. This is the domain of standards bodies like IPC and ASTM. Key questions include: How many flex cycles must a joint endure? What is the maximum acceptable resistance at a joint? How do we simulate and report failure modes? Standardized test protocols are essential not only for benchmarking but also for informing material datasheets and validating EDA assumptions. Some progress is underway, for instance, IPC-8981 includes joint durability as part of broader reliability classifications, but much remains undefined, particularly in terms of testing mixed-material interconnects under dynamic conditions (e.g., strain, wash, heat).

EDA Design Rule Integration:

With robust methods and standardized performance thresholds in place, EDA tools can begin to encode interconnect-related rules. These include tolerance values for added resistance per joint type, geometric constraints to reduce strain concentration, and rules for material compatibility at junctions. For instance, a rule might flag when a high-strain seam intersects with a soldered joint or estimate the lifetime of a conductive yarn connection based on stitch density and substrate stretch. These rules rely on having consistent data about joint behavior, data that currently must be extracted from hands-on testing or case studies. As this knowledge base grows, so too will the ability of EDA tools to make intelligent recommendations and simulate the electrical and mechanical impacts of specific joining strategies.

Application Objectives and Simulation Requirements:

Finally, the performance requirements of a joint must be contextualized by the product's intended use. Application-specific goals, such as extreme washability for medical wearables, or minimal profile for fashion garments, determine what kind of joint is feasible or necessary. In simulation environments, this means not only modeling the electrical behavior of the joint but also simulating how stress and strain propagate through it across use scenarios. This level of predictive modeling is still in its infancy, particularly for soft, stretchable substrates. But as Participant 7's quote underscores, advancing simulation fidelity for joint regions will be essential for scaling up reliable, functional e-textile products.

4.4.2 Electrical Resistance as a Central Design Variable and Performance Indicator

Electrical resistance emerged as one of the most critical properties in TCB design, cited repeatedly by experts as both a **key input variable** and a **central performance indicator**. Unlike traditional PCBs, where resistance can be reliably calculated using known geometric parameters and stable material properties, **resistance in textile systems is far more variable, context-dependent, and unpredictable**. Its variability is a source of significant design complexity and a major obstacle to system reliability and repeatability.

From expert feedback, resistance is not only the most frequently characterized electrical property, but also one of the most **challenging to model** due to the inherently soft, flexible, and heterogeneous nature of textile substrates. Several factors contribute to this complexity:

- **Uneven mechanical tension** during fabrication (e.g., stitching, printing, weaving) can alter the effective cross-section of a conductive path.
- **Contact variability** between conductive elements (e.g., threads, inks, components) introduces unpredictable junction behavior.
- **Thread fraying or fiber migration** can cause localized changes in conductivity or even open circuits.
- **Moisture and environmental exposure** (such as bending, washing, or humidity) can dynamically affect resistance over time.

These challenges were echoed across interviews. For example, **Participant 5** emphasized that "*resistance is the main issue for printed electronics and e-textiles, even the interconnects."* They noted that without the ability to simulate material-specific resistance (e.g., for a 5 mm printed trace), designers are left relying heavily on prototyping and trial-and-error. Similarly, **Participant 10** remarked that *"whenever I bend something, resistance changes,"* highlighting the dynamic, real-time variability of resistance under mechanical stress.

Participant 8 summarized the importance of resistance clearly, stating: *"A key performance metric, which is, you know, can often be resistance or breaking strength or contact resistance."* This underscores the dual role resistance plays, it is both a **predictor of system behavior** (as a simulation input) and an **indicator of performance integrity** (as a measured outcome).

In light of these findings, experts advocated for the development of a **dedicated resistance modeling framework** that accounts for:

- **Trace geometry** (length, width, thickness)

- **Conductive material type** (threads, inks, filaments)
- **Stitch or trace pattern**
- **Environmental conditions** (humidity, movement, temperature)

Such a model would be essential for integration into future EDA systems, particularly electrical simulation tools, enabling designers to estimate resistance and anticipate failure risks *prior* to committing to physical prototyping. This predictive capability would not only reduce the cost and time associated with iterative sampling but also improve design consistency, reliability, and manufacturability across product lifecycles.

At the heart of this capability lies **resistance**, a linchpin variable that captures the complex interaction between **material properties**, **manufacturing processes**, and **environmental influences**. Resistance is not simply a material attribute, it is an emergent property shaped by how materials are handled, configured, and assembled. As such, managing and predicting resistance is vital for ensuring the functional integrity of e-textile circuits.

Responsibility for modeling resistance is necessarily distributed across multiple stakeholders. **Component suppliers** must provide foundational data, such as nominal resistance values, acceptable variability along the material length, and potentially even more nuanced properties like resistance as a function of mechanical tension or strain. These values form the baseline for design assumptions and simulation input.

Beyond the component level, **manufacturing process parameters** play a critical role. Stitch density, pattern geometry, thread overlap, and substrate stretch characteristics all influence actual in-use resistance. **Layout and geometry** are also major factors, curves, turns, and intersections can introduce variability and localized hotspots that deviate from idealized models. Recent work is beginning to address this need. For example, Juchnevičienė et al. (2017) examined how the embroidered pattern width differs from digital designs and the implications for conductive trace geometry. Also, Rho et al. (2022) and Zhang et al. (2021) proposed ways to predict resistance in embroidered e-textiles. Rho et al. (2022) established measurements and correlations between thread consumption and electrical resistance, supporting optimization strategies for embroidery machine parameters. And Zhang et al. (2021) proposed an equivalent resistance model for double-layer embroidered traces on nonwoven fabric, offering an analytical framework for predicting resistance in more complex configurations. Together, these studies highlight the urgent need for **multivariate resistance models** that account for fabrication-induced variations, material stretch, and 3D form factors, all of which are central to e-textile applications. These models can serve as the backbone for developing **tolerance-aware EDA rules**, allowing designers to simulate not just ideal performance but performance within realistic fabrication limits.

Overall, building a predictive resistance model is a shared effort: **suppliers** must provide reliable material specifications; **researchers and manufacturers** must characterize how process variables impact resistance; and **EDA developers** must translate this knowledge into rule-driven simulation tools that support informed, traceable design decisions. Only with this collaborative foundation can e-textile systems advance toward scalable, simulation-informed, and performance-assured design.

4.4.3 Failures as Reflections of Variables

Failures reported by expert participants were not viewed as isolated incidents or random anomalies. Instead, they were seen as symptomatic of deeper mismatches among key design variables, such as materials, geometries, fabrication processes, and environmental conditions. In this light, failure analysis emerged as one of the most revealing entry points for understanding variable interdependencies, identifying which parameters are most sensitive, and highlighting where design rules are critically needed to support reliability and repeatability in e-textile systems.

Interview data analysis clustered failure types into three broad but interconnected domains:

- **Mechanical Failures** - including fraying, tearing, delamination, and fatigue, often stemmed from material incompatibilities, uneven strain distribution, or insufficient structural resilience during wear and washing. As Participant 8 explained, *"a lot of the failures are mechanical failures that lead to an electrical failure of some sort,"* underscoring the cascading effects poor mechanical robustness can have on overall functionality. These types of failures are application-specific to some extent (e.g., infant wear vs. military gear), but they also fall into the domain of **Method Development and Convergence**. In many cases, fabrication processes themselves, such as stitching strategies, adhesive types, or yarn-structure interactions, were not robust or repeatable enough to withstand everyday use. While some **Standardization** (e.g., for fatigue or abrasion testing) could help define durability thresholds, the underlying fabrication methods must first reach a level of stability before such standards can be meaningfully applied. Eventually, **electromechanical simulation models** that account for wear and tear could serve as an important tool to predict and mitigate these failure modes, but such models are not yet available in e-textile EDA systems.

- **Electrical Failures -** such as high resistance, disconnections, or shorts, were frequently attributed to **weak or inconsistent joints**, **poor conductive thread performance**, or **degradation from use**. Participant 1 noted that *"the main failure you get is from going from rigid to soft,"* drawing attention to the critical and persistent problem of mechanical–electrical interface design. Like mechanical failures, these also point to shortcomings in fabrication process maturity **(Method Development and Convergence)**, where issues like **inconsistent tension**, **inadequate joining techniques**, or **poor routing strategies** compromise reliability. While some **electrical standards** exist for resistance thresholds or continuity checks, many are difficult to apply to stitched, woven, or knitted traces. Again, the gap is not just about standards but also about **tooling**, EDA tools for e-textiles currently lack the ability to simulate degradation over time or model resistance based on stitch density, material variability, or trace geometry. These failures reinforce the need for **combined electrical-mechanical simulation models**, which could serve as both predictive and diagnostic resources in future systems.
- **Systemic Failures** - rooted in **fragmented workflows**, **insufficient tool support**, and **disciplinary silos**, emerged as a persistent challenge. Participant 8 described a *"lack of transdisciplinary understanding"* as a recurring failure point, where mismatches between textile and electrical knowledge led to flawed assumptions or missed constraints. These failures lie squarely within the **domain of EDA rule systems and interface design**. A well-structured EDA tool that can incorporate and surface multiple design dimensions (e.g., manufacturability, durability, electrical performance) would help bridge gaps across

disciplines and reduce the reliance on informal or manual debugging. While such a tool cannot fully resolve all systemic challenges (e.g., organizational silos or proprietary constraints), it can facilitate shared language and traceable decision logic, thus lowering the barrier for collaboration and design handoff across teams.

It is important to note that these three categories are not independent. Failure often propagates across them: a mechanical failure can disrupt electrical continuity, and both can be masked or aggravated by systemic fragmentation in documentation or testing. As Participant 9 explained, *"so many other variables are going to change when one variable is altered,"* necessitating a process of **isolating and cross-mapping variable interactions post-failure**. Participant 9 described this as *"making a matrix of those variables,"* effectively a manual design-of-experiments strategy to diagnose root causes, something a robust EDA system could eventually automate or support interactively.

Participant 9 further emphasized that *"controlling critical points"* through standardization and repeated development can significantly reduce failure likelihood. This aligns with the larger research goal: to codify these fragile interactions into a **rule-based design environment**, where such empirical knowledge directly shapes design logic, error checking, and manufacturability criteria.

In this context, **failures are not merely endpoints, they are diagnostic insights** that illuminate the latent complexity of textile electronics. By examining them through the lenses of method development, standardization, and system-level rule modeling, they become key contributors to an intelligent EDA framework capable of enabling more robust, repeatable, and scalable e-textile product development.

4.4.4 Layout as a Central Design Construct

Layout, defined as the spatial configuration of components, traces, and interconnects on a textile substrate, was consistently identified by participants as a foundational element in e-textile design. Beyond simple visual arrangement, layout serves as the structural and conceptual backbone through which variables, rules, and performance indicators are realized and constrained. Layout plays a pivotal role across several dimensions:

- **Design Rule Management:** Layout is the physical site where **trace spacing**, **routing paths**, and **component placements** are planned and governed by design rules. It reveals **interdependencies**, such as material stretch direction, pad alignment, and interconnect path planning, that need to be encoded into logic-based constraints.
- **Enabling Automation and Simulation:** Layout supports automation by enabling trace routing, netlist generation, and simulation-ready component placement. Without it, EDA tools cannot evaluate design viability, simulate electrical or mechanical behavior, or validate manufacturability.
- **Manufacturability and Reliability:** Participants emphasized layout as a determinant of system robustness. Misaligned seam crossings, sharp trace bends, or poor placement of stress-sensitive joints can cause mechanical fatigue or electrical failure. As Participant 7 stated, "*what we often redesign is the circuit layout*", because many downstream issues can be traced back to layout-level decisions.

To position Layout within a broader e-textile design domains, layout considerations intersect with several major areas of e-textile development:

- **Standards:** Layout-specific guidance remains underdeveloped in e-textile standards. Where PCB design has well-established layout rules, textile circuits must still contend with variables like fabric deformation, seam movement, and multi-layered routing under strain, none of which are yet fully formalized in industry specifications.
- **Application Objectives:** Layout must respond to application-driven constraints. For example, in the BiliOnesie, routing was planned to avoid high-movement areas, and component positions were adjusted to recover as much surface area on the infant's body as possible. In sportswear, symmetrical layouts might be preferred for balance and wear resistance. In that case, layout is not generic, it is contextual.
- **Fabrication Process Maturity:** Layout is also shaped by the capabilities and limits of the fabrication method in use, be it embroidery, screen printing, lamination, or soldered joint integration. Each technique has tolerances that affect how tightly traces can be placed, how sharp the angles can be, or whether vias and seam crossings are feasible. Until fabrication processes are more standardized, layout decisions will remain tightly coupled to material-method compatibility.
- **Simulation and Modeling Needs:** Critically, layout highlights the need for electromechanical 3D simulation tools. Current 2D EDA systems cannot capture how fabric stretches, bends, or folds during wear. Knowles (2023) underscores this need in her work on 3D textile behavior simulation, showing how body movement and textile structure interact to deform embedded traces. While this current research framework does not include full electromechanical simulation, the insights reinforce that future EDA systems must support dynamic modeling that considers textile behavior in motion, especially for applications involving stretchable or form-fitting garments.

This means that layout should be treated as a **central interface for decision-making**, not a secondary output of the design process. It is the space where materials, mechanical properties, electrical performance, and fabrication methods collide, and where design rules must be actively enforced and balanced. For an e-textile EDA framework to succeed, it must prioritize layout as a live, editable construct, integrating spatial, material, and logical constraints into a single design canvas that enables simulation, optimization, and reliability from the earliest stages of design.

4.4.5 Manufacturing Process Insights

These insights reinforce the need for a **process-aware EDA system** that supports both **design logic and manufacturing constraints**. While some issues, such as component selection or placement, may fall under **application-specific design decisions**, others expose deeper structural gaps that EDA could help address. For instance, in the apparel industry, we see many "standards" in theory, yet actual manufacturing still depends on **custom workflows**, **manual fixtures**, and **bespoke tooling**, a challenge now mirrored in the e-textile space. Some of these process gaps may eventually evolve into formal **design rules or even standards**, while others will likely remain embedded in the **application objective** layer. A telling parallel comes from ongoing struggles in digital apparel development: as brands increasingly rely on **3D rendering**, questions arise about **who is responsible for digitizing fabric properties**, the designer, the textile vendor, or the 3D software company? Similarly, e-textiles face major challenges around responsibility and documentation. Across our interviews, recurring bottlenecks included: a **lack of standardized workflows** across materials and fabrication methods; a **frequent need for manual intervention** (e.g., custom jigs or stitching adjustments); **scarce or incomplete datasheets** for textile-specific components; and **informal or poorly instrumented testing** that makes it hard to benchmark performance. Collectively, these findings underscore that developing an effective EDA system for e-textiles will require more than encoding known variables, it will also require clarifying the division of labor and responsibility across the design-to-manufacturing pipeline.

4.4.6 Standards and Interoperability Challenges

While some participants referenced multiple existing standards, such as **IPC-8981** and **IPC-8961** for e-textile performance and solder joint testing, along with broader frameworks from **ASTM**, **ISO**, **AATCC**, and **IEC**, it became clear that many of the most critical elements of e-textile development remain unstandardized. Key issues raised include:

- **Incompatibility across software platforms**, particularly between electronics and design tools like Altium, CLO3D, Eagle, and Rhino. As Participant 6 noted: *"When I get files from Altium or Cadence… they're just a mess, and I have to spend a lot of time trying to clean it up to make it usable for me in my program there's a lot of rework that goes into something like that.*
- **Lack of standardized file formats** for textile-based circuit design. While file types like Gerber, DXF, and STL are commonly used, they are implemented inconsistently across platforms, making it difficult to move seamlessly between design, simulation, and fabrication. Participant 3 shared: *"We have to use the 2008 version DXF in order for [our machines] to function properly… Adobe Illustrator does something each year to their DXF files that basically compromises or corrupts them and makes it hard for different equipment to read it."*

- **Reliance on workarounds**, like plugins, outdated file versions, or manual conversions, that might work for small-scale prototyping, but are **not scalable for production**.
- **Gaps in equipment capability and validation protocols**, as echoed in recent reviews (e.g., Knowles, 2023), further limit the ability to translate design rules into repeatable manufacturing processes

This feedback reinforces the need for standardized infrastructure, not just in hardware or materials, but in the digital ecosystem that supports textile-electronics integration. As Participant 4 reflected: *"Rather than worrying about blanket standards for e-textiles, perhaps if one focuses on standards for the most value-added products."*

Addressing these interoperability and standardization challenges is critical for developing an EDA framework that can not only support textile-specific design logic, but also interface effectively with the broader design and manufacturing ecosystems. Without such alignment, even the best design rules risk becoming siloed or unusable at scale.

4.4.7 Performance Indicators

An extensive range of performance indicators emerged across expert interviews. While many of these metrics are tightly linked to specific applications, they collectively serve as essential tools for evaluating TCB reliability, functionality, and system-level behavior. Compared to the more fluid and variable nature of design inputs (such as materials or methods), performance indicators tend to be more discrete and measurable, offering designers clear criteria for assessing success.

Yet, a critical insight from participants is that designers rarely make a sharp distinction between *generalizable system performance* and *application-specific requirements*. As discussed in the summary section of Chapter 3, while this dissertation aims to build a structured framework for organizing design inputs, designers themselves often approach these relationships more fluidly and contextually. As Participant 1 put it, *"it depends so so much on application,"* underscoring that performance cannot be evaluated in the abstract or isolation, it must be assessed through the lens of specific use cases, user expectations, and environmental conditions.

Participant 8 further clarified this complexity, distinguishing between (1) a component's performance in isolation versus within a system, and (2) performance negotiated with customers versus measured through technical benchmarks. For instance, a conductive thread may demonstrate low resistance in bench tests but behave unpredictably in a garment due to body movement, moisture, or laundering cycles.

This layered relationship means that design input variables such as stitch type, substrate, or layout decisions cannot be mapped to performance in a straightforward or universal way. Instead they are interpreted through multiple performance lenses. The design process becomes iterative and responsive: performance feedback prompts recalibration of design choices, and customer requirements help define what "success" means for a given product.

4.4.7.1 Distinguishing Types of Performance Indicators

To clarify the landscape, performance indicators can be grouped into three broad categories:

1. **General/System-Level Functionality**

   These indicators reflect baseline requirements for whether a TCB works as intended at the electrical and functional level, regardless of application. They are universal to almost all circuit designs and can often be evaluated using objective testing or simulation.

- **Conductivity**
- **Continuity**
- **Stable Resistance**
- **Shorting (prevention)**
- **Functionality**
- **Accuracy**
- **Insulation**
- **Heating (where relevant)**
- **Low Power Performance**

2. **Standardizable and Cross-Application Benchmarks**

   These indicators can be standardized within particular domains (e.g., IPC or ISO categories), even if the performance thresholds vary. They often concern durability and user interaction and can be meaningfully compared across different use cases, as in the case of flammability or washing resistance.

