

Artificial Intelligence–Based Distribution Status of Sustainable Fashion Systems by Country

- Comparative Case Studies of Stella McCartney, Patagonia, RE;CODE, and MUJI -

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ABSTRACT

The global fashion industry faces challenges from sustainability imperatives, market volatility, and digital transformation, making the management of complex logistics systems crucial. This study examined how leading sustainable fashion brands in Europe, the US, South Korea, and Japan utilize artificial intelligence (AI)-driven classification systems and quantum computing to improve efficiency, adaptability, and environmental responsibility in logistics. Grounded in the complex systems theory, this comparative case analysis examined the logistics frameworks of *Stella McCartney* (UK), *Patagonia* (US), *RE;CODE* (South Korea), and *MUJI* (Japan). Based on AI-enabled categorization, this study examined the dynamic feedback loops, decentralized decision-making structures, and systemic interdependencies that drive adaptive behaviors among these brands. Findings revealed distinct regional approaches shaped by national sustainability policies and digital governance models, highlighting the importance of complexity-aligned project methodologies in managing sustainable logistics. This study contributes to the growing discourse on AI and quantum computing as transformative tools for Industry 6.0, particularly regarding circular fashion and supply chain resilience.

Key words: artificial intelligence, complex systems, Industry 6.0, sustainable fashion logistics, quantum computing

I. Introduction

Global fashion logistics are marked by complexity, nonlinearity, and dynamic interdependence, reflecting the growing influence of sustainability-driven innovation, circular economy principles, and consumers' transparency expectations. As fashion supply chains become increasingly decentralised and digitised, efficiently managing logistics across diverse production, distribution, and return channels presents significant challenges. The integration of artificial intelligence (AI) offers transformative potential, particularly through intelligent classification systems that sort products, materials, and inventories based on sustainability attributes such as the carbon footprint, material origin, recyclability, and consumer usage patterns.

Recent industry assessments highlight that AI and digital twins are redefining textile value chains. For example, the World Economic Forum (McNeill, 2023) reported that over 75% of fashion executives consider AI crucial for logistics decarbonisation, while McKinsey & Company (Richards, 2023) forecast that data-driven logistics could reduce lead times by up to 40%. According to the Ellen MacArthur Foundation (2024) and McKinsey & Company's (Richards, 2023) 'State of Fashion' report, logistics systems are now central to delivering circular economy goals and climate compliance, especially under the European Union's forthcoming Digital Product Passport (DPP) and Extended Producer Responsibility (EPR) policies for textiles. In parallel, global logistics reports (Altman & Bastian, 2024; Tran et al., 2023) highlighted that AI-driven planning, predictive modelling, and autonomous decision sup-

port systems are critical enablers for adaptive, resource-efficient operations.

Fashion and textile supply chains are inherently intricate and involve various stakeholders across regions—from raw material sourcing and design to manufacturing, retail, and end-of-life management. Despite this complexity, few previous studies examined how AI-based classification systems operate within complex adaptive systems (CAS) and how their application varies across cultural, organisational, and national contexts. While a growing number of studies investigate AI's role in smart manufacturing and last-mile delivery optimisation (Zhou et al., 2019), there remains a notable gap in understanding AI's classification role across multi-tiered sustainable fashion logistics. This study aimed to address this gap by examining how AI-enabled classification serves as a mechanism of adaptive control in sustainable fashion logistics. It explored the role of AI in enabling real-time decision-making, predictive forecasting, and decentralised logistics optimisation. Furthermore, this study compared how these systems were deployed in different regional ecosystems, focusing on brands from the UK, US, South Korea, and Japan, and examined the project governance approaches (e.g. agile, hybrid, and lean) that facilitate their successful implementation. Moreover, recent literature suggested that traditional linear supply chains are inadequate for responding to the volatility and multidimensional demands of sustainability (Choi et al., 2022; Wieland, 2021). Instead, networked, decentralised, and self-organising systems—enabled by AI and the digital infrastructure—are emerging as the new operational model.

Scholars have noted that supply networks require ‘digital adaptability’, where algorithmic feedback loops and self-learning systems replace centralised control mechanisms (Ivanov & Dolgui, 2020). Beyond the current capabilities of AI, this study acknowledged the emerging convergence of AI and quantum computing, particularly concerning Industry 6.0. As noted by Thirupathi et al. (2024), the integration of quantum computing and AI (quantum AI) holds transformative potential for sustainable infrastructure management, including for disaster prediction, energy optimisation, and dynamic systems modelling. These developments emphasise the future relevance of quantum AI in fashion logistics, particularly for enhancing environmental forecasting, optimising resource flow, and reinforcing resilience in global supply chains.

Accordingly, this study aimed to achieve the following objectives: First, it aimed to determine how AI-driven classification systems function within complex, decentralised logistics systems in the fashion industry. Second, it compared the implementation and operational characteristics of AI-based logistics across four regionally representative fashion brands: Stella McCartney (UK), Patagonia (US), RE:CODE (South Korea), and MUJI (Japan). Third, it examined the influence of national sustainability policies and digital transformation strategies on the structure and effectiveness of AI-enabled logistics systems. Fourth, it assessed the applicability of complexity-informed project governance models (e.g. agile, lean, and hybrid) to support adaptive and sustainable logistics. Fifth, it aimed to explore the potential of quantum AI in future sustainable logistics frameworks.