   - **Durability**
   - **Washability**
   - **Abrasion Resistance**
   - **Twisting/Torsion Resistance**
   - **Fatigue**
   - **Flammability**
   - **Impact Resistance**
   - **Elongation (Mechanical Deformation)**

- **Tumble Drying**
- **Ultraviolet Resistance**
- **Alkalinity / Acidity Resistance**
- **Biocompatibility**
- **Safety**
- **Wick Testing**

3. **Application-Specific Performance Objectives**

   These indicators depend on product context, use environment, or wearer experience. They are not easily generalizable and are often defined through stakeholder negotiation and iterative prototyping.

   - **Fit**
   - **Comfort**
   - **Breathability**
   - **Flexibility**
   - **Sustainability**
   - **Scalability**
   - **Modularity**
   - **Repairability**
   - **Grading (fit across sizes)**
   - **Machine Transferability (ease of manufacturing)**
   - **Usability**
   - **Waterproofing**

- **Repeatability (across small batch runs)**
- **Manufacturing Speed**

4.4.8 Synthesizing Key Variables into Groups

Design variables identified from expert interviews can be broadly categorized into two major types: electrical and mechanical (Figure 33 & 34). Some chemically related variables, chemical coatings of traces, were grouped under mechanical, as their primary impact is physical. A hybrid "Material" category also emerged, encompassing characteristics relevant to both electrical and mechanical variables

4.4.8.1 Types of Variables

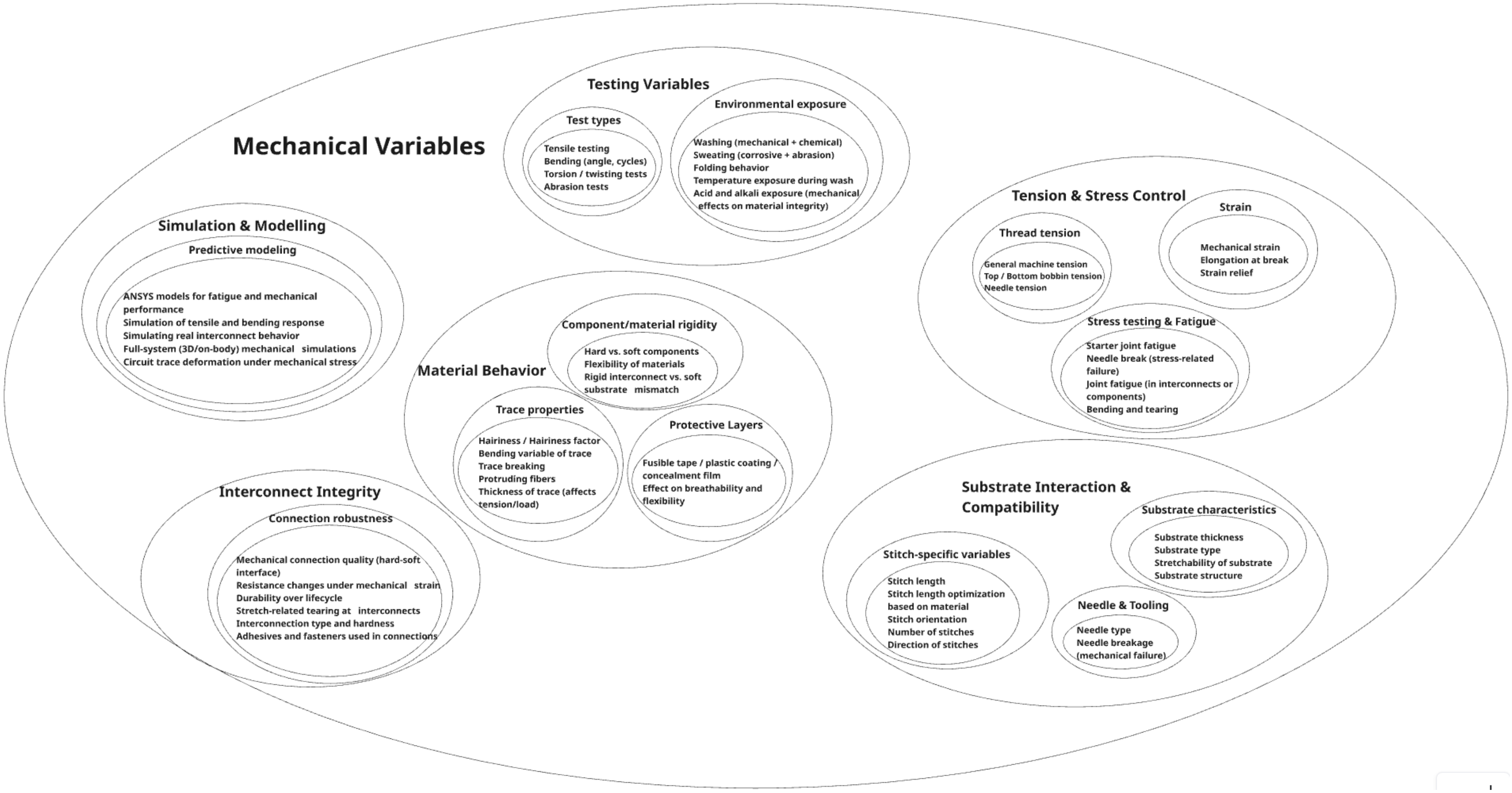


Figure 33 - Mechanical variables

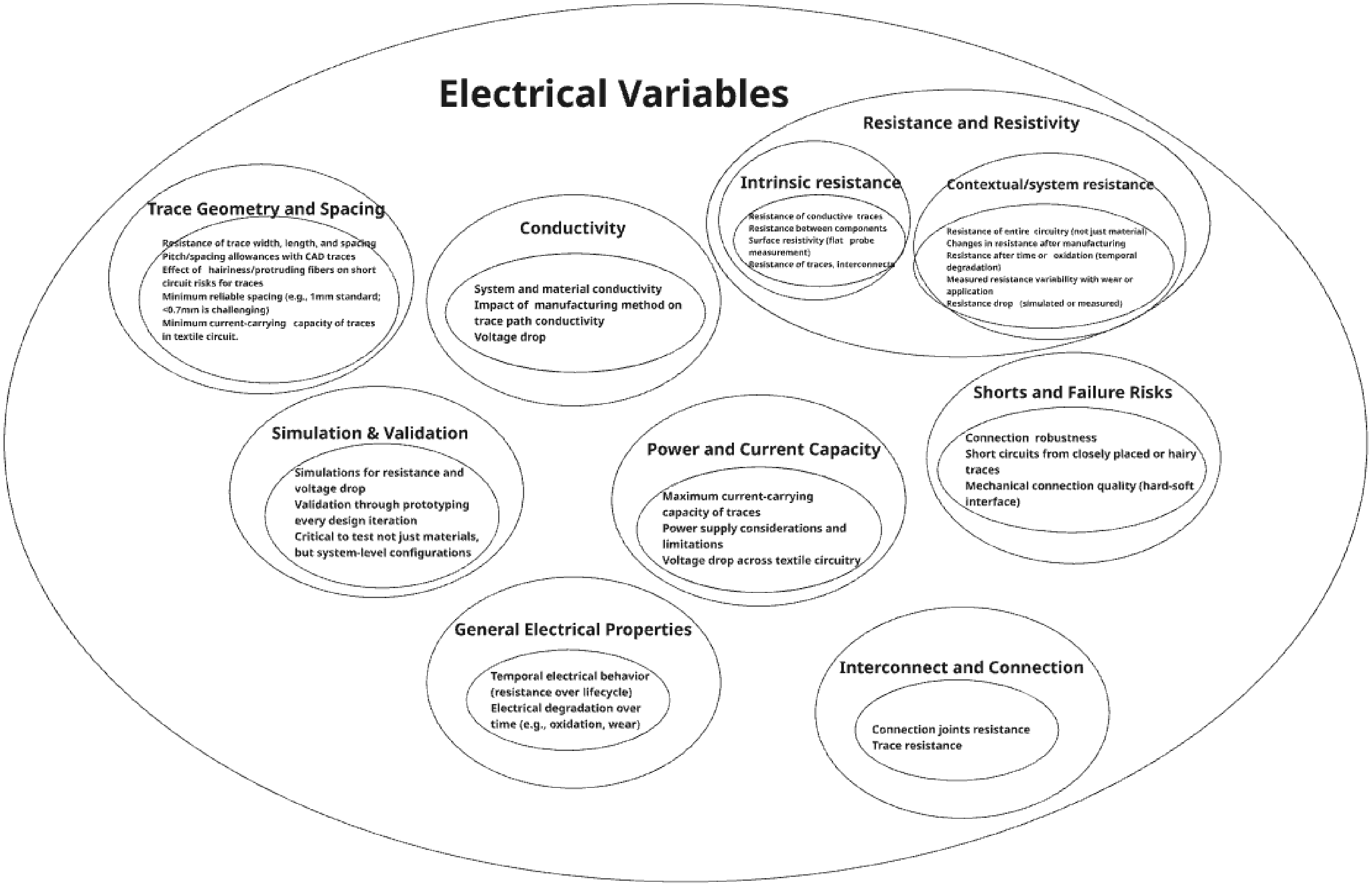


Figure 34 - Electrical variables

4.4.8.2 Grouping Variables Using the Six Ms Framework

The Six Ms framework was used to categorize variables, offering a process-aligned structure for understanding design and manufacturing complexity.

1. **Man (Human Factors):** *Variables related to human involvement, expertise, and decision-making across the design and manufacturing lifecycle.*
    - Decision-making in trace paths and component placement
    - Variability between operators
    - Ergonomic and wearable design considerations
    - Skill level of operators in different methods/techniques (sewing, soldering, embroidery)
    - Team members' familiarity with textile and electronics integration
    - Assembly consistency between technicians
    - Different interdisciplinary team members in this process

A. **Machine (Tools and Equipment):** *Variables related to the use, capability, and limitations of machinery used in e-textile production.*
    - Equipment type (e.g., single-needle, multi-head embroidery machines)
    - Machine resolution for components placement
    - Testing/calibration devices for performance evaluation
    - Machine behavior compatibility with conductive materials
    - Identification of automated vs. manual fabrication tools

B. **Method (Processes and Procedures):** *Variables describing how the manufacturing or design processes are carried out.*

   - Different kinds of methods e.g. - Stitching methods (subcategories –types under each subcategory)
   - Lead attachment methods (e.g., soldering, adhesives, crimping)
   - Quality control methods
   - Testing protocols for durability and performance
   - Workflow or assembly sequence
   - Design rule decision paths

C. **Material:** *Variables concerning the properties and compatibility of substrates, threads, components, and interconnections.*

   - Conductive trace/thread properties (e.g. resistance, fray resistance, etc.)
   - Substrate properties (e.g. stretch, thermal behavior, etc.)
   - Component types (e.g. LEDs, sensors, etc.)
   - Interconnection materials (adhesives, encapsulants)
   - Material degradation overtime.
   - Biocompatibility for wearables
   - Sourcing and supply chain variability.

D. **Measurement:** *Variables used to evaluate, validate, or compare performance and quality of the textile circuit.*

   - Performance Indicators

2. **Mother Nature (Environmental Factors):**

- Humidity and moisture impacts
- UV exposure and thermal cycles
- User-induced mechanical stress
- Recyclability and sustainability

4.5 Summary

This chapter synthesized expert perspectives and prototyping experiences to define the core variables, challenges, and organizing constructs that underpin EDA for e-textile systems. The study revealed that:

- **Design variables in e-textiles** can be systematically classified into electrical and mechanical subdomains. These include stitch types, conductive materials, trace geometry, layout strategies, and component joining methods. Their interactions are complex and often context-dependent.
- **Failures function as diagnostic tools**, not just outcomes to avoid, but signals of where variable misalignments or process weaknesses exist. Failures related to mechanical fatigue, electrical discontinuity, or integration breakdowns pointed to the importance of interconnect design, stitch/material compatibility, and process control.
- **Layout emerged as a central design construct**. Rather than a downstream artifact, layout plays a strategic role in organizing design variables, enforcing constraints, and enabling simulation and automation. Experts repeatedly emphasized that many reliability issues trace back to layout decisions, especially where transitions occur between rigid and flexible elements.

- **Performance indicators**, while often application-specific, can be grouped into reusable categories: general circuit functionality (e.g., conductivity, resistance), standardized benchmarks (e.g., washability, abrasion resistance), and application-driven metrics (e.g., comfort, flexibility). Among these, **resistance** surfaced as a particularly central performance proxy, reflecting the interplay between material, geometry, and environment.
- **Automation in textile circuit design** is critically dependent on the ability to encode layout, variables, and performance indicators into structured, logical relationships. Without these structures, EDA tools cannot simulate, validate, or iterate effectively on soft-circuit designs.
- The **Six Ms framework**, mapping Materials, Methods, Measurements, Mechanics, Models, and Manufacturing, offers a comprehensive structure for grouping and connecting system components, design variables, and decision logic across domains. It helps unify the vertical stack of design concerns from low-level physical characteristics to high-level functional requirements.

These findings extend and deepen the foundational insights presented in **Chapters 2 and 3**. Chapter 2 (the literature review) provided the initial taxonomy of variables, standardization gaps, and the need for context-aware design strategies. However, much of that discussion remained theoretical. Chapters 3 and 4 built on the theoretical foundation laid in Chapter 2 by showing how those ideas played out in real-world practice. Chapter 3, in particular, offered deep, situated insight through a single case study, highlighting how design decisions unfold in context. While grounded in one experience, the interview-based analysis in **Chapter 4** allowed those insights to be extended and tested across the broader field, revealing how designers interpret, adapt, or resist generalized frameworks in their own practice.

One of the most illuminating insights from interviews was how interpreted **failures are not as isolated defects, but as evidence of deeper variable mismatches**, for example, a recurring issue like delamination was traced back to specific interactions between substrate flexibility, bonding method, and load-bearing geometry. These reflections not only uncovered sensitive design parameters but also revealed how performance breakdowns can serve as diagnostic tools for refining rules and methods, an insight not evident in the literature alone. Similarly, the literature's general guidelines on trace spacing were found to be insufficient without accounting for fabric behavior, stitch tension, and orientation.

By capturing lived design knowledge and operational failures, this chapter adds generalizability, empirical weight, and practical nuance to the concepts first outlined in the literature. Together, Chapters 2, 3, and 4 now establish a foundation for the rule-based, logic-driven structure introduced in the next chapter. That framework will present the **comprehensive variable map**, spanning physical materials, design parameters, and decision pathways, and formalize the logic that supports early-stage e-textile design automation. Table 11 shows the comprehensive e-textile design variables with domain categorization.

Table 11- Comprehensive set of e-textile design variables with domain categorization

Category	**Variable**	**Relevant Domains**
Electrical	Trace width	MD, DR
	Trace spacing	MD, S, DR
	Resistance (nominal, stable, under strain)	S, MD, AO
	Conductivity	MD, S
	Continuity	MD, S
	Shorting	S, AO
	Power requirements (low power operation)	AO, DR
	Heating behavior / power dissipation	AO, MD
	Electrical failure types (open, short, unstable contacts)	S, MD
	Resistance vs. elongation	MD, DR, S
	Contact resistance at joints	MD, S, DR
	Component behavior under tension	AO, S

Mechanical	Stitch type	MD
	Stitch pitch	MD, S
	Stitch density	MD
	Stretchability (uniaxial, biaxial)	AO, MD
	Flexibility	AO
	Fraying	S, MD
	Fatigue resistance	S, AO
	Torsion, twisting resistance	S, AO
	Bending radius of traces	MD, DR
	Abrasion resistance	S
	Insertion strain / pull forces	MD, AO
	Delamination	S, MD
	Mechanical support for leads	MD
	Thread path orientation (e.g. warp/weft)	MD, DR

Material	Conductive thread type	MD, S
	Yarn diameter	MD
	Fabric substrate (material type, stretch profile)	MD, AO
	Lead type (gull wing, L-bend, J-lead)	MD
	Soldering method (hand, reflow, low-temp)	MD, S
	Adhesive material (for bonding components)	MD, S
	Encapsulation material (breathable, thermally safe)	AO, S
	Needle size	MD
	Component footprint (LED, battery, etc.)	MD, DR
	Insulation method	MD, S
	Fabric breathability	AO
	Flame resistance / flammability	S

	Biocompatibility	AO, S
Layout	Component placement	DR, MD
	Routing path (e.g., serpentine, straight)	DR
	Netlist/topology	DR
	Layer transitions	DR, MD
	Seam crossings	MD, DR
	Pattern design (for garment ease and circuit protection)	MD, AO
	Edge distance for traces	MD, S
	Interconnect spacing and orientation	DR, S
	Pad size and spacing	MD, S
Environmental/Use Context	Washing durability	S, AO
	Tumble drying tolerance	S, AO
	Sweat/perspiration resistance	S, AO
	Ultraviolet exposure resistance	S

	Alkalinity/acidity resistance	S
	Waterproofing	AO, S
	Impact resistance	AO, S
	User movement profile	AO
	Breathability and thermal regulation	AO
System Integration	Modularization (garment layout)	MD, AO
	Ease of donning/doffing	AO
	Repairability	AO
	Transferability (between machines/fabricators)	MD
	Debugging capability	DR
	Toolchain compatibility	DR
	Simulation support (current limitations)	DR
	Communication between disciplines	DR, S
	Reliability	S, AO

Performance Indicators	Repeatability	S
	Accuracy	S, MD
	System functionality (does it “work”)	AO
	Manufacturability	MD, DR
	Robustness	AO, S
	Grading / scalability across sizes	AO, MD
	Speed of fabrication	MD
	Sustainability	AO, S
	Safety	S, AO
	Comfort	AO
	Usability	AO
	Stable resistance	S, MD, DR

DR- Design Rules, AO- Application Objective, S-Standard, MD – Method Development

4.6 Study Limitations and Mitigation Strategies

This study is subject to some limitations. The sample size was limited to 12 expert participants; however, each was intentionally selected for their deep knowledge and to ensure broad representation across sub-domains within the e-textiles field. One limitation is tool bias participants' insights were often shaped by the tools and equipment available to them, for instance, those without access to certain fabrication machines may have underreported challenges or overlooked alternative methods. While rigorous thematic coding was used, the qualitative analysis remains susceptible to researcher bias inherent in manual coding processes. The field itself is also rapidly evolving, meaning that some practices or metrics discussed may become outdated or refined as new materials and methods are introduced.

Additionally, literature data used in this study may reflect only the specific application contexts in which they were originally gathered. To address this, a triangulation strategy was employed, cross-referencing findings from literature, expert interviews, standards documents, and the researcher's own design experience. Another limitation involved the challenge of articulating tacit knowledge: some participants struggled to verbalize their decision-making processes. To mitigate this, we walked the interviewees through practical textile circuit examples, which often helped surface embedded knowledge. Finally, because e-textile EDA is a new and emerging space, no single stakeholder holds all the answers. Most participants were not experts in EDA systems specifically, so it became the researcher's role to interpret their input and extrapolate its relevance for tool development. Again, triangulation across interviews, literature, and practical prototyping was essential in building a coherent, grounded understanding from these diverse and partial perspectives.

5. Framework Development and Validation

5.1 Introduction

This section presents the resulting EDA framework, developed through a synthesis of insights from the literature review (Chapter 2), empirical findings from the BiliOnesie design probe (Chapter 3), and thematic analysis of expert interviews (Chapter 4). These earlier chapters surfaced key variables, design rules, process constraints, and performance considerations essential for e-textile system development. Drawing on this foundation, the framework organizes design knowledge into a structured, rule-based system that captures material-method relationships, layout logic, and application-driven constraints. The framework was then validated and refined through expert feedback, ensuring its relevance, clarity, and alignment with real-world design challenges.

The framework is built directly upon the foundational work of Knowles (2023), who articulated the need for layout automation and constraint-checking mechanisms tailored to the unique challenges of e-textile design. While Knowles introduced a broader conceptual model for rule-based systems in smart textiles (see Figure 35), the present framework focuses specifically on mid-stream decision-making, connecting fabrication methods, variable dependencies, and layout logic to support early-stage design and rapid iteration.

To ensure its validity and real-world relevance, the framework was reviewed and refined through expert validation. Feedback was gathered from targeted interviews with experienced practitioners, and the resulting comments informed both structural and content-level adjustments. This second round of engagement also prompted a reanalysis of earlier insights, enabling cross-comparison and alignment between exploratory findings and practitioner validation. As Knowles (2023) underscores, the development of design rules for e-textiles must be grounded not only in technical logic but also in iterative feedback and consensus-building among experts.

5.2 Method

5.2.1 Framework Development Process

The development of the EDA framework followed a multi-stage, iterative methodology grounded in the triangulation of three primary data sources: (1) the literature review (Chapter 2), (2) the Research-through-Design case study of the BiliOnesie (Chapter 3), and (3) expert interviews (Chapter 4). These sources collectively surfaced a broad range of variables, interdependencies, and failure modes, which were synthesized into an initial structure. Early in this process, the "Six Ms" framework, Material, Method, Measurement, Modeling, Man, and Machine, was adapted as a developmental scaffold to help categorize and map the design dimensions of e-textile systems. This structure provided a way to group the variables according to their role in the design process and to ensure that the emerging logic of the framework could accommodate a range of fabrication methods, stakeholder needs, and system behaviors.

5.2.2 Validation Study Design

A multi-stage validation process was conducted to assess the usability, completeness, and logic of the framework. Following synthesis, the draft framework was iteratively refined through feedback sessions with two additional experts in e-textile design. These sessions focused on testing the validity of proposed categories, challenging assumptions about variable dependencies, and refining the structure for clarity and usability. Their input helped improve both the granularity and the modularity of the framework. The final version was rendered visually to communicate the high-level logic, node relationships, and detailed sub-variable structures using a Miro board and a Neo4j graph database model. This dual representation allowed for both conceptual clarity, laying the foundation for future variables expansion.

To further validate the structure and refine the framework, we also re-engaged three "lead" experts from the original participant group. These individuals were purposefully selected for their cross-cutting expertise in materials, fabrication methods, and product development, enabling them to evaluate the framework holistically rather than from a narrow technical lens. One-hour interviews were conducted via Zoom, with each session recorded and transcribed for analysis. Participants were shown both the Miro board and the Neo4j database interface in a semi-structured interview. We also designed interview questions to probe the framework's clarity, relevance, and completeness (see Table 12).

Table 12– Follow-up Interview Questions

Structure & Logic	Does the hierarchy of variables reflect how you typically approach e-textile circuit design? Are the relationships between categories (e.g., methods, components, layout) accurate and meaningful? Are any key elements or major nodes missing from the current variable mapping?

	Does the level of abstraction used in the framework align with how you conceptualize major elements in e-textile circuit development? Are there any nodes or paths that feel unnecessary or redundant?
Terminology	Is the terminology consistent with how you describe your work in e-textiles? Are there any technical terms that should be rephrased, clarified, or defined more precisely? Does the structure reflect your actual decision-making or design workflow?
Usability	Are there any variable relationships or mapping elements you think should be added to better support early-stage circuit planning?
Interactivity & Visualization	Would an interactive visualization enhance your understanding or use of the framework?

Data collected from these sessions included annotated feedback directly on the Miro board, written session notes, and partial transcriptions of the Zoom discussions. This combination of visual, verbal, and written feedback allowed for a rich and triangulated understanding of where the framework succeeded, where it needed refinement, and how it could better serve as a foundation for future e-textile EDA tools.

5.3 Results

5.3.1 EDA Design Framework

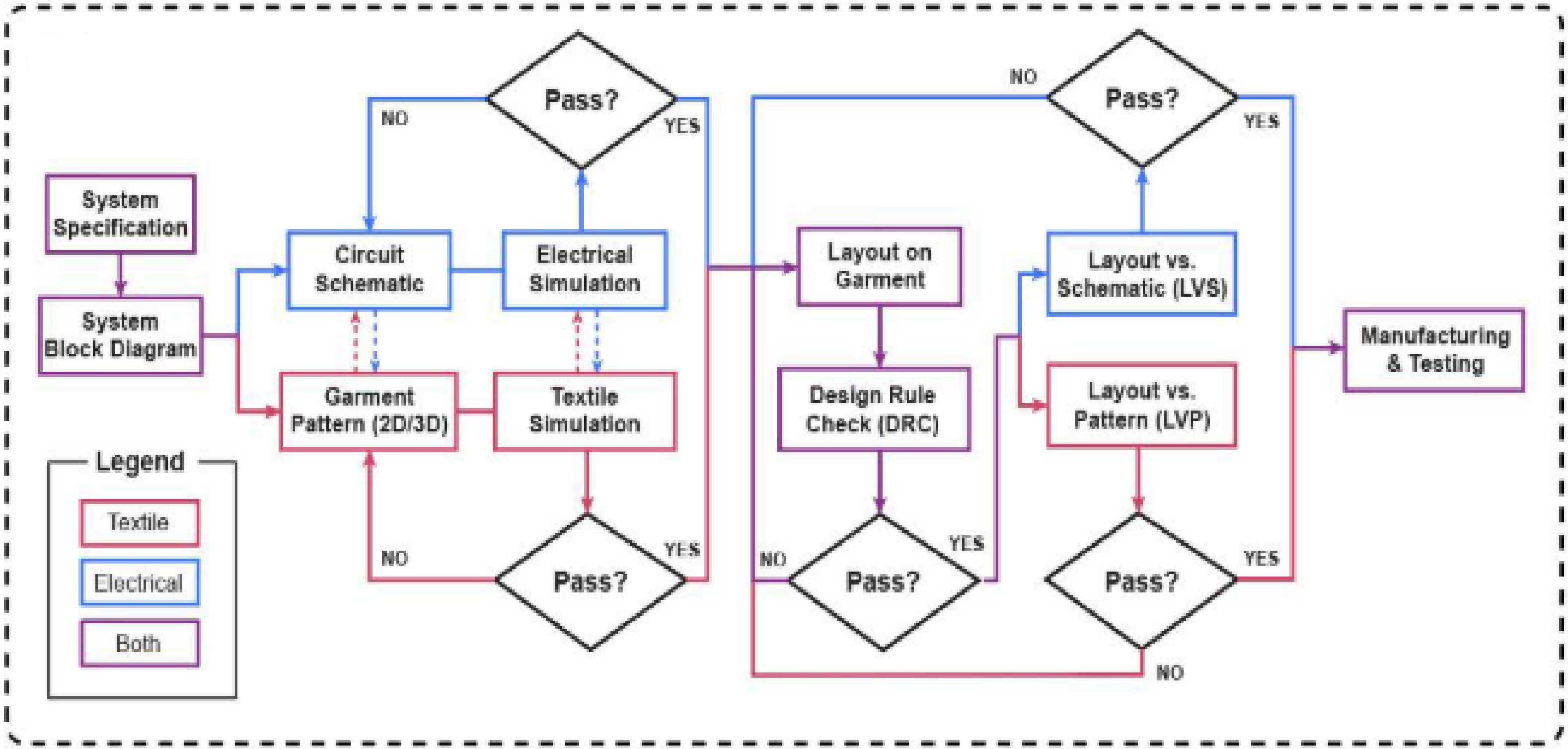


Figure 35 - E-textile design process framework (Knowles 2023)

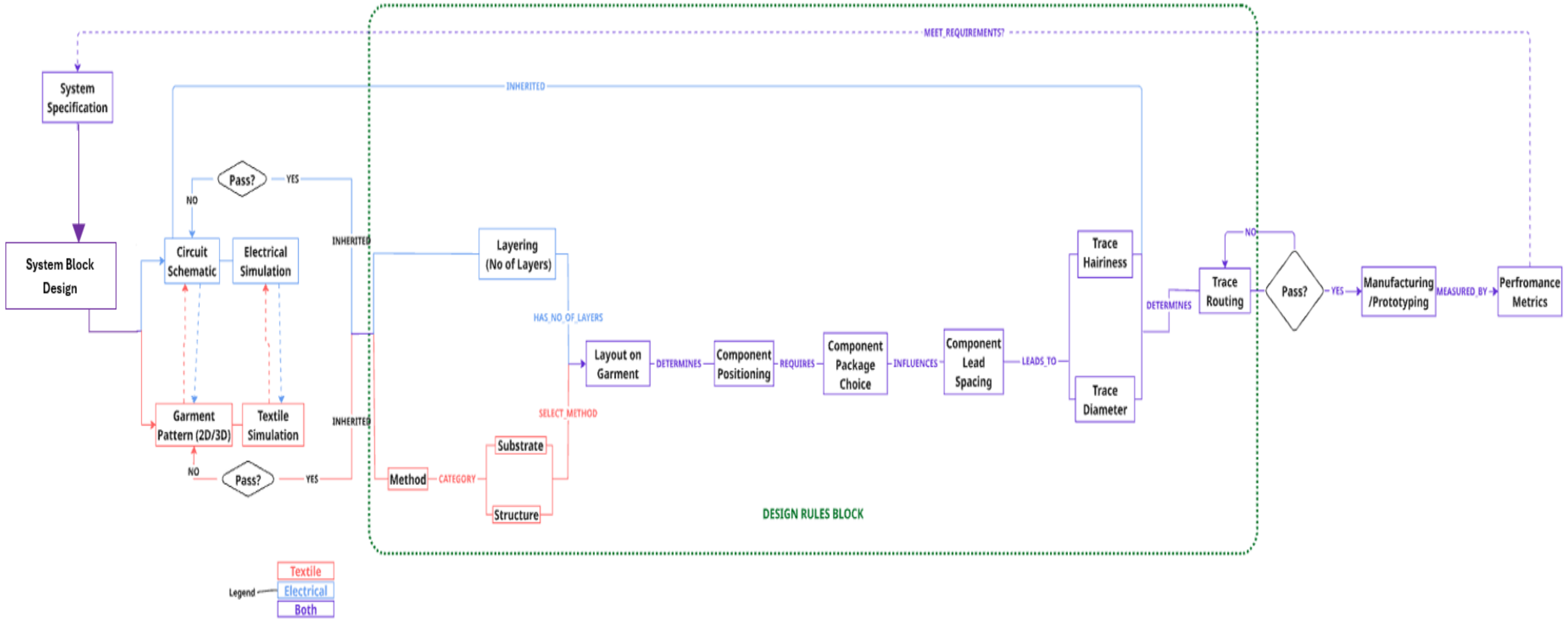


Figure 36 - Our initial resulting framework (built on Knowles (2023) framework)

Our framework builds upon and extends the foundational work of Knowles (2023) by operationalizing the conceptual logic into a modular process structure with interconnected rule paths. Specifically, the green-dotted "Design Rules Block" shown in Figure 36 above represents the core logic engine and the primary focus of the work presented in this chapter. To support clearer navigation and understanding, we retained the color-coded domain logic approach introduced by Knowles: textile-related variables and decision flows are highlighted in red, electrical ones in blue, and overlapping or hybrid processes in purple. This visual coding reinforces the interdisciplinary nature of e-textile design and helps distinguish between domain-specific logic and cross-domain dependencies.

The framework encodes not just the categories of variables, such as components, substrate, and traces, but also the conditional logic that governs how decisions in one category affect available options in the next. By explicitly defining these interdependencies, the system enables machine-readable rule execution and paves the way for automation in e-textile design environments. In this way, the framework transforms abstract design reasoning into a structured, dynamic system capable of supporting intelligent, guided decision-making.

One key insight that emerged from our mapping efforts was the need to divide textile processes into two major classes: substrate-based methods and structure-based methods. Substrate-based methods such as printing, embroidery, or lamination apply material and electrical features *onto* an existing textile base. Structure-based **methods**, such as knitting and weaving, build the material system from the ground up, thereby embedding function *into* the textile architecture itself. This distinction, introduced in Chapter 2 during the literature review, now informs the classification of variables in the design framework.

These two sub-categories under the method category follow distinct logic paths and require different variables to be tracked and conditioned. Simultaneously, within the method selection, the framework specifies the **number of layers** involved in the design. This determines the stack height and informs signal routing options, trace separation requirements, and component placement feasibility. Once the layering strategy is established and the designer chooses the primary fabrication method. This selection activates a corresponding variable path for subsequent rule filtering before the system moves into layout stage. For example, if the designer selects a **two-layer embroidery approach**, the system prioritizes variable paths that include **stitch pitch, thread type, and needle size**. These variables become active constraints, filtering out incompatible rules such as those optimized for planar printing processes or multi-layer lamination methods. This tailored rule path ensures that only context-relevant parameters shape the design space, improving accuracy and reducing the likelihood of incompatible design decisions during layout generation.

At the layout stage, the goal is to determine whether components will be integrated on the garment (surface-mounted) or within its structure (embedded or laminated) and within how many layers. From here, the flow proceeds to **component positioning**, which is a geometric and ergonomic placement step. Rather than selecting a specific component at this point, the framework treats components as abstract functional blocks. What becomes critical instead is the **package choice** that defines the component's mechanical footprint and, importantly, its **lead pitch**. By specifying package type, designers effectively signal how closely leads are spaced. This is essential information for layout constraints and trace routing feasibility. The system does not need to know if the designer is using an LED or an accelerometer, it only needs to know the pitch class (e.g., SOIC, QFN, or 0603).

Component positioning is a critical area where the EDA system can support designers in making application-specific choices, while still leaving room for human expertise. In its current form, the framework allows designers to place components based on aesthetic, ergonomic, or functional priorities, such as avoiding pressure points in wearable contexts or optimizing light distribution for therapy garments. While future systems may eventually offer automated suggestions to flag suboptimal placements (e.g., proximity to high-strain zones or poor thermal dissipation), the current iteration assumes that designers will draw on domain knowledge to make these decisions. However, the strength of the EDA framework lies in its ability to digitally encode these positions and dynamically update all dependent design variables, such as trace routing, interconnect geometry, or insulation needs, based on new layouts. This digital adaptability streamlines iterative revisions, enabling rapid prototyping and reducing the overhead typically associated with reworking physical garment designs.

Once **lead spacing** is defined, the system calculates **the required spacing for traces**. This is a critical rule-checking node, as inadequate spacing between traces can lead to short circuits, especially in flexible or stretchable garments where conductive elements may shift during use. In addition, the relationship between lead spacing and trace width introduces the possibility of an **interposer layer**, a buffer that adapts fine-pitch component leads to broader, more robust textile traces. At this stage, **trace diameter** becomes a key design parameter. However, the framework also acknowledges that trace behavior is not solely governed by geometry; **material characteristics**, particularly **hairiness**, play a significant role. Hairiness refers to the tendency of the thread or trace material to fray, snag, or degrade, issues that directly affect **trace spacing**, **insulation reliability**, and ultimately, circuit functionality. As emphasized by Participant 2, *"take example of fraying, in embroidery, it frays really. In stitching, it frays. In woven, and it's gonna fray... and then it's gonna give you a malfunctioning substrate… But again it goes back to the proper material characterization"* Participant 10 reinforced this concern: *"you need to know what that hairiness factor is so that you don't put two things too close, so they don't short."*

For example, if the selected method was printing, hairiness is zero by default, and trace edges are clean. But if the selected method was stitching or weaving, the trace is made from uninsulated thread, yarn, or another fibrous medium, hairiness must be quantified and factored into spacing and routing rules. The combination of trace hairiness and diameter are passed into the **trace routing** stage. This is where automated layout generation becomes viable. With sufficient characterization of material behavior and spacing constraints, the framework can inherit auto-routing logic from existing PCB design systems. Such logic must, however, be adapted to the peculiarity of textile substrates, including curvature, stretch, and mixed-material layering. The design rule engine performs conditional checks to validate whether the proposed routing meets trace integrity and separation requirements and also enforces constraints like stretchable trace geometries. If it does not, the flow loops back to modify spacing, method, or component placement until a pass is achieved. Once a design passes routing validation, it advances to the **prototyping and manufacturing** phase. Here, the system translates logic-defined layouts into machine instructions or manual assembly guides. Performance of the resulting physical products can then be evaluated based on predefined metrics such as continuity, mechanical durability, or comfort, using standardized test methods and metrics or domain-specific assessments.

Importantly, the entire process flow framework is cyber-physical in nature, it is not structured as a linear pipeline but as a feedback loop that integrates real-world testing outcomes into upstream design logic. This supports iterative refinement based on empirical performance data, allowing the system to improve and adapt through successive prototyping and evaluation cycles. Looking ahead, if advanced simulation modules, such as the electromechanical and strain-propagation models discussed by Knowles (2023) and envisioned by expert participants, were fully developed and integrated, a greater portion of the design cycle could be carried out virtually. This would allow designers to simulate multiple design iterations, anticipate failure risks, and fine-tune trade-offs with fewer physical builds, ultimately accelerating development timelines while reducing material waste.

While that future vision is still emerging, the current framework already enables fully cyber-implemented rule-based decision support, provided that design rules are translated into machine-readable instructions. By encoding decision paths as conditionally linked logic structures, the system transforms the complex e-textile design process into a guided, intelligent workflow. It enables designers to systematically navigate tradeoffs between materials, integration methods, and layout strategies through validated steps. More critically, it lays the foundation for machine-assisted design tools to reason through textile-electronic interdependencies in a way that accounts for real-world constraints, bringing clarity, scalability, and consistency to a field often challenged by fragmentation and tacit knowledge.