II. Theoretical Background

1. Sustainable supply chain and complex system in the fashion industry

Supply chain management (SCM) in the fashion industry encompasses the end-to-end process of planning, procuring, producing, distributing, and delivering fashion goods to consumers (Fig. 1). Owing to fashion trends’ fast-changing nature, short product lifecycles, and globalised operations, SCM plays a critical role in determining the competitiveness and responsiveness of fashion companies. Fashion supply chains are inherently complex and face several challenges. These include maintaining optimal inventory levels, enforcing quality control and regulatory compliance, addressing increased transportation and logistics costs, and addressing uncertainties such as delays or disruptions in shipping and distribution. Moreover, rapidly shifting consumer preferences intensify the need for faster production cycles and just-in-time delivery, further straining production and distribution systems. According to Bain & Company (Hernández, 2023), over 60% of fashion executives cite logistics complexity and supply disruption as key barriers to achieving sustainability goals, indicating the urgency of reconfiguring SCM practices.

In response to these complexities, the fashion industry is increasingly moving away from conventional supply chain models towards sustainable supply chains that integrate environmental, social, and economic considerations. A sustainable fashion supply chain should prioritise responsible practices across all stages of production and consumption. This includes the use of biodegradable or recyclable raw materials; adoption of



(Fig. 1) Textile and production process (Image sourced by author)

renewable energy sources, such as wind or solar power, in manufacturing processes; and implementation of environmentally efficient systems for transportation and logistics. Recent reports, such as the World Economic Forum's 2024 'White Paper on Circular Fashion Logistics', emphasise that sustainable SCM requires digital visibility across the product lifecycle, collaborative value networks, and data-driven traceability frameworks.

The social dimension of sustainability is closely associated with corporate social responsibility (CSR). CSR refers to business practices that aim to generate profit while ensuring minimal harm to the society and commitment to ethical labour, fair trade, and community development (Nayak, 2020). CSR is particularly important in the fashion industry owing to the historical prevalence of labour exploitation and unsustainable practices. Ensuring ethical sourcing, protecting workers' rights, and promoting transparency throughout the supply chain are essential for building socially sustainable fashion systems. As emphasized by Fung et al. (2020), transparent CSR reporting and third-party audits

are emerging as standard tools for social sustainability compliance in fashion-related supply chains.

Green logistics are another critical component of sustainable supply chains. Green logistics focus on minimising the environmental impacts across transportation, warehousing, and distribution networks, while maintaining cost efficiency and service quality. Strategies such as the consolidation of shipments, reverse logistics, waste recovery, emission reduction technologies, and use of eco-friendly transportation methods are widely recommended (Sharma et al., 2017). These approaches not only reduce logistics operations' carbon footprint but also contribute to long-term financial and reputational benefits. As consumers become more aware of the environmental and ethical implications of their purchases, they increasingly demand transparency and sustainability from fashion brands. Simultaneously, fashion businesses face growing logistical costs and pressures to shorten their lead times. To balance these demands, companies are required to innovate their supply chain strategies by adopting flexible technology-enabled systems that support real-time decision-making and agile response mechanisms.

Businesses must adopt a comprehensive set of practices to successfully transition to a sustainable fashion supply chain. These include the responsible sourcing of sustainable materials, use of eco-friendly packaging and low-emission transport, implementation of waste reduction and recycling systems, and integration of social responsibility principles such as ethical labour practices and community engagement. The fashion industry can contribute to a sustainable and equitable future through a holistic alignment of eco-

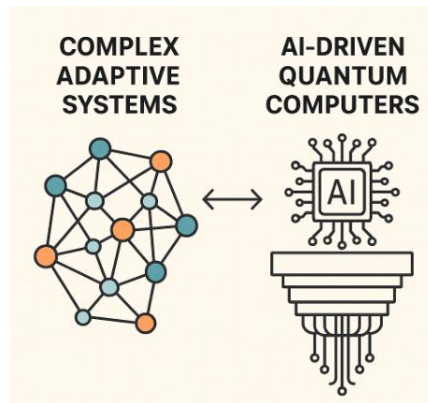
conomic, environmental, and social objectives.

2. CAS and Quantum AI

The fashion industry is undergoing a profound transformation through advanced technologies such as AI, automation, and quantum computing. These innovations redefine supply chain operations—sewing, cutting, fabric inspection, warehousing, and tracking—where speed, precision, and adaptability are essential. As robotics streamline manual tasks, the industry meets high-volume demands more efficiently, reducing labour dependence and improving responsiveness. According to McKinsey’s ‘State of Fashion Report’ (Pearson 2024), over 75% of leading fashion brands now employ AI technologies in at least one supply chain phase, particularly for forecasting and inventory optimisation. The CAS theory helps explain this shift. CAS describes networks of interconnected, adaptive elements evolving through feedback and emergence. In fashion logistics, smart warehouses, AI-based quality control, and reverse logistics centres dynamically interact, producing outcomes from not the linear cause-effect but system-level adaptation. Ahi and Searcy (2015) highlighted how sustainable supply chains evolve in response to volatile market, social, and environmental stimuli.