5.3.1.1 Inner Variable Mapping of the EDA Framework

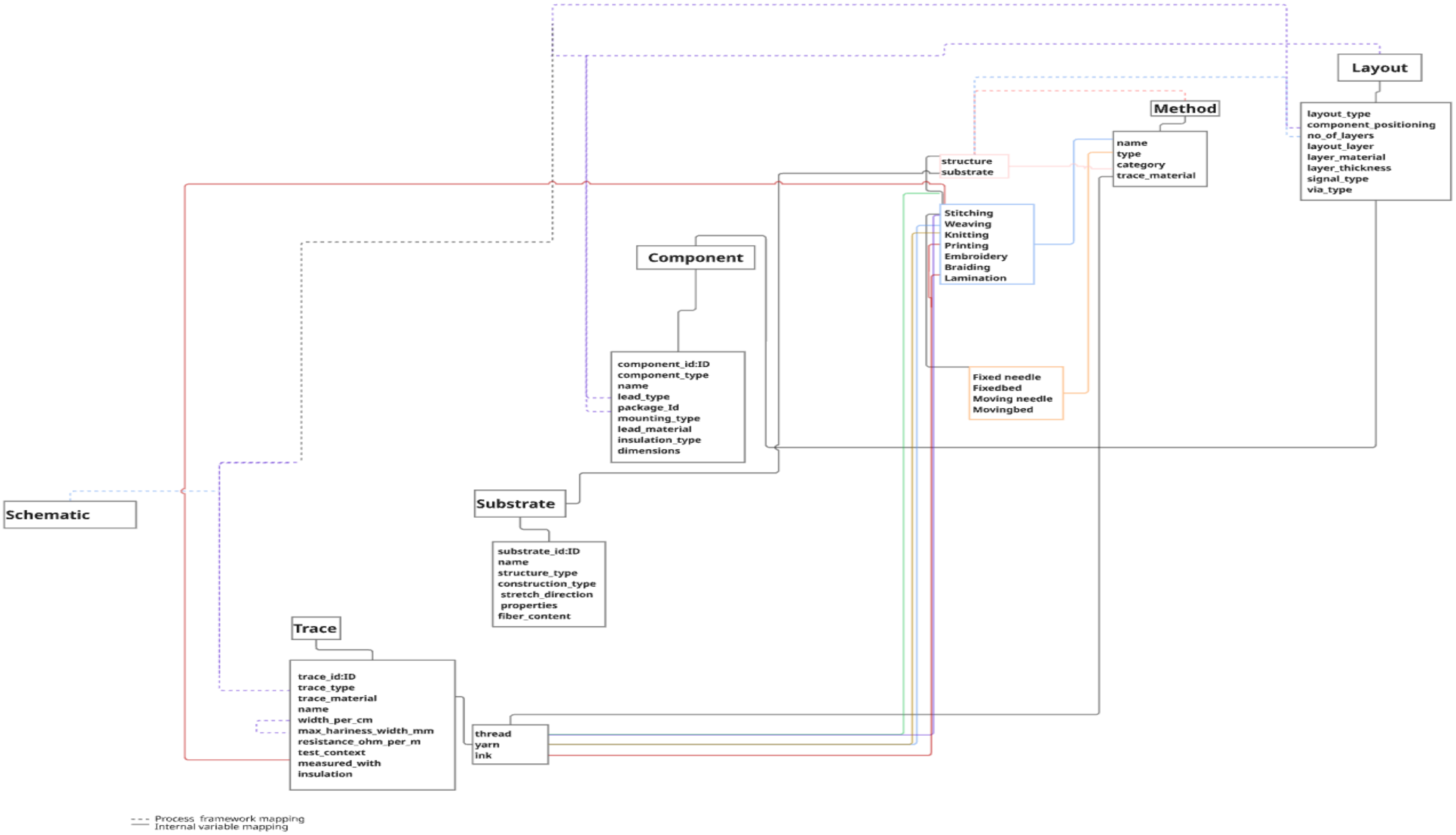


Figure 37 - Figure showing variable structuring and internal mappings

This section explains the architecture of the e-textile EDA framework as visualized in Figure 37 above. It focuses on how the key categories, referred to as major nodes, and their corresponding subcategories, sub-nodes, are mapped and interconnected. These relationships are illustrated through connecting lines in the diagram: **solid lines** represent internal variable mappings, while **dotted lines** indicate mappings tied to the process framework. Together, they reveal the dependencies and decision pathways that must be studied, formalized, and encoded into the EDA system. The framework also clarifies the internal logic of e-textile circuit construction by showing how different categories interact. Each connection in the diagram signals a specific design dependency that must be characterized to support rule-based, reliable system development.

The primary categories (or major nodes) in this framework include **Method, Component, Substrate, Trace, Layout**, and **Schematic**. Each of these nodes contains sub-properties or design variables such as thread type, substrate structure, resistance, or stitch geometry. The lines between nodes represent either logical design flows or fabrication interdependencies, both of which serve as the foundation for conditional design rules within the EDA environment.

While the previous section introduced the broader structure of the design process, including method selection, layering, and layout definition, this section dives deeper. It examines the internal structure of each major category and shows how they decompose into specific sub-variables that inform design constraints. Each node in the framework not only defines a core design element but also acts as a **filter**, guiding downstream decisions and enabling the EDA tool to generate meaningful, context-aware design pathways.

From right to left, we begin, as with the process framework, with method and layout, which are foundational in shaping every downstream requirement. Method selection, in particular, acts as a branching logic node from which the rest of the design space is inherited. In this deeper mapping, method is not treated as a singular label (e.g., "stitching" or "printing") but as a structured category with multiple sub-properties. These include type, category, and trace material. Each of these sub-properties introduces its own decision-making logic. This structured breakdown is critical. For instance, when stitching is chosen as the method, the EDA tool must now consider what kind of stitching machine will be used, whether a fixed needle, a moving needle, or a moving bed. This decision directly influences the circuit's resolution and allowable garment geometries. These aren't cosmetic details; they are encoded parameters that affect variables like allowable minimum trace spacing for that machine type. By building out the method node with this internal structure, the framework can begin to simulate not only what can be designed, but what can be manufactured reliably.

Likewise, **layout**, while appearing as a singular design step, is broken down internally into variables such as layout type, component positioning, number of layers, layer material, layer thickness, signal type, and via type. Each of these variables is treated as a filtering system, capable of conditioning subsequent design choices. For example, selecting a layout type that involves layering (i.e., placing conductive traces between fabric layers) immediately filters the insulation types that are compatible and the layer number points to which layer the insulation is going on.

Each of the remaining major categories, Component, Substrate, and Trace, follows a similar structure. **Component** is not treated as a simple label like “LED” or “sensor,” but instead is defined through attributes such as lead type, package type, mounting style, lead material, insulation type, and dimensions. These properties allow the system to reason about space allocation, positioning, and interconnection strategies. For instance, the component lead type influences how the trace connects to the component, while the package type helps determine required clearances and trace fan-out strategies. The inclusion of insulation type within the component node acknowledges that not all components are pre-insulated, and that additional encapsulation logic may be required downstream.

The **Substrate** category also opens up into a defined list of properties that condition every interaction in the textile circuit. These include structure type, construction type, stretch direction, fiber content, and whether or not the substrate is conductive. Each of these features filters compatibility with integration methods, trace materials, and component mounting strategies. A stretch direction variable, for instance, can be used to dynamically adjust serpentine trace paths to accommodate expansion and contraction.

Trace, another critical logic node, expands into attributes such as type, material, max width per cm, hairiness width, resistance per mm, measurement method, and associated insulation type. These internal variables are used not just for descriptive purposes, but as constraints and input conditions for rules. For example, if a trace is defined as a thread-based material with high hairiness and variable resistance, the system can automatically trigger spacing recommendations or suggest encapsulation layers. Furthermore, the resistance per unit length informs routing constraints and power analysis in electrical simulations.

In this internal structure, each node becomes a container for rules and conditional logic. But more importantly, each line connecting nodes represents a dependency pathway that must be characterized, understood, and, eventually, translated into machine reasoning. For example, the line from Component → Trace is more than a symbolic relationship; it reflects the reality that the component's lead pitch defines how traces must fan out from the pad, and that this interaction must be simulated for routing to be viable. Similarly, Trace Substrate reflects that certain substrates (e.g., loose knits) cannot support ultra-fine dimensions for trace paths unlike the way a substrate type like a woven polyester would.

In summary, this section has demonstrated how the major categories in the EDA framework are internally decomposed into structured, interdependent sub variables. These decompositions are essential for automated design tools, because they allow conditional logic to operate at the variable level rather than the object level. By treating every selection as a filter, and every property as a design rule gate, the framework transforms from a static taxonomy into a dynamic decision-support engine. The next step in this development is the validation of the framework and encoding of these relationships into a formal rule language, one that can inform simulations, guide layout generation, and ultimately make e-textile circuit design more robust, repeatable, and intelligent.

5.3.2 E-Textile EDA Framework Validation

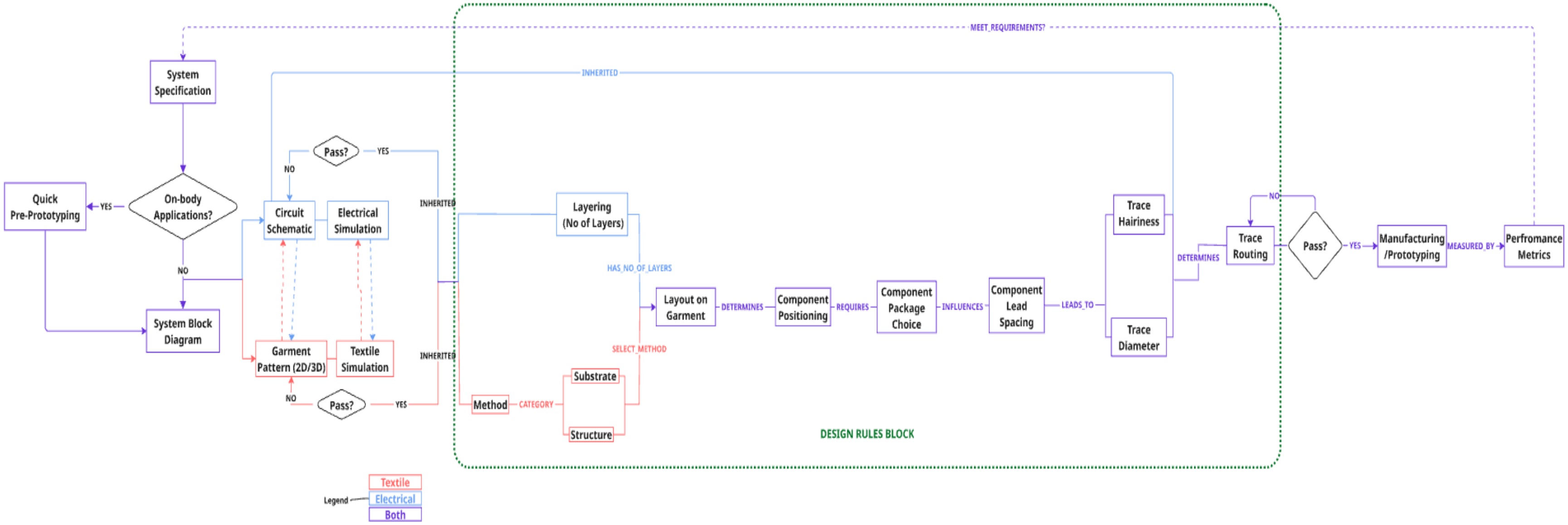


Figure 38 - Revised EDA framework for E-textile design based on experts' feedback

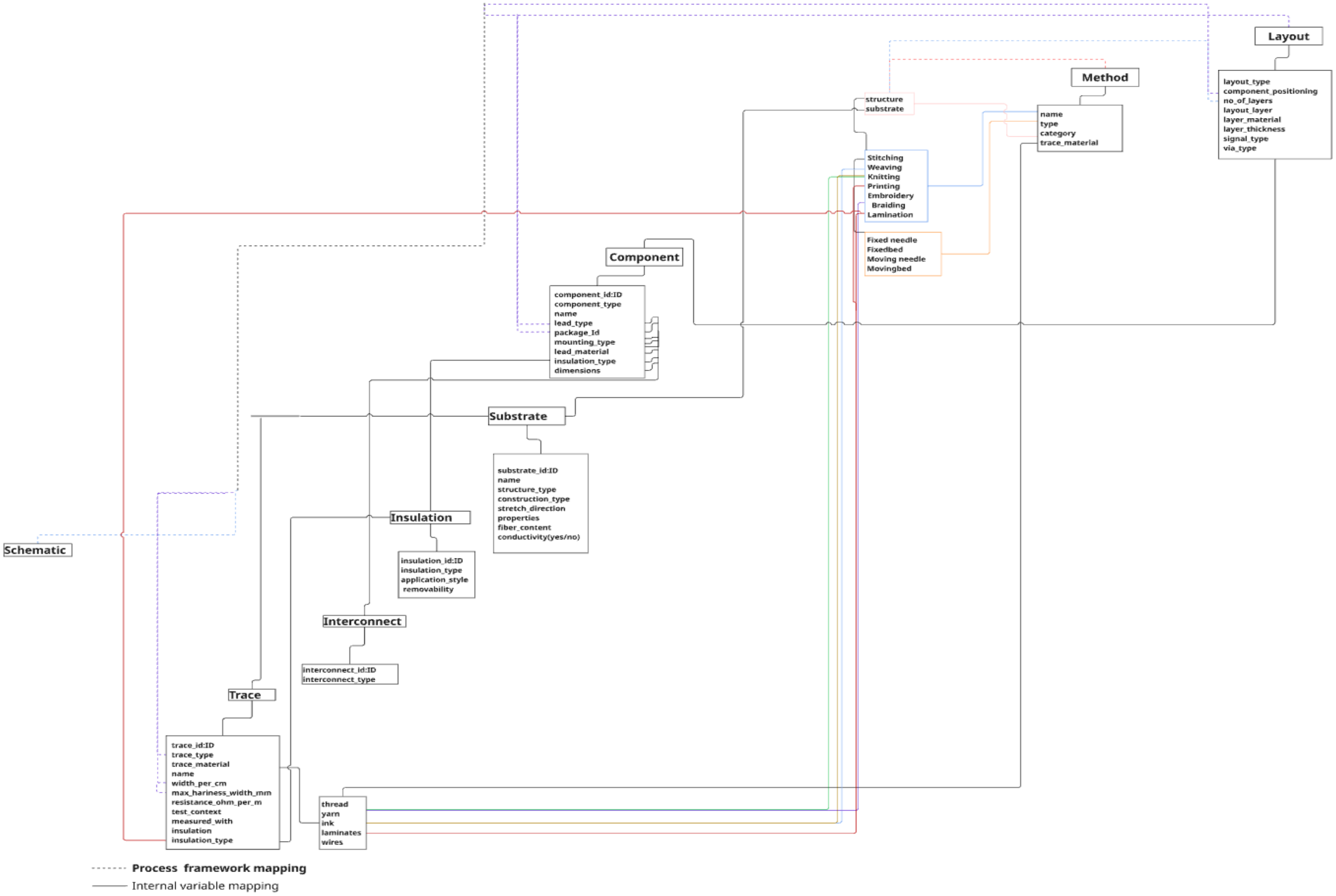


Figure 39 - Revised internal mapping of design variables based on experts' feedback.

5.3.2.1 Overview Framework Revisions

The refined version of the EDA framework (Figures 38& 39 above) benefited significantly from expert validation interviews, which confirmed the structure's underlying logic while also identifying areas for improvement. One of the most important additions to the overall framework was the inclusion of a "Quick Pre-Prototyping" pathway designed specifically for body-worn applications. This new track, which bypasses the more traditional block-diagram design logic, was directly informed by feedback about the importance of early, garment-centered iteration. As Participant 6 explained, *"sometimes you don't know where on the body the best location for the components, so being able to test placement quickly by taping or adhering components onto a textile or garment… just to see how it feels on the body is essential."* This pathway supports exactly that kind of rapid feedback loop, enabling early assessments of comfort, mobility, and garment fit before designers commit to circuit-level decisions. It reinforces the value of application-driven iteration and adds a flexible, human-centered entry point to the framework.

The experts generally validated the overarching structure and logic of the framework. Participant 1 remarked, *"It was like all of my thoughts were put to one visual, which was very, very nice," and confirmed that "everything was relevant… nothing was redundant."* However, they also highlighted the importance of guided navigation: *"It was easy to follow when you walked me through it, but otherwise… if I would just open a book and see this visual, then I would be like, oh, this is too much information."* This reinforces a key insight: the framework is not intended to be a user-facing tool, but rather a **roadmap for technology development**, a back-end logic layer that powers the future of e-textile EDA systems. Ideally, most stakeholders will never interact with the framework directly. Instead, they will experience its benefits through a well-designed graphical user interface (GUI) that distills complex logic into intuitive prompts and intelligent defaults. In this sense, the framework is meant for system developers and toolmakers, while the end users, designers, engineers, and manufacturers, engage only with its outputs through accessible, application-aware software tools. Participant 3 further affirmed the structure's logic: *"Your explanation of each category and how they relate and feed into each other seemed totally logical… I didn't think anything was missing."*

The importance of defining the framework's target user was also raised. Participant 1 asked, *"Who is this for? Is it for the engineer, the designer, or altogether?"* This question underscore the need for role-specific entry points or modes of interaction in future iterations. Overall, the high-level structure was affirmed as logical, modular, and clearly aligned with expert workflows, with useful abstraction that paralleled real-world collaborations between textile and electrical engineers.

5.3.2.2 Revisions to Inner Variable Mapping

In addition to validating the high-level logic of the framework, experts provided detailed feedback that helped reshape the internal structure of the variable mapping. Several key refinements were introduced to more accurately reflect real-world fabrication workflows and decision-making processes in e-textile development.

Interconnects as an Independent Node

One of the most significant changes was the elevation of *interconnects* to a top-level node. Initially treated as a subset or type of components, interconnects were recast as a standalone category to reflect their critical role at the junction of mechanical and electrical domains. Also, Participant 6 highlighted an interesting distinction, noting, *"At my previous job we called it the interconnect…*

but connector is fine too." This comment highlighted the importance of standardized terminology. The revised structure accounts for interconnect types, such as conductive threads, wires, laminated films, and inks, as well as their associated joining methods. Each type can be linked to design rules involving joint fatigue, electrical resistance, and substrate adhesion. This change reflects expert consensus that interconnects warrant their own design logic and failure criteria, distinct from those of traces or components.

Addition of Laminates and Wires

Experts also emphasized the importance of representing *laminated* and *wire-based* traces explicitly. These were added as distinct subtypes under the *Trace* category to account for fabrication approaches that deviate from traditional stitched or printed paths. This change enhances the framework's ability to model modern production methods that use flexible films or discrete wiring for signal routing, as was also discussed in Chapter 2.

Insulation as a Dedicated Node

A new *Insulation* node was introduced to model both inherent and applied insulation strategies. As Participant 2 explained, *"You don't necessarily need... TPU or some sort of lamination [for insulation], but that's probably the most common. You could theoretically put another layer of fabric over it."* Experts also noted that certain trace types (e.g., coated conductive threads) are pre-insulated, while others require post-processing, such as lamination or encapsulation. To reflect this, the insulation node is linked to the trace node using inheritance-style logic. It captures key variables such as insulation type, application method, removability, and compatibility with downstream operations like soldering. This addition ensures that insulation strategies can be flexibly represented and conditionally applied based on trace and application context.

Material Characterization Relationships

Another critical revision was the addition of a formal relationship between *Trace* and *Substrate* nodes to reflect the importance of *material characterization*. Experts highlighted that trace–substrate compatibility, including stretch behavior and thermal tolerance, is often a determining factor in the success of a design. This new relationship enables the framework to support early-stage compatibility checks and performance-driven material pairing.

Unresolved Divergence: Printing vs. Lamination

While most feedback was resolvable, one topic remained unresolved: whether *printing* and *lamination* should be treated as separate fabrication methods or grouped under a broader surface application category. Participant 6 pointed out that these techniques are sometimes functionally similar, "*You could theoretically like layer another [fabric]… so that's why I don't necessarily want to lump those two explicitly together.*" In contrast, Participant 3 stressed their differences: *"Lamination is different than the screen printing."* Given this divergence, the framework currently includes *printing* and *lamination* as distinct method nodes, allowing for future consolidation if practices converge.

These revisions enhance the granularity, traceability, and interdisciplinary fidelity of the framework. By refining how variables relate to each other, the inner mapping now more accurately supports automated reasoning and rule-based logic, while remaining flexible to future advancements in tooling and fabrication practices.

6. Characterization Design Study: Translating Variables into Design Rules

This chapter presents the experimental characterization phase of the research, which builds directly on the variable mappings and framework established in previous chapters. The goal is to demonstrate the translation of observed design relationships and dependencies into a formal rule language, one capable of guiding layout generation, and ultimately enabling a more robust, repeatable, and intelligent approach to e-textile circuit design. While the broader aim of this work is not to produce a completely automated design tool, this phase lays essential groundwork by demonstrating how an empirical investigation of selected variables and their interrelationships is necessary for developing design rules, paving the way for future automation in TCB design. Rather than treating variables as abstract concepts, this chapter focuses on how individual design parameters, identified during literature review, RtD, expert interviews and framework mapping, can be formalized through structured testing. We employed standardized methods to evaluate a subset of these variables, with the goal of generating quantifiable data that could directly inform the design logic within an EDA framework. Furthermore, this chapter serves to furnish a discussion of where the responsibility for the various tasks needed to achieve an integrated, evidence-based EDA tool might lie (among stakeholders like researchers, standards developers, software engineers, and component suppliers).

Trace behavior was selected as the focus for this phase, as it consistently emerged in the qualitative study as a critical concern spanning multiple domains of the framework. Specifically, trace behavior intersects with **electrical performance** (e.g., resistance stability, conductivity under strain), **mechanical reliability** (e.g., flexibility, fatigue resistance, and delamination), and

material-method compatibility (e.g., the interaction between trace type and substrate, and the suitability of traces for stitching, printing, or lamination). It also directly informs **design rules** related to **layout (identified through expert interviews as a critical intersectional circuit development element)**, such as spacing, routing paths, and insulation strategies. Experts emphasized the importance of trace behavior in shaping both electrical reliability and mechanical robustness, as well as in facilitating integration with other components. By focusing on trace variables, this phase demonstrates how a single design domain can yield actionable design rules through targeted characterization, and demonstrates the iterative, exploratory approach needed to identify influential variables to prioritize as inputs to rule models. The methodology and outcomes presented here offer a transferable model for future expansion into other domains, such as interconnects, insulation, or components.

6.1 Research Questions

To close the gap between high-level design decisions and their physical implementation, this characterization study is guided by the following research question:

RQ3: What variables, method characteristics, and relationships must be established to implement TCB design rules in practice?

To answer this research question, we sub-divided the research question into some sub research questions under different experiments as shown in Table 14.

6.2 Method

6.2.1 Experimental Setup

This study leveraged the fabrication method developed by Molla et al., in which a Brother BAS-342G pattern- stitching machine was used to stitch on woven textile substrates. The Brother BAS-342G stitching machine differs slightly from a full embroidery machine in that it produces a progressive stitch using a single needle that moves only on the Z-axis, perpendicular to the X and Y movements of the textile substrate. For this study, we used a woven fabric (100% cotton canvas) with varying thicknesses/fabric weights: 7oz (237.34 gsm), 10oz (339.1 gsm), and 12oz (406.92 gsm). Drawing inspiration from the study by Molla et al. (2020), which examined a singular thread type, we expanded our scope to encompass multiple conductive thread types, to demonstrate how design rules might depend on specific properties of different components, and to explore the information that component suppliers might need to contribute to component libraries to facilitate design rule checking. Our investigation included five threads in three common categories of conductive threads utilized in e-textile applications: silver-coated Vectran, silver-coated nylon, and stainless steel, Le et al. (2023); Berglund et al. (2015); DexMat (2020); Stanley et al. (2021)). The specific threads characterized were: silver-coated Vectran conductive thread (Syscom Liberator 40); 2-ply stainless steel thread (Adafruit); 3-ply stainless steel thread (Adafruit); 2-ply silver-coated nylon (Shieldex); and 4- ply silver-coated nylon (Shieldex).

Table 13– Conductive thread properties

Identifier	**Name**	**Manufacturer**	**Fiber**	**Metal**	**Coating**	**Thickness**	**Ply**	**Reported Resistance**
SS2	2 ply stainless steel thread	Adafruit	N/A	316L Stainless Steel	N/A	0.2mm	2	1.3 ohm/inch
SS3	3 ply stainless steel thread	Adafruit	N/A	316L Stainless Steel	N/A	0.25mm	3	0.83 ohm/inch
N2	117/17 2-ply HC+B	Shieldex	nylon	Silver	N/A	(not specified)	2	< 300 ohm/meter
N4	235/36 4-ply HC+B	Shieldex	nylon	Silver	N/A	(not specified)	4	40 ohm/meter
L40	Liberator 40	Syscom Advanced Materials	Vectran	Silver	Silver-coating	0.22mm	N/A	1 ohm/ft

The thread properties table (Table 13) showcases where the manufacturer's datasheets were incomplete or inconsistent. While some threads included details such as fiber content, ply number, thickness, or thread width, others lacked this critical information. For example, certain entries reported thread diameter but omitted ply count or thread pitch (TPI), while others provided fiber type but no dimensional data. This inconsistency reflects a broader lack of standardization in how thread manufacturers report product specifications. This complicates the selection and comparison process during design. Variability in manufacturers' approaches to characterization, likely also reflects lack of understanding of which parameters are needed by circuit designers. Highlighting this gap not only underscores the need for more uniform reporting but also sets the stage for identifying what additional parameters must be measured or estimated independently for reliable use in e-textile applications.

Each conductive thread type possesses distinct physical, mechanical, and electrical properties, influencing its behavior in stitching and fabrication processes. Our objective was to gain comprehensive insights into the interplay between thread characteristics, fabric properties, and thread cleaning. The variables considered under different experiment tests in this characterization study are listed in Table 14.

Table 14- Overview of experimental categories and parameters studied

S/N	Experiment	Independent Variables	Dependent Variables	Purpose	Research questions
1.	Pilot Test	Thread type, trace spacing, trace termination style	Short/no short & (qualitative observation)	Exploratory test to identify common failure modes, such as short circuits or excessive fraying	What are the key failure points, spacing concerns, and stitching behaviors observed during early prototyping of stitched conductive traces?
2.	Trace Spacing, Cleaning, and Termination Test	Trace spacing (0.5–10 mm), cleaning method (with/without), termination geometry (fanned-out, non-fanned-out), thread type	Short-circuit rate, resistance (Ω), minimum safe spacing	Determine safe spacing limits; assess how terminations and cleaning impact electrical isolation	How does trace spacing affect the likelihood of electrical shorts between stitched conductive traces? Does post-stitch cleaning (trimming and applying fray check) reduce short-circuit occurrence at narrow trace spacings? Do different conductive thread types exhibit different safe

S/N	Experiment	Independent Variables	Dependent Variables	Purpose	Research questions
					spacing thresholds under identical conditions?
3.	Trace Width and Fill Configuration Test	CAD-defined trace width, fill method (1-trace/2-stitch, 2-trace/4-stitch, 3-trace/6-stitch), thread type	Actual stitched width, variation from target width	Measure deviation between CAD design and stitched output to inform trace layout conversion rules	How accurately do stitched traces reproduce CAD-defined trace widths across different thread types and fill configurations? What is the deviation between designed and stitched trace width under different fabric thicknesses and fill densities?
4.	Electrical Resistance Measurement Test	Thread type, trace width	Resistance across 9 measurement point	Quantify resistance performance across configurations	How does conductive trace fill density affect electrical resistance across different fabrics and thread types? What are the resistance trends across conductive thread types

S/N	Experiment	Independent Variables	Dependent Variables	Purpose	Research questions
					and fabric thicknesses under controlled stitching conditions?

6.2 Pilot Test – Preliminary Exploration

To inform the development of grounded, rule-based guidelines for stitched circuit layout, a preliminary round of experimentation was conducted to investigate key performance variables. This pilot study aimed to evaluate whether conductive thread type, trace spacing, and termination configurations affect electrical outcomes such as resistance and short circuiting. These early insights addressed foundational aspects of RQ3 by exploring how specific component and fabrication characteristics might influence the practical implementation of design rules in TCBs.

This phase of experimentation focused on four representative conductive threads commonly used in e-textile development: silver-coated Vectran (L40), silver-coated nylon in 2-ply and 4-ply constructions (N2 and N4), and 3-ply stainless steel thread (SS3). These threads were selected due to their wide usage and their differing mechanical and electrical properties. The variables are described in Table 15.

Table 15 – Pilot test variables description

Variable Type	Parameter	Description / Levels
Independent	Thread type	N2, N4, SS3, L40
	Trace spacing	0.5 mm to 2.0 mm
	Termination type	No backstitch, N-backstitch, V-backstitch
Dependent	Short-circuit occurrence	Yes / No
	Resistance (Ω)	Measured across 9 points
	Observational notes	Fraying, thread tangling, stitch instability

Variable Type	Parameter	Description / Levels
Controlled	Fabric type	12 oz (406.92 gsm) cotton canvas
	Machine speed	500 rpm

To assess the relationship between trace spacing and short circuit risk, traces were stitched with spacing intervals ranging from 0.5 mm to 2.0 mm, in 0.25 mm increments. Each spacing configuration was repeated across three termination methods: no backstitch, a V-backstitch, and an N-backstitch. For each configuration, continuity testing was conducted using pointed probes attached to digital multimeters (AstroAI AM33D and Fluke 8846A). Testing was performed three times per configuration to ensure reliability and consistency.

6.2.1 Pilot Test Results

The results revealed a clear trend: narrow spacing (0.5–1.0 mm) often resulted in electrical shorts, regardless of the thread or termination method used. This was especially the case when backstitching was applied, where the added bulk and fraying increased the probability of contact between traces. Surprisingly, stainless steel (3-ply) thread shorts for all trace conditions, showing worst isolation performance than the rest of the threads in this pilot study. This behavior is what we would naturally expect from Vectran thread due to its relative stiffness and fraying, At 2.0 mm spacing, Nylon (4-ply), Nylon (2-ply), and Vectran threads with no backstitch avoided shorting reliably. Table 16 shows the frequency of short circuits across spacing interval and thread types. One means the presence of shorts and 0 means no short circuit.

Table 16 – Pilot test results

Trace Spacing	**Vectran**			**Nylon (4-ply)**			**Nylon (2-ply)**			**Stainless Steel (3-ply)**		
Termination Methods	none	N-back	V-back	none	N-back	V-back	none	N-back	V-back	none	N-back	V-back
2.00mm	0	1	1	0	1	1	0	0	0	1	1	1
1.50mm	1	1	1	1	1	1	0	1	1	1	1	1
1.25mm	1	1	1	1	1	1	0	1	1	1	1	1
1.00mm	1	1	1	1	1	1	0	1	1	1	1	1
0.75mm	1	1	1	1	1	1	1	1	1	1	1	1
0.50mm	1	1	1	1	1	1	1	1	1	1	1	1

This led to a key insight: **termination zones contribute significantly to shorting behavior**, and therefore, the spacing guidelines for terminations should be separated from those for mid-trace routing. Shorts were most prevalent near terminations, where thread overlaps and loose fiber ends created higher risk zones. The distinct electrical behavior of terminations recommended a secondary analysis focused specifically on the spatial geometry and fray spread of backstitched terminations. To explore how stitching affects conductivity, we compared the resistance values of stitched versus unstitched threads of identical lengths (101.6mm or 4 inches). Measurements were taken three times per sample and averaged. The stitched threads consistently exhibited increased resistance. For example, the 4-ply silver-coated nylon thread increased from 2.22 Ω (unstitched) to 4.55 Ω (stitched). Similarly, 2-ply nylon rose from 41.35 Ω to 47 Ω; 3-ply stainless steel from

5.75 Ω to 7.8 Ω; and Vectran from 0.3 Ω to 0.35 Ω. The increase in resistance highlights that mechanical and structural deformation introduced by the stitching process, such as bending, compression, and fray, alters the electrical characteristics of the material.

The observed changes in resistance across different thread types and fabrication configurations affirm the necessity of in-situ characterization for stitched conductive elements, rather than relying solely on datasheet specifications for raw threads. Datasheets typically reflect idealized measurements under controlled conditions and do not account for the impact of stitching parameters, substrate interaction, or post-processing. These findings raise an important question for future work: could a predictive model be developed that estimates resistance changes based on known fabrication parameters and thread selection? Such a model could enable designers to input their specific thread type, substrate, and fabrication process, such as stitch density, tension, or cleaning method, and receive an adjusted estimate of in-use resistance. This would support more accurate circuit planning in textile EDA tools, bridging the current gap between raw material specifications and performance in context-specific applications.

Further characterization focused on **backstitch geometries**, specifically measuring the lateral spread of the trace ends after stitching. Using calipers, we captured the minimum and maximum widths of each backstitch across multiple samples. Nylon 4-ply traces ranged from 0.83 mm to 5.18 mm, 2-ply nylon from 0.69 mm to 4.99 mm; Vectran from 1.09 mm to 3.87 mm; and stainless steel (3-ply) from 1.08 mm to 5.00 mm as shown in Table 17 . These ranges indicate that termination zones can occupy up to 5 mm of space, far exceeding the trace width itself. This suggests that spacing and routing strategies should treat backstitch regions as separate zones with enlarged safety margins.

Table 17 - Width variability of backstitch terminations (with fray)

Thread	**Backstitch Width (mm)**
Nylon 2-ply	0.69 – 4.99
Nylon 4-ply	0.83 – 5.18
Vectran	1.09 – 3.87
Stainless Steel 3-ply	1.08 – 5.00

This pilot study established critical thresholds for safe trace spacing, quantified the impact of stitching on the electrical resistance of conductive threads, and documented the spatial footprint of various termination configurations. Building on these initial insights, the following sections refine the experimental parameters and expand the characterization to include additional thread types, specifically 2-ply stainless steel thread. In this subsequent phase, measurements were repeated systematically to ensure reproducibility and improve the robustness of the data.

6.3 Trace Spacing, Cleaning and Termination Test

Building on the insights gained from our pilot experimentation, this phase continued our efforts to define the rules for spacing traces stitched with different thread types. Specifically, we focused on key variables emerging from the pilot test, characterizing how post-processing and termination strategies influence the electrical integrity of stitched conductive traces. While the initial trials yielded valuable observations on trace spacing and backstitch geometry, many of the recorded electrical shorts were traced back not to the conductive paths themselves but to contacts at the trace terminations. Termination zones, which often coincide with interconnect points for component connections, are widely recognized in the literature (e.g., Poupyrev et al. (2016)) and from our interviews with experts, are viewed as critical failure points in e-textile circuits.

To design reliable circuits, it was first necessary to develop and refine the underlying techniques for constructing stitched conductive pathways, particularly in relation to spacing limits and trace terminations. Rather than defining design rules outright, this phase focused on technique development in parallel with characterization toward design rules, acknowledging that the immaturity of current methods presents a major challenge to EDA for TCBs, as discussed earlier in the dissertation. We needed to establish a baseline understanding of how variables such as trace spacing and termination behavior interact under real fabrication conditions. A key part of this involved exploring how post-processing decisions, especially the cleaning or treatment of trace ends, impact performance. In this context, post-processing serves to control issues like fraying or thread tangling, which can inadvertently expand the conductive area and increase the risk of short circuiting. These foundational investigations were essential precursors to being able to reliably measure relationships and, ultimately, inform the development of future design rules.

Fraying in conductive traces typically results from a combination of thread properties (such as fiber twist and staple length), mechanical abrasion, excessive stitching tension, or regular handling and wear. Within lockstitch structures, the stiffness imbalance between conductive and non-conductive threads also leads to tangling at the termination zones. These tangles contribute to an effective widening of the conductive area and significantly impact the required minimum trace spacing. Examples of such fraying and tangling at terminations are illustrated in Figure 40.

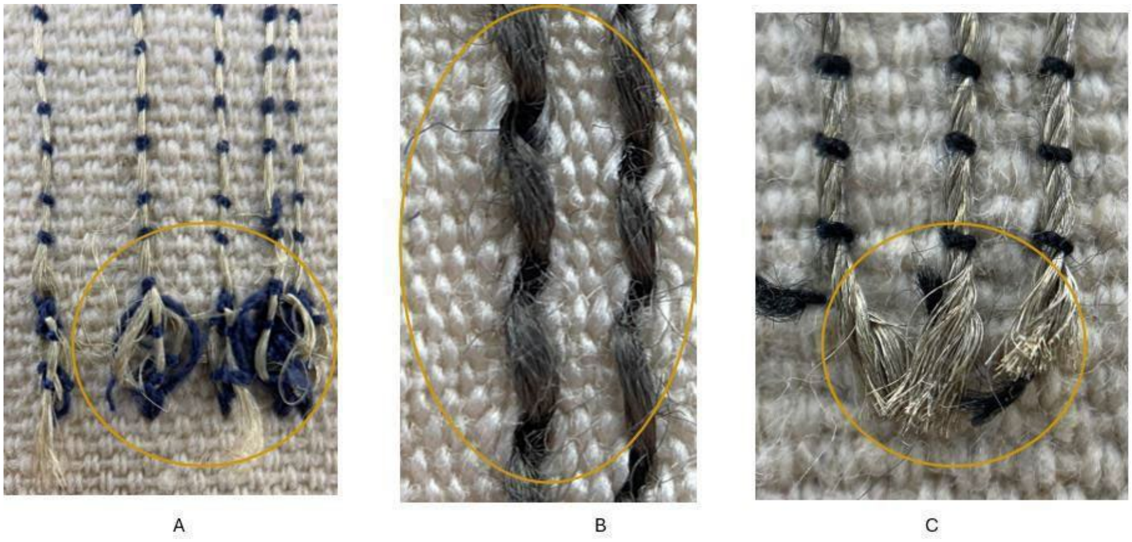


Figure 40 - Different types of shorts caused by: (A) tangle in the lockstitch termination, (B) fray along the trace due to fiber protrusion from the twist, (C) fraying at the cut end (Images were magnified 30x to provide a detailed view)

While fraying along the length of a stitched trace is mainly determined by the thread type, the geometry of the backstitch and whether the thread ends are trimmed influence fraying at the terminations. Trimming, although useful for removing excess thread and reducing tangles, can cause the thread to untwist and expand. To minimize this effect, we applied a Dritz® fray check solution to trimmed terminations, effectively sealing the ends and reducing post-trim splay.

To systematically assess these effects, we divided our experimental configurations into two main categories: (1) with post-processing cleaning, and (2) without post-processing cleaning. Within the "with-cleaning" group, we introduced two layout styles: "fanned-out ends" and "no fanned-out ends." Fanned-out ends used a trace layout with wider spacing at the terminations than along the trace body, rather than the simple straight traces in the "no fanned-out ends" group, allowing us to isolate and assess the effect of termination behavior without confounding it with the trace spacing itself. This layout mirrors common practices in interposer design, where spreading out connections at endpoints is used to reduce the likelihood of shorts and to manage space constraints at interfaces. These variations are represented in Figure 41 below and the variables are described in Table 18.

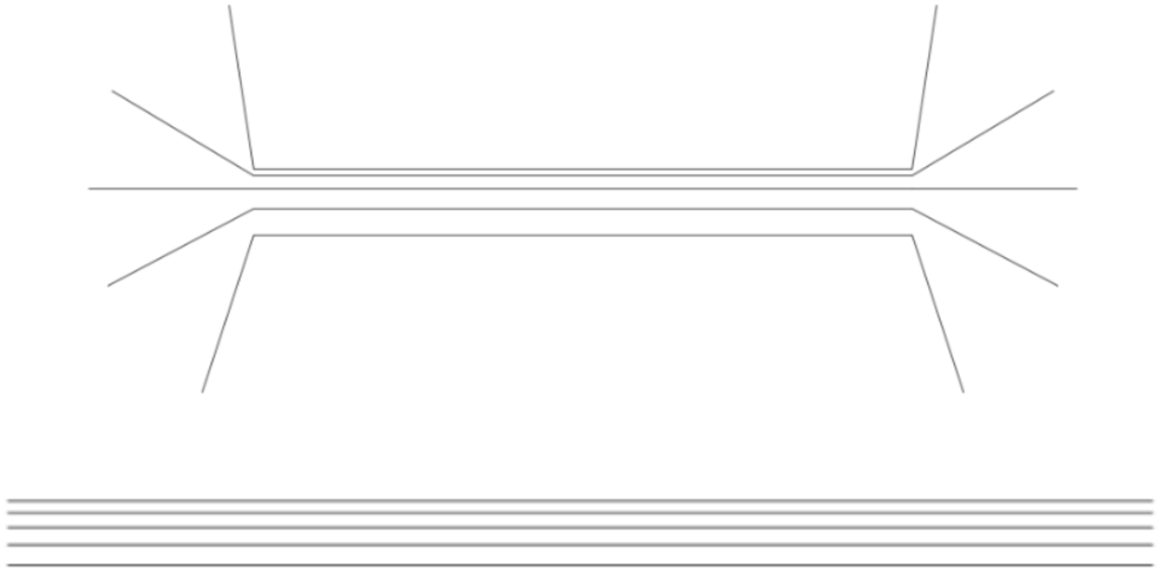


Figure 41 - Schematic showing fanned vs. non-fanned terminations

Table 18 – Trace spacing, cleaning and termination test variables description

Variable Type	**Parameter**	**Description / Levels**
Independent	Post-processing cleaning	Yes (with cleaning: includes fanned-out and no fanned-out ends) / No (no cleaning)
	Termination geometry *(only within cleaning)*	Fanned-out ends / No fanned-out ends
	Thread type	N2, N4, SS2, SS3, L40
	Trace spacing	0.5 mm – 2 mm (with cleaning), 2 mm – 10 mm (no cleaning)
Dependent	Short circuit rate (%)	% of stitched samples per configuration that exhibited shorts
	Minimum achievable spacing	Spacing at which no shorts occur
Controlled	Stitching machine	CNC (Brother BAS-342G)
	Stitch length / design	Standard straight trace length (101.6mm)
	Fabric type	10 oz cotton canvas
	Termination type	No backstitch (used consistently across this test)

6.3.1 Trace Spacing, Cleaning and Termination Results

Each trace spacing condition was evaluated across a range of conductive threads, stitch geometries, and termination strategies. Under the "with post-processing cleaning" condition, we performed six independent trials per trace spacing for each of the five thread types, covering trace spacings from 0.5 mm to 2.0 mm. Under the "without post-processing cleaning" condition, we extended the tested spacing range to 2.0 mm–10.0 mm, where fewer short circuits were expected based on pilot data. For this phase, we eliminated both the “V-backstitch” and “N-backstitch” configurations, focusing solely on “no-backstitch” terminations for consistency and to avoid introducing additional termination-induced variation.

Electrical shorts were assessed using digital continuity tests with pointed probe attachments on AstroAI AM33D and Fluke 8846A multimeters. Measurements were taken meticulously, with each trace tested at multiple points across its length and at terminations. The percentage of shorts per configuration was then calculated to quantify the reliability of each setup (Figure 42).

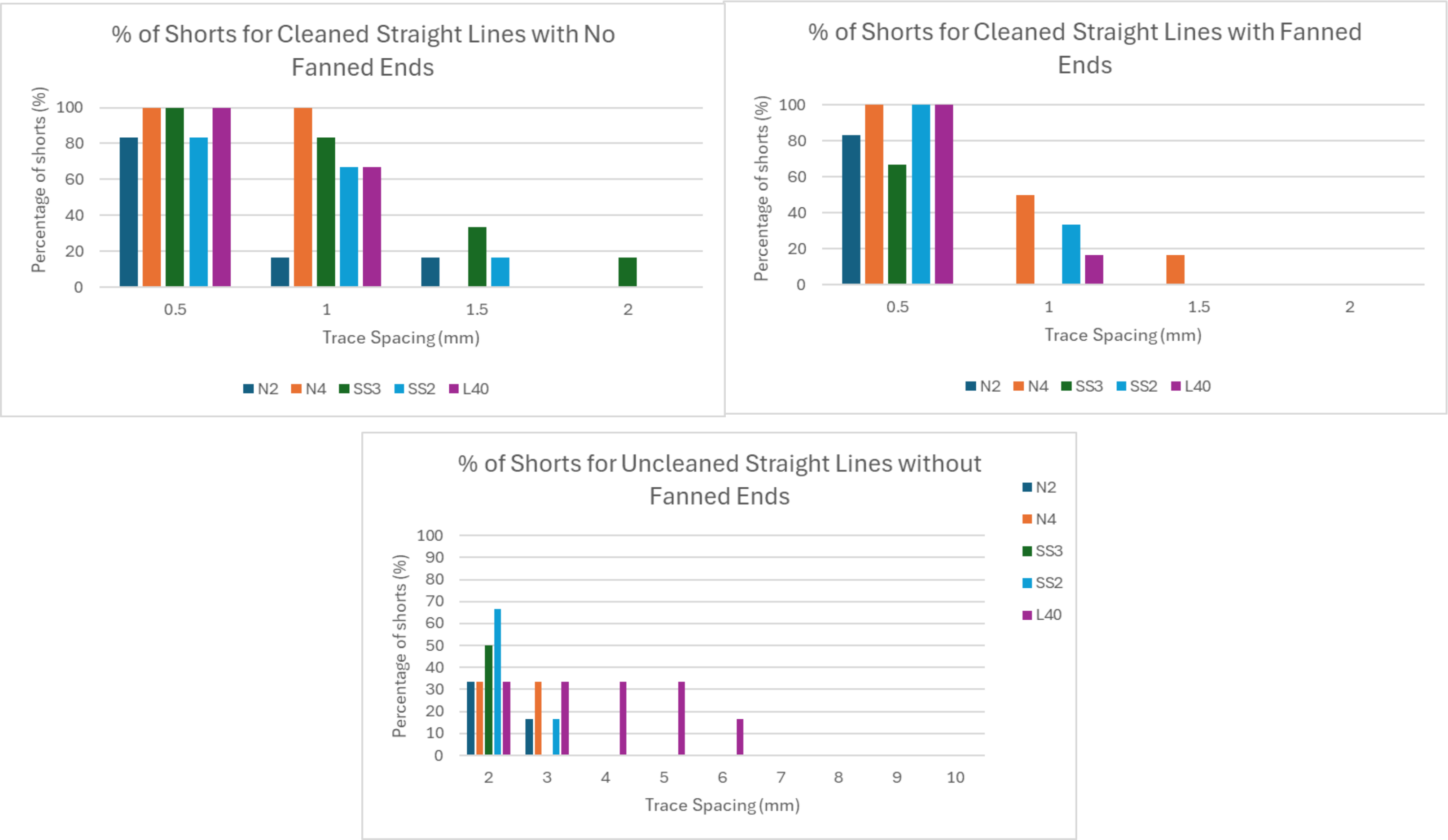


Figure 42 - Bar charts showing percentage of shorts for all three trace conditions

As the trace spacing decreases, the percentage of shorts increases. Configurations with larger trace spacing (2.00mm) have a lower likelihood of shorts (16.67%) if the termination ends are trimmed and cleaned. Conversely, configurations with smaller trace spacing

(0.50mm) have a higher likelihood of shorts (>60%), even with the post- processing cleaning. As expected, larger trace spacing provides a more reliable stitching configuration for short-circuit prevention, but cleaning is helpful in reducing that minimum spacing distance. It is also important to note that some instances of shorting were not caused by the physical proximity of the stitched traces themselves, but rather by interference from microscopic protruding frays along the threads, even after post-stitch cleaning. These fine, often invisible fibers can extend beyond the visible boundary of the trace and establish unintended electrical contact, highlighting the need for additional spacing or insulation to mitigate the effects of thread hairiness.In cases where a post-processing cleaning method is not feasible which we suggest might be true for most industrial manufacturing of electronic textiles, a minimum spacing of 4mm would be ideal to avoid shorts across most of the thread types we tested. In our experiment, only the Vectran (Liberator 40) conductive thread had a minimum spacing of 7mm to avoid shorts. This is because the Vectran (Liberator 40) thread is very stiff, which frequently led to the lateral deformation of stitches, thereby increasing the functional width of the stitched trace. In cases where deformation can't be mitigated through post-processing cleaning, the L40 thread needed the minimum spacing to be extended to 7mm rather than 4mm, as seen with the other conductive threads.

When termination end effects are not eliminated by fanning out the ends, but terminations are post-processed to minimize shorts, the minimum spacing is reduced considerably. For N4 and L40 threads, minimum spacing with post-processing was reduced to 1.5mm; for SS2 and N2, to 2mm; for SS3, to 2.5mm. These spacing requirements are illustrated in Figure 42 above. An EDA system might allow users to account for these more expensive treatment steps in selecting manufacturing parameters, in order to achieve a denser board layout.

The fanned-out ends condition allowed us to investigate minimum spacings without the effects of the terminations. Minimum spacings for the stitched traces themselves were 1mm for SS3 and N2; 1.5mm for L40 and SS2; and 2mm for N4. These might serve as functional trace spacing limits for parts of the circuit outside of the termination ends. Importantly, these spacings are considerably larger than the diameters of the threads themselves, reflecting the effect of thread “hairiness” in addition to stitch deformation.

RQ2a:

How does trace spacing affect the likelihood of electrical shorts between stitched conductive traces?

As trace spacing decreases, the likelihood of electrical shorts between stitched conductive traces increased across all tested thread types. In all test conditions (with and without cleaning, fanned vs. unfanned ends), higher short rates were consistently observed at smaller spacings, particularly at or below 2 mm. At ≥ 6–10 mm spacing, all thread types exhibited 0% shorting, indicating this range is generally safe. L40 showed early failure beginning at 6 mm, while most others remained short-free until 3 mm or below. At 2 mm, all thread types exhibited shorting, with rates as high as 100%, confirming that narrow spacing is a critical risk factor regardless of thread type or stitching geometry. This trend underscores that trace spacing is a primary determinant of short-circuit risk and must be tuned based on the electrical insulation performance of each thread.

RQ2b:

Does post-stitch cleaning (e.g., trimming and applying fray check) reduce short-circuit occurrence at narrow trace spacings?

Yes, post-stitch cleaning significantly reduces the occurrence of shorts, especially at narrow spacings (1–2 mm). First, comparing results from "cleaned straight stitch, no fanned ends" vs. "cleaned straight stitch, fanned ends”, several thread types showed marked improvements: SS3 had an 83% short rate at 1.0 mm with no fanned ends but 0% when fanned. N2 also dropped from 16.7% (unfanned) to 0% (fanned). Now, comparing cleaned with uncleaned at 2mm which is common to both groups, there was no short rate for cleaned traces except SS3 (at 16.67%) while short rate happened for all threads at 2mm for uncleaned conditions. Even L40, which performed poorly without cleaning, showed reduced short rates for cleaned conditions (66.7% → 16.7% at 1.0 mm from no fanned ends to fanned ends). However, some threads like N4 and SS2 still experienced moderate shorting at 1.0 mm even after cleaning, suggesting cleaning mitigates, but does not eliminate, shorting risks at tight spacings. These results demonstrate that cleaning is an impactful post-processing step, particularly when dense circuit layouts are required, but should be combined with sufficient spacing and thread-specific design rules for optimal reliability.

RQ2c:

Do different conductive thread types exhibit different safe spacing thresholds under identical conditions?

Yes, different conductive thread types exhibit different safe spacing thresholds under identical conditions. For a straight stitch without fanned ends, N4 and L40 showed no shorting even at 1.5 mm spacing, suggesting a safe threshold at or above this spacing. SS3 had shorting at 2.0 mm and increasingly higher short rates at narrower spacings, suggesting that it requires larger spacing for reliability. N2 performed similarly to SS2, but slightly better than SS3. This indicates that thread structure and construction (e.g., coating, ply, twist) influence safe trace spacing, and therefore spacing guidelines should be thread specific.

Fanned end geometry improves trace isolation for certain conductive threads at intermediate spacings (e.g., 1.0–1.5 mm). Threads like SS3 and N2 showed a complete elimination of shorts at 1.0 mm when fanned ends were used. However, the effect is thread-dependent; some threads (e.g., N4, SS2) still exhibited moderate shorting even with fanned ends. All threads shorted at 0.5 mm, indicating that fanned geometry alone is not sufficient to ensure electrical isolation below 1.0 mm spacing.

When no cleaning was performed, threads behave more reliably at wider spacings (≥ 6 mm). All threads were safe down to 7 mm, with L40 showing the earliest failures at 6 mm. At 3 mm, multiple threads began to short intermittently, and by 2 mm, all threads show significant risk of shorting. SS3 was the most resilient, with a 0% short rate at 3 mm and 50% at 2 mm. L40 was the most failure-prone, beginning to short at 6 mm and maintaining a 33% rate down to 2 mm. This suggests that thread-specific spacing recommendations may need to account for post-process cleaning.

These findings from our pilot study and trace termination test offer critical inputs for the development of rule-based stitched circuit layout models, particularly those aimed at enabling automated layout generation in textile EDA tools. The results make clear that safe and functional stitched circuit design is not determined solely by the characteristics of the selected conductive thread (including diameter, twist, and fiber content), but also by the geometry of the stitching, the method of termination, and the mechanical behavior of threads under deformation. Importantly, terminations in stitched circuits can take various forms: they may simply mark the end of a trace, such as when preparing for a seam crossing or connector interface, or they may serve as functional "lands" for interfacing with a component pin, sensor, or connector. In either case, the layout must explicitly account for the geometry and behavior of the termination area. This highlights the need for termination-specific design rules, where a stitched connection must not simply end arbitrarily, but be defined in terms of its function and physical footprint. Eventually, such termination types and their associated constraints could be formalized in a component library, allowing stitched layout tools to match stitching processes with component requirements (e.g., pin spacing, land area, or orientation). This would move stitched textile circuit design closer to the structured, rule-driven workflows seen in traditional PCB design.

6.4 Trace Width and Fill Configuration Test.

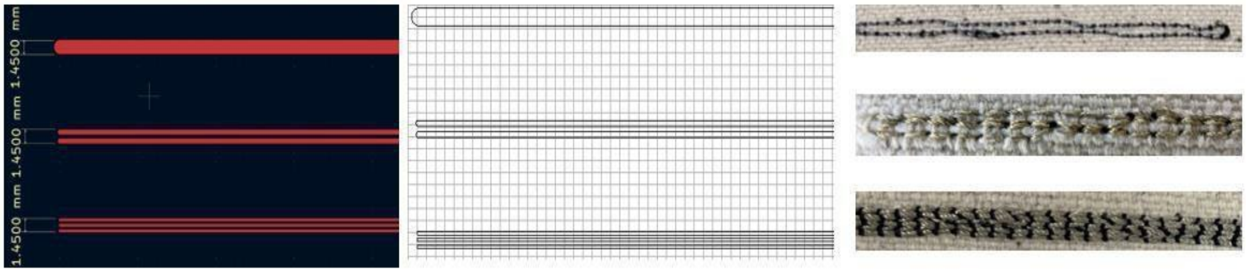
For the trace width experiment, we delved into the intricacies of trace width variations, aiming to check the disparities between the trace widths intended in CAD software and their actual dimensions post-stitching. To accomplish this, we used the same five conductive threads and subjected them to testing across three fabric thicknesses/weights: 7oz, 10oz, and 12oz. The traces we designed in CAD software were specified to have a width of 1.46mm and a length of 74.98mm. We initially designed the traces in KiCAD, an open-source engineering CAD software known for its prowess in designing electronic circuit schematics and their conversion into PCBs. Subsequently, we exported the DXF file of the stitched trace and imported it into the PS300B Brother stitching software for the stitching process. Using this stitching layout, we stitched the five types of conductive thread onto fabric samples of varying thicknesses, with each trace sample configuration replicated three times. To assess the resulting widths, we measured the width of each stitched trace at three specific positions: left, middle, and right, utilizing the Westward digital measurement caliper. These measurements were then averaged to derive a representative value for each trace width.

Table 19 – Trace width and fill configuration test variables description

Variable Type	Parameter	Description / Levels
Independent	Trace-fill configuration	1-trace/2-stitch, 2-trace/4-stitch, 3-trace/6-stitch
	Cad trace width	1.46 mm
	Thread type	N2, N4, SS2, SS3, L40
	Fabric thickness	7 oz, 10 oz, 12 oz cotton canvas
Dependent	Stitched trace width (mm)	Measured width of stitched region per configuration
	Fill deviation (%)	Difference between stitched trace width and original CAD trace
Controlled	Stitch speed	Held constant (500 rpm)
	Stitching machine	CNC embroidery machine (Brother BAS-342G)
	Needle size	Standardized for all trials

Trace samples were organized into three configurations: 3-trace/6-stitch; 2-trace/4-stitch; and 1-trace/2-stitch, as shown in Figure 43 below. These naming conventions arise from how KiCAD exports traces as boundary outlines rather than filled areas. When imported into the PS300B embroidery software, each boundary is interpreted as a separate stitching path, so each trace is stitched as two lines (its left and right edges). For example, a "3-trace/6-stitch" configuration means that KiCAD defined three traces, and PS300B stitched both edges of each, resulting in six stitched lines. Each configuration occupies the same total width of 1.46 mm. In the 1-trace/2-stitch setup, a single full-width trace spans the entire width. In the 2-trace/4-stitch setup, two narrower traces share the width. In the 3-trace/6-stitch setup, three even narrower traces are packed into that same width.

Testing these configurations is essential to determine how many stitched traces can be accurately fit into a fixed width when translating from CAD to machine embroidery. For example, in the 3-trace/6-stitch configuration, more stitched lines are packed into the same 1.46 mm width, and this increases the likelihood of overlapping stitches. On the other hand, configurations with fewer traces, like the 1-trace/2-stitch layout, show that even minimal stitch counts can vary depending on the available width. These tests help define the practical design boundaries for e-textile CAD layouts, ensuring that stitched outputs remain precise and manufacturable. The variables are described in Table 19.



KiCAD PS300B Actual Stitched Traces

Figure 43 - Image showing trace samples in three configurations: 1-trace/2-stitch, 2-trace/4-stitch, and 3-trace/6-stitch in KiCAD, PS300B, and actual stitch layout

6.4.1 Trace Width and Fill Configuration Result

Figure 44 - Bar charts showing results for trace width and fill configurations across thread types and fabric thicknesses/weights

RQ3a:

How accurately do stitched traces reproduce CAD-defined trace widths across different thread types and fill configurations?

As shown in Figure 44 above, stitched traces consistently deviated from the CAD-defined width of 1.46 mm, with the degree of overfill, meaning that there is a wider trace, depending on both thread type and fill configuration. Across all configurations tested (1T2S, 2T4S, 3T6S), measured trace widths were always larger than the intended CAD width, confirming that stitching inherently overbuilds the intended geometry. The extent of this deviation varied with fill density: lighter fill configurations such as 1T2S had the smallest standard deviations, typically ranging from +0.17 to +0.27 mm, denser configurations like 2T4S resulted in larger deviations from +0.24 to +0.50 mm, and 3T6S, from +0.15 to +0.27 mm.

Thread type further influenced the degree of expansion. Threads such as N4 and SS3 (higher ply number) consistently produced wider traces, whereas N2, SS2, and L40 yielded comparatively narrower traces, though still exceeding the original CAD width. Importantly, neither fill configuration nor thread type alone fully explains the deviation in trace width; rather, it is their interaction that determines the final stitched trace dimensions. These findings have important implications for layout planning in densely routed e-textile circuits, where small variations in trace geometry could lead to spacing violations or shorts if not accounted for in the design phase.

RQ3b:

What is the deviation between designed and stitched trace width under different fabric thicknesses and fill densities?

Higher fill densities (2T4S and 3T6S) generally produced greater deviations (wider stitched traces), especially on thinner fabrics, e.g., N4 at 2T4S_7oz & 3T6S_7oz = +1.61 mm (resulting in 3.0 mm actual width), SS3 at 2T4S_7oz = +1.88mm (resulting in 3.33 mm actual width). Lower fill densities (1T2S) resulted in smaller deviations, closer to the intended 1.46 mm and were relatively consistent across thicknesses. Deviation values here are typically between +0.5 mm and +1 mm. Fabric thickness played a small moderating role, e.g., for 3T6S, increasing thickness (from 7 to 12 oz) tended to reduce deviation slightly. Also, thread type mattered: N4 consistently produced higher deviations across all fill configurations and thicknesses. SS2 and L40 were more stable, with moderate and consistent deviations.

6.5 Electrical Resistance Experiment.

This test measured the electrical resistance of stitched conductive traces to evaluate how thread type, trace configuration, and fabric thicknesses influenced conductivity. It was conducted to establish resistance readings changes for stitched e-textiles and to identify factors affecting electrical reliability in textile circuits. Variables are described in Table 20.

Table 20 – Electrical resistance test variables description

Variable Type	**Parameter**	**Description / Levels**
Independent	Trace fill configuration	1-trace/2-stitch, 2-trace/4-stitch, 3-trace/6-stitch
	Thread type	N2, N4, SS2, SS3, L40
	Cad trace width	1.46mm
	Fabric thickness	7 oz, 10 oz, 12 oz cotton canvas

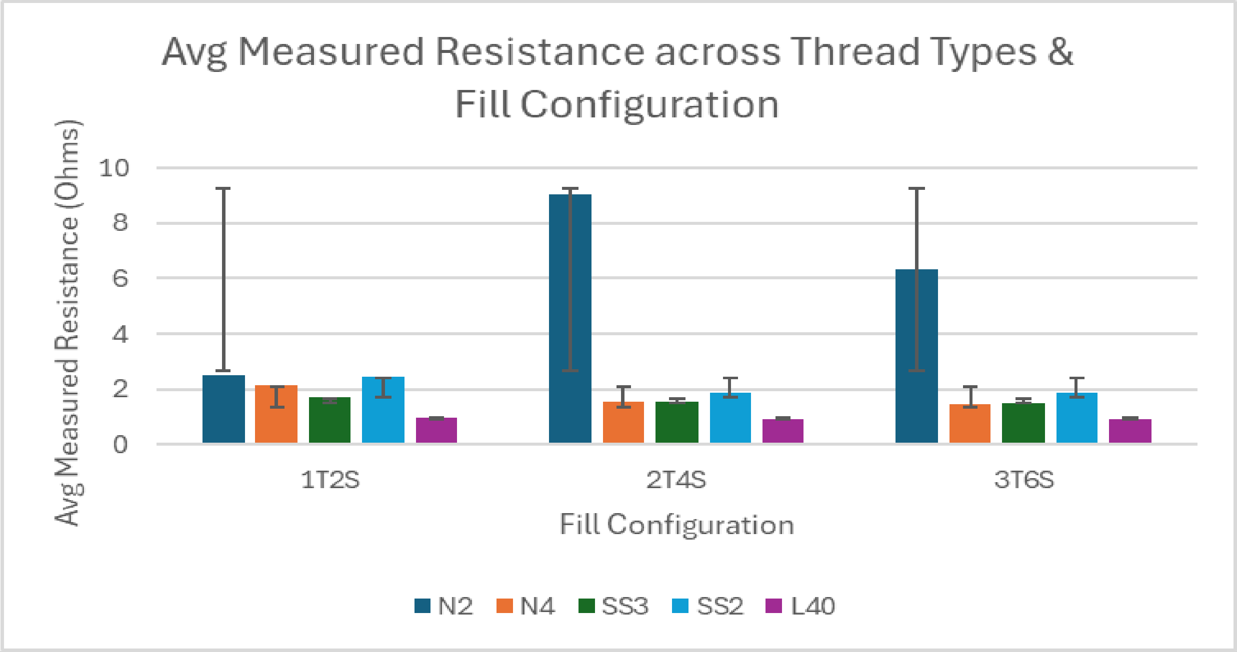
Variable Type	**Parameter**	**Description / Levels**
Dependent	Electrical resistance (ω)	Measured using Fluke 8846A digital precision multimeter
	Resistance stability	Variation across repeated measures (3 repeats × 3 positions)
Controlled	Measurement device	Fluke 8846A with alligator-teeth probes
	Stitching configuration	Same as for trace width test; machine-stitched CNC layout
	Measurement protocol	Nine readings per condition (3 reps × 3 fabric zones)

Maintaining the same setup for the trace width measurement, electrical resistance measurements were necessary to assess the conductivity of various stitched trace width configurations. We utilized a tabletop Fluke 8846A digital precision multimeter to ensure precision in our readings. To establish reliable contact with the traces, we employed "alligator-clip" probes. For each round of measurements, we evaluated each combination of stitched trace width and fabric thickness three times, resulting in nine readings for each combination of trace width, thread type, and fabric thickness. Repeated measurements were essential because electrical resistance readings can be sensitive and prone to fluctuations, especially when dealing with conductive threads. We obtained a comprehensive dataset comprising 405 electrical resistance readings using this protocol. This dataset provided a robust foundation for our analysis, allowing us to assess the conductivity behavior of stitched traces. By averaging the electrical resistance values and plotting the data, we aimed to identify any discernible trends or disparities across different combinations of conductive trace width, thread types, and fabric thicknesses.

It is crucial to highlight that the method of measuring electrical resistances can significantly impact the accuracy of the readings, particularly when using probes. We observed that the readings tended to be erratic and inaccurate when the alligator teeth probes were pressed against the fabric instead of clipped directly onto the stitched conductive traces. To address this issue, we adjusted our approach by placing the alligator probes at the sides of the stitched traces during resistance measurements. This adjustment was feasible since we were measuring the electrical resistance for multiple traces, allowing us to obtain more reliable readings. However, a different method may be necessary for accurately measuring the electrical resistance of a singular stitched trace. Further, this measurement challenge is also a factor that will affect quality test methods for e-textile manufacturing.

It's important to acknowledge a significant limitation in electrical resistance characterization, which is the effect of chemical changes like oxidation on the resistance of silver-coated threads over time. Over time, reactions with air and moisture can cause an increase in the resistance of these threads, impacting the accuracy of resistance measurements. To mitigate this issue in our experiment, we took proactive measures by using new batches of all threads to fabricate test samples. This ensured that we weren't testing older, more exposed threads, thereby minimizing the potential impact of aging effects on resistance measurements during our investigation. However, it's essential to recognize that aging remains a factor that can contribute to increased resistance in the future. Despite our efforts to control for this variable, researchers and practitioners in e-textile manufacturing must consider the long-term effects of aging on the performance of conductive threads. This awareness can inform strategies for circuit design that account for the reliability and durability of e-textiles over extended periods.

6.5.1 Electrical Resistance Results



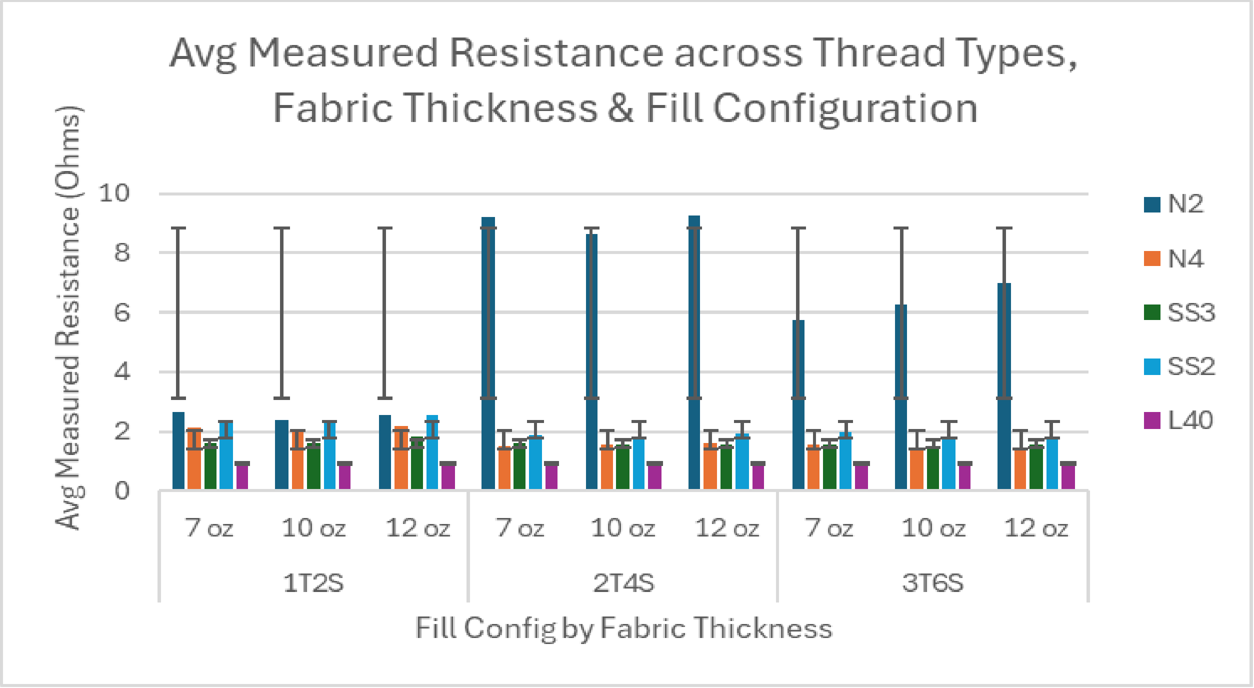


Figure 45 - Bar charts showing results for electrical resistances across thread types and fabric thicknesses

RQ4a:

How does conductive trace fill density affect electrical resistance across different fabrics and thread types?

As shown in Figure 45 above, as the fill density increased (from 1T2S to 2T4S to 3T6S), resistance generally decreases across most thread types and fabric thicknesses, particularly for N4, SS3, SS2, and L40. The N2 thread is the exception here. While one might expect resistance to drop with denser fill, N2 actually showed an *increase* in resistance at higher fill densities (e.g., jumps from ~2.5 Ω at 1T2S to ~9 Ω at 2T4S and 3T6S). This suggests that too much fill with N2 may cause overlapping or structural issues, leading to higher resistance. SS3, SS2, and L40 all showed consistent *resistance reduction* with increased fill density. For example: SS3 at 10 oz dropped from 1.59 Ω for the 1-trace/2-stitch configuration to 1.57 Ω for the 2-trace/4-stitch configuration, to 1.44 Ω for the 3-trace/6-stitch configuration. Similarly, L40 at 10 oz dropped from 0.95 Ω to 0.92 Ω to 0.89 Ω for the same three configurations.

Higher trace fill density improves conductivity only if the thread and fabric combination supports it structurally. This improvement is due to more conductive material being laid down, resulting in broader conductive pathways and lower resistance, but only if the thread maintains good contact and spacing.

RQ4b:

What are the resistance trends across conductive thread types and fabric thicknesses under controlled stitching conditions?

Across the tested conditions, **thread type** emerged as the most significant determinant of electrical resistance. **L40** consistently demonstrated the lowest resistance, typically below 1 Ω, indicating excellent conductivity and stability across all fill densities and fabric thicknesses. In contrast, **N2** exhibited the highest resistance overall, with values increasing substantially at higher fill densities. This suggests that N2 may be poorly suited for dense stitching applications where low resistance is essential. **SS3** and **SS2** fell in the mid-range but showed reliable and consistent performance, making them strong candidates for general-purpose use. While the resistance results for **N4** more variable, it performed well under high fill conditions (e.g., 2T4S and 3T6S), delivering low resistance and demonstrating potential for applications that require dense, conductive trace layouts.

While **thread type and fill density** were the strongest influencers of resistance, **fabric thickness** had a more modest impact. Nonetheless, optimal performance depends on the interplay of all three variables. Some combinations, such as **N2 with high fill density**, produced less predictable results, reinforcing the need to evaluate thread–fill–fabric combinations holistically when designing stitched e-textile circuits.

6.6 Design Rules Translation

Ideally, design rules for minimum trace spacing would be structured as relational models rather than fixed thresholds, enabling greater flexibility and integration within an EDA framework. Specifically, the **Minimum Trace Spacing (MTS)** can be defined as:

$MTS=D+T_1+T_2+T_3+T_4$

where:

- **D** is the designed CAD layout spacing (the nominal distance planned between traces),
- **T_1** is the thread diameter tolerance (average stitched thread diameter – CAD trace width),
- **T_2** is the straightness tolerance (how woggle the stitched traces are),
- **T_3** is the hairiness tolerance, and
- **T_4** is the end-splay tolerance.

Each tolerance term is derived from measured or estimated thread behaviors and Figure 46 illustrates pictorially what these tolerances mean in a stitched trace:

- **T_1** depends on the nominal thread diameter and the ply tightness or looseness of the thread.
- **T_2** accounts for straightness of the stitched trace, which varies significantly depending on whether the weave structure of base fabric and thread type.
- **T_3** accounts for protruding fibers (hairiness), which varies significantly depending on whether post-processing such as trimming or fray-checking is applied.
- **T_4** reflects how much the thread tends to splay at terminations, which depends on the termination style.

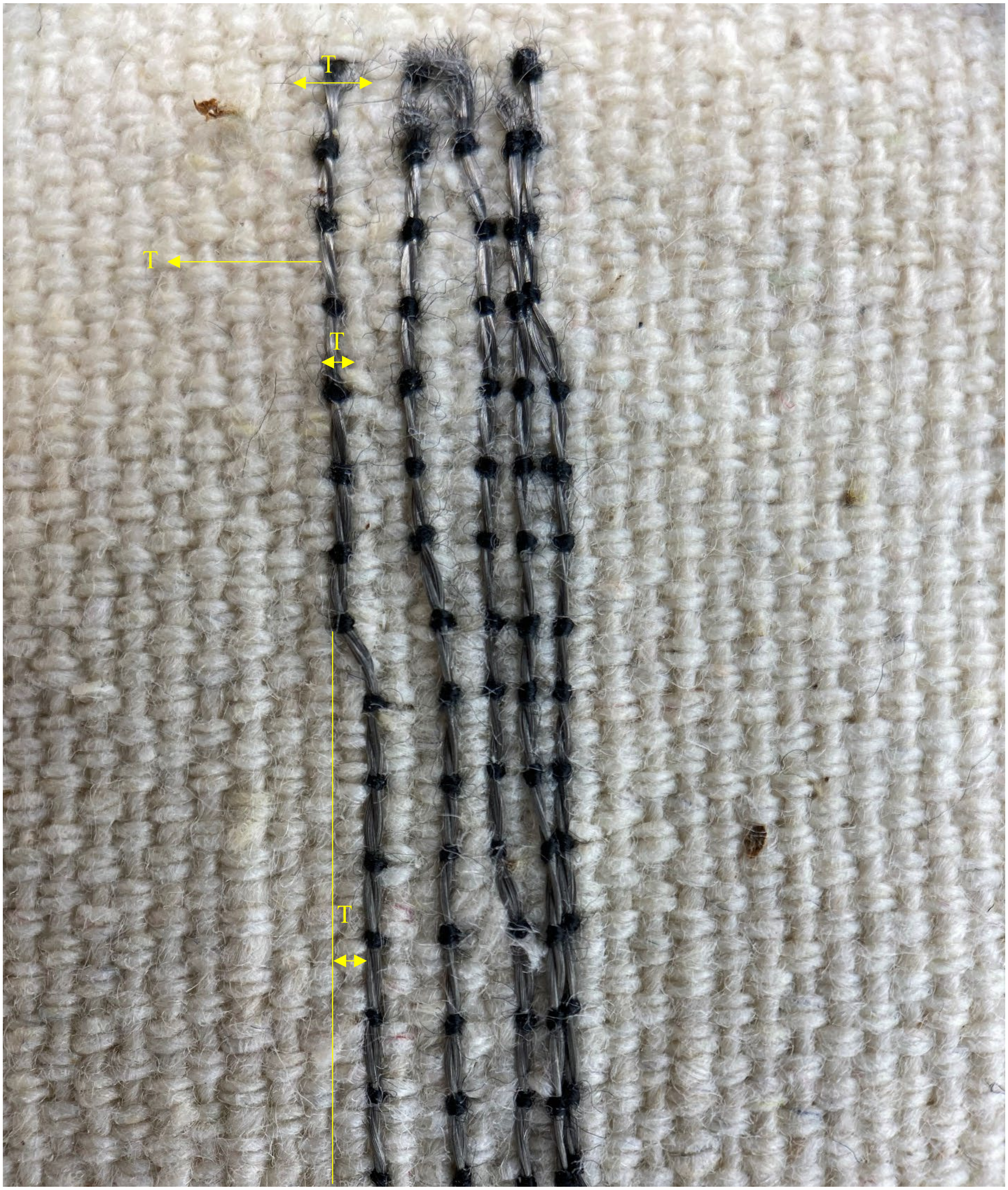


Figure 46 - Image illustrating the model-defined tolerances on a stitched trace at 10× magnification

The tolerance variables might be applied or removed depending on material choices and circuit characteristics. For example, hairiness tolerance may not be necessary for insulated threads, and the end-splay tolerance may not be necessary for interior portions of traces (away from ends). Applying this model to different thread types (N2, N4, SS2, SS3, L40) demonstrates how their unique physical and processing characteristics influence spacing requirements. This parameterized, relational approach transforms static spacing rules into a scalable framework that incorporates fabrication variability, an essential consideration for developing robust, automated stitched circuit design tools.

This model enables designers to calculate minimum trace spacing dynamically based on thread properties and processing conditions, facilitating more accurate and reliable e-textile circuit layouts.

A key open question is the modeling and reporting of hairiness. As seen from the manufacturer-reported information in Table 13, thread manufacturers report diameter (or “thickness”) in a variety of ways. More effective datasheets might report nominal diameter in addition to a hairiness tolerance or might report diameter as the minimum area beyond which the thread can be expected to be electrically isolated, i.e., thread diameter plus hairiness tolerance. If hairiness is a tolerance added to diameter (as shown here), relationships between reported diameter and the hairiness tolerance might be established such that a usable hairiness tolerance could be estimated for threads based on their nominal diameter and, perhaps, factors such as twist or fiber content. A standard for measuring and reporting thread diameters would help considerably in this area and the process of developing the standard might engage all of the stakeholders discussed here: manufacturers, circuit designers, EDA developers.

6.7 Insights from the Modeling Approach

The modeling approach presented in this chapter provides critical insights into which variables most significantly influence trace spacing, and by extension, which ones merit priority in future rule-based design systems and data reporting conventions. Among the variables studied, **cleaning status** emerged as the single most impactful factor affecting minimum trace spacing. Cleaning directly affects both T_3 (hairiness tolerance) and T_4 (end splay tolerance), which together represent the "invisible" margins around a stitched trace where shorts are most likely to occur. Empirical data demonstrated that with post-processing (e.g., trimming, fray-checking), $T_3 + T_4$ can be reduced. In contrast, without cleaning, this same margin can increase significantly. This magnitude of change directly accounts for the observed increase in minimum spacing, from roughly 2 mm to as high as 7 mm in uncleaned L40 traces. These findings point to a critical opportunity: a model for minimum spacing could be dynamically adjusted based on whether or not a cleaning step was performed, effectively “unlocking” tighter layouts for threads that respond well to post-processing.

Another highly influential factor is **thread type**, which impacts mostly three tolerance terms: T_1 (diameter), T_3 (hairiness), and T_4 (end splay). Threads such as N4 and L40 consistently showed larger diameters and greater variation in trace width, both from protruding fibers and from end deformation. These characteristics suggest that such threads inherently require larger spacing buffers. On the other hand, threads like SS3 and N2 exhibited tighter structures and more consistent geometry, even in the absence of cleaning. These thread-level differences confirmed that thread type can, and should, be built into future spacing models. A thread’s ply count, structural tightness, material composition, and surface treatment all influence the base diameter and its associated tolerances. Modeling these characteristics accurately would enable material-aware trace design and allow users to predict fabrication behavior from a standard datasheet or thread database entry.

By contrast, **fabric thickness** had a relatively minor impact on the trace width and spacing tolerances. Comparing 7 oz and 12 oz substrates revealed only slight differences in how stitches floated or compressed on the surface. While these differences were not negligible, particularly when spacing margins were extremely tight, they generally remained sub-millimeter and secondary to the more dominant effects of thread type and cleaning status. This suggests that while fabric thickness should be documented and considered, it may not need to be a primary driver in trace spacing models unless paired with specific stitching conditions or mechanical stress considerations.

Together, these findings emphasize a core methodological insight: **the purpose of modeling here is not to finalize universal rules, but to identify which variables matter most and where design efforts should be focused.** The space of potential variables, thread composition, stitch type, spacing, substrate, tension, and post-processing, is vast. This study does not aim to be exhaustive or to generate a one-size-fits-all model. Instead, it contributes a process of **feature engineering**, i.e., using preliminary empirical data to flag the highest-impact variables for future standardization, modeling, or inclusion in EDA-compatible component libraries.

For stakeholders, such as thread manufacturers, standards bodies, and EDA system developers, this modeling approach offers guidance on where to invest. Variables like thread diameter and cleaning responsiveness could be standardized in datasheets. Similarly, parameterized tolerance bands (e.g., for hairiness or end splay) could help EDA tools simulate realistic spacing needs. By prioritizing which variables to include, and which relationships to model, this early characterization effort lays the groundwork for more efficient, predictable, and automated stitched circuit design.

6.8 Conclusion

As shown here, there remains a gap between insights collected through expert experiences and controlled characterization experiments and generalizable design rules. The results presented here allow for the translation of experimental findings into structured guidance that can inform stitched circuit layout for these specific parameters. For example, the observed variability in resistance across these thread types and stitch geometries translate into rules format specifying allowable trace lengths or stitch densities to ensure electrical reliability. However, these investigations also illuminate the areas in which process development is still immature, and areas in which more data is needed to build generalizable models relating factors like thread diameter, hairiness, and trace spacing. Early-stage experiments like these can facilitate discovery and prioritization of variables. For example, findings related to termination behavior demonstrate the need for rules that require all trace endpoints to be explicitly defined with associated geometric and process constraints, and for the full spectrum of these options to be established, matured, and characterized. Rather than treating these rules as static values which must be empirically measured for all instances, a generalizable approach involves defining them as relationships between material characteristics, layout geometry, and fabrication-specific tolerances. For instance, minimum trace spacing could be modeled as the designed trace-to-trace distance, composed of (1) a tolerance for thread diameter variability, (2) a tolerance for straightness of stitched traces influenced by thread type and substrate structure type(3) a tolerance for hairiness influenced by thread construction and post-stitch cleaning, and (4) a tolerance for end-splay, which depends on the termination method and thread behavior. By structuring the rule in this way, it becomes possible to account for both design intent and fabrication realities. Understanding and predicting the way that material characteristics (such as twist) might affect factors like hairiness would circumvent the need to measure every component in every implementation scenario.

This relationship-based rule structure was demonstrated using data we collected for the thread types characterized in this study, illustrating how each factor influences the final spacing requirement and leading to empirically derived minimums under different conditions. Our approach also demonstrates how a priority order might be established for variables within the space, to streamline data collection and the development of models and rules. This approach can be adopted for other thread types, fabrication processes configurations to provide a scalable and flexible model for integrating stitched circuit constraints into an EDA framework for textile electronics.

Chapter 7 Conclusion & Future Work

The evolution of circuit design was fundamentally reshaped by the introduction of EDA tools in the 1970s, which enabled scalable, standardized, and manufacturable electronic systems (see Figure 3 above). While traditional electronics now benefit from a mature ecosystem of standards and automation tools, the emerging domain of e-textiles has yet to realize similar advancements despite increasing complexity and commercial interest.

This delay is not solely due to the field's newness. A more fundamental barrier lies in the lack of clearly defined boundaries between what should be addressed by standards organizations, what should be formalized as engineer-designer-driven design rules, and what remains the responsibility of application objectives. This research has also identified a fourth critical category: **Method Development (MD)**, which captures the practical, often novel, techniques that enable fabrication and integration in real-world textile systems.

Together, these four domains: **Application Objectives (AO), Standards (S), Design Rules (DR), and Method Development (MD)** form the foundation of decision-making in e-textile design. However, until now, the field has lacked a structured framework to clarify their interdependencies and sequence of influence.

For example, the selection of fabric or yarn is typically dictated by application-level needs, such as comfort, breathability, flexibility, or biocompatibility. These material choices then trigger relevant standards, such as those addressing safety, toxicity, and wash durability. Next, design rules translate some of those material choices into implementation guidelines such as minimum trace spacing on different substrate types, allowable stitch configurations, or routing constraints to ensure functionality and reliability. Underpinning all of this is the work of method development, which introduces the tools and techniques (e.g., sewing strategies, adhesive bonding, or via stitching) necessary to realize the design.

Unlike rigid electronics, textiles introduce variables that are highly heterogeneous, multidimensional, and often poorly understood in abstract terms. These include, but are not limited to:

- Fiber microstructure and yarn construction,
- Surface finishes and coatings,
- Stretch and deformation behavior, and
- Textile-specific dynamics during wear, washing, or movement.

Because of this complexity, most current e-textile designs are developed through trial-and-error rather than predictive, rule-based design. Through this work, several categories of guidelines and process-based methods were identified as critical to enabling design automation:

Material Characterization Rules: defining tolerances and behavior ranges based on fiber, yarn, or fabric properties.

- **Process-Dependent Design Rules**: linking fabrication methods (e.g., stitching, printing, lamination) to expected electrical and mechanical performance.
- **Layout and Geometry Constraints**: governing trace placement, routings, spacing, and orientation to avoid shorts or breakages.
- **Post-Processing and Finishing Guidelines**: addressing how fray-checking, trimming, or protective coatings affect circuit durability and performance.

In parallel, software compatibility emerged as a critical challenge. Most current EDA platforms are designed for rigid PCBs and lack the capacity to account for deformable substrates, mechanical coupling between circuit and garment, or textile-specific processing steps. Key gaps include the inability to model variable material behaviors, non-linear geometry changes due to fabric stretch, or layout rules that reflect real-world sewing tolerances.

Responsibility for building a robust e-textile design ecosystem spans multiple stakeholder groups:

- **Standards bodies** must define baseline criteria for safety, washability, and performance under environmental stresses.
- **Engineers and developers** must codify fabrication-specific design rules based on experimental results and empirical thresholds.
- **Application designers** bring contextual insight that defines use-specific constraints and priorities, helping to guide material and layout choices.
- **Method developers** create the procedural “know-how” that makes novel integration or fabrication approaches possible, often preceding rule formalization.

To bridge these domains, the EDA framework developed in this dissertation maps the relationships among AO, S, DR, and MD, providing a roadmap for tool development. The ultimate goal is not for designers to interact with the framework directly, but for EDA developers to use it as a backend logic layer. The average user, whether a fashion designer, circuit engineer, or manufacturer, should experience only a user-friendly graphical interface, where complex logic is embedded in intuitive choices and guided design flows.

The framework developed in this research aims to clarify where and how these interventions are needed. It surfaces areas where design rules require adaptation such as accounting for thread variability, material stretch, and garment form factors and suggests how existing PCB rules (e.g., trace spacing) need to be reformulated for textile-specific constraints. However, more work is needed to determine whether these reformulations can be managed through designer awareness and rule substitution, or whether future EDA tools must dynamically encode and apply context-specific logic.

Looking forward, several trajectories emerge:

- **Near-Term Progress**: Immediate efforts should focus on formalizing textile-specific design rules, benchmarking the proposed framework through controlled studies, and developing modular plug-ins or rule libraries that can augment existing PCB and textile design software for e-textiles. This includes incorporating material databases, such as standardized conductive threads and addressing software compatibility challenges. While application-level software issues are primarily a concern within the industry, collaboration between e-textiles researchers and software companies is essential to enable seamless file transfer and integration. Additionally, greater emphasis should be placed on rigorous method development. If research, ideally in partnership with industry, can establish reproducible methods that are translatable to real-world manufacturing, these could serve as the foundation for both standards and design rules. This raises a critical question: should we prioritize developing better machines and materials, or should we first deepen our understanding of their limitations? Current findings suggest that while access to equipment remains important, the more significant barrier may lie in the design tools themselves, specifically, the lack of a logic-driven, textile-aware design system. If such tools were available, many of today's challenges could potentially be addressed using the machinery that already exists.

- **Mid-Term Development**: The integration of this framework into an interactive EDA tool should be a priority, with a focus on automating aspects of the design process that currently depend heavily on expert intuition. Key areas for automation include trace routing algorithms that consider factors such as trace behavior, seam crossings, and deformation under mechanical stress. Importantly, the tool should demonstrate that automation can coexist with craft knowledge, particularly in contexts like sustainable or artisanal production, where human expertise remains essential. This EDA tool could take several forms: it might be developed as a stand-alone platform built from the ground up, as an extension of existing tools through modular libraries or new rule sets, or as an open-source initiative led by the e-textiles community.
- **Long-Term Vision**: The ultimate goal is to establish a robust, end-to-end TCB (design and fabrication ecosystem), one supported by standardized materials, interoperable design tools, and purpose-built fabrication platforms. Realizing this vision will require deep interdisciplinary collaboration across materials science, textile and fashion design, engineering, software development, testing, process optimization, and human-centered design. To achieve this, current design software paradigms will need to evolve. For instance, such a system can no longer be built solely on platforms like Altium or Eagle by simply adding plug-ins or libraries. If 3D rendering and simulation are to be integrated, we may need tools that interface with platforms like CLO3D, or potentially a ground-up

solution developed by a new company, or a comprehensive open-source initiative led by the e-textile community.

Beyond tool development, this vision involves a fundamental shift from purely manufacturing-oriented metrics to those that also value user safety, comfort, aesthetics, and sustainability. Imagine a designer being able to lay out a circuit across garment pattern pieces using functional components from a schematic or library and then simulate the full garment in 3D, both mechanically and electrically to evaluate comfort, fit, and performance.

BiliOnesie provides a concrete example of how the proposed design ecosystem could transform e-textile development. In the near term, addressing foundational issues like standardized conductive thread databases and textile-specific design rules could streamline early design decisions, reducing the need for trial-and-error when selecting threads, stitching methods, or substrates for consistent irradiance delivery. If a textile-aware EDA tool were available, the BiliOnesie's circuit layout, currently created manually and iteratively, could instead be generated using rule-based logic that accounts for stretch zones, seam crossings, and garment curvature. This would not only save time but also improve reliability by enabling trace routing that anticipates deformation during wear. With a fully integrated ecosystem, including compatibility between garment CAD tools like CLO3D and e-textile simulation environments, the BiliOnesie could be visualized and evaluated in 3D before a physical prototype is made. Designers could test mechanical fit on newborn body scans, verify electrical continuity and irradiance distribution in simulation, and iteratively refine both garment and circuit in a unified workflow. This level of integration would accelerate development, reduce waste, and ensure better alignment between clinical requirements, comfort, and manufacturability, ultimately resulting in a safer, more scalable phototherapy e-textile solution.

Finally, these technical ambitions must be accompanied by critical conversations around equitable access, workforce transformation, and long-term resilience to ensure that innovation in this space is inclusive, sustainable, and future-ready.

Additionally, several lines of development are needed to operationalize this framework and realize true design automation for e-textiles:

- **Parametric Rule Development**: Continue building rule libraries that express mechanical and electrical constraints as tunable parameters linked to material behavior and process effects.
- **Software Integration**: Develop plug-ins or extensions to existing EDA platforms (e.g., KiCad, Altium) that include textile-aware modeling of geometry, tolerances, and deformation.
- **Standardization Initiatives**: Partner with industry consortia and standards bodies to codify textile-relevant design, testing, and safety criteria.
- **Empirical Dataset Expansion**: Build richer datasets of material-process-performance relationships to refine rule accuracy and enable better simulation tools.
- **Cross-Disciplinary Workflows**: Create shared protocols and interfaces that connect textile engineering, materials science, and circuit design communities.

The EDA framework presented here provides the groundwork for scalable, reliable, and automated e-textile design. It:

- Codifies design knowledge into reusable logic,
- Incorporates real-world insights (e.g., trace behavior, stitch variability) often overlooked in literature,
- Supports computational reasoning and simulation, and
- Lays the foundation for next-generation software tools that make textile electronics accessible, reliable, and manufacturable.

At the same time, this work reinforces that e-textile performance is not the only indicator that matters, **design process efficiency** is equally critical. Many of the failures observed in this research were not the result of flawed designs but stemmed from the immaturity of the surrounding infrastructure. Compared to the rigid PCB industry, which operates with customized equipment, high-end automation, and decades of refinement, the TCB field is hindered by access limitations, incomplete design tools, and rudimentary manufacturing setups.

Finally, as e-textiles increasingly intersect with domains such as wearables, healthcare, fashion, and defense, new concerns emerge, like, user comfort, aesthetic integration, ethical labor considerations, and sustainability. Automation and standardization, if poorly managed, may risk displacing the skilled labor and tacit knowledge currently sustaining the field. Yet if approached thoughtfully, these tools can extend expert knowledge, improve design reproducibility, and reduce waste while making smart textiles more accessible and inclusive.

In conclusion, this dissertation establishes not only the need for a TCB-specific EDA framework but also provides the structure and roadmap to build it. While it does not yet deliver a complete solution, it offers a comprehensive starting point to guide near-term tool development, longer-term standardization, and interdisciplinary collaboration, paving the way for a future where e-textile design is as scalable, reliable, and expressive as traditional electronics.

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