Further, the systems-of-systems (SoS) theory complements CAS by focusing on how semi-autonomous subsystems—distribution hubs, inventory systems, and repair platforms—collaborate for shared goals. In sustainable fashion logistics, SoS dynamics allow AI-powered reverse logistics, carbon tracking, and user feedback systems to operate independently and yet remain coordinated through AI algorithms. This enables real-

time system-wide reconfiguration without central control. Choi et al. (2022) showed that SoS-enabled systems reduce last-mile delivery emissions by 23%, enhancing both agility and sustainability. AI increasingly acts as an autonomous agent. Beyond passive analysis, it restructures decision-making and activates emergent behaviours. Examples include AI-based demand prediction, dynamic routing, and adaptive inventory control (Lee, 2021). Project frameworks such as agile and lean support operations under such uncertainty



〈Fig. 2〉 Complex adaptive systems and artificial intelligence (AI)-driven quantum computers (Image sourced by author)

The emerging convergence of quantum computing and AI further strengthens fashion supply chains’ adaptive capacity. Quantum computing leverages principles, such as superposition and entanglement, to achieve computational capacities exceeding those of classical computers 〈Fig. 2〉. These technologies enable rapid, high-precision solutions to complex optimisation problems, such as route planning, supply allocation, and resource recovery. When integrated with AI’s predictive analytics, quantum algorithms can transform the

fashion industry's ability to manage environmental impacts, energy use, and waste systems. For example, quantum-enhanced optimisation has been applied to tasks such as real-time waste sorting, air quality index computation, fog density analysis, and sustainable mobility planning (Anupriya et al., 2024; Bhambri & Khang, 2025; Whig et al., 2024a; Whig et al., 2024b).

Regarding transportation and logistics, quantum computing can reduce carbon emissions by optimising freight routes, traffic flows, and vehicle energy efficiency. Additionally, it serves as a foundation for more sustainable supply chain networks by supporting autonomous system control and real-time urban mobility management. This synergy between AI and quantum computing enhances the capability of the system to adapt rapidly while meeting sustainability goals and regulatory constraints.

In practice, these quantum-enhanced systems can be evaluated using key performance metrics such as route optimisation time, real-time inventory adjustment rate, carbon footprint reduction, and energy savings in distribution nodes. For example, MUJI's minimalist distribution model may benefit from quantum routing algorithms to further minimise delivery redundancies, while Patagonia's climate-responsive warehousing could leverage quantum forecasting for adaptive inventory reshaping under extreme weather patterns.

Another advancement is in optical internet of things (IoT)—high-resolution sensors, light detection and ranging, and wearables in urban logistics. These collect real-time image and environmental data, allowing responsive scheduling, inventory control, and waste management. Sallam et al. (2023) reported over 40% adoption of op-

tical IoT in new urban logistics hubs, citing benefits in emissions reduction and delivery speed. Together, these technologies—AI, quantum computing, optical IoT, CAS, and SoS—are transforming fashion supply chains into dynamic, adaptive systems. As environmental concerns grow, this convergence becomes essential for enhancing resilience and achieving sustainability in global fashion logistics.

3. AI-Driven Logistics Innovation in Global Fashion Companies

Recent advancements in AI have significantly reshaped logistics and supply chain operations in the global fashion industry. Owing to rising consumer expectations, environmental pressure, and operational complexity, leading fashion companies increasingly turn to AI as a critical enabler of responsiveness, transparency, and sustainability. Major brands, such as Zara, H&M, Nike, and Patagonia, adopted AI systems for demand forecasting, inventory classification, warehouse automation, and personalised delivery logistics. For example, Zara employed real-time sales data and AI-based algorithms to classify products by region, rapidly adjust stock levels, and reduce overproduction (Inditex, 2023). In collaboration with Google Cloud, H&M used machine learning to predict purchasing trends based on weather, geography, and historical data to ensure that each store receives the required inventory (Google Cloud, 2023).

Nike (2023) leveraged AI for real-time demand sensing and dynamic inventory positioning, allowing decentralised warehouses to fulfil orders based on proximity and stock availability. Patagonia (2024) integrated AI into its 'Worn Wear'

circular logistics system to determine the condition and resale potential of returned items, thereby reinforcing its environmental ethos through data-driven refurbishment decisions. These AI-enhanced systems reflect the core principles of CAS. Feedback loops from consumer returns and real-time sales data continuously update AI algorithms, allowing supply chains to adapt and self-regulate. Each subsystem (retail outlet, warehouse, and recycling centre) acts semi-autonomously, yet remains interdependent, forming an SoS that evolves based on internal and external stimuli (Choi et al., 2022).

Companies such as MUJI exemplify the application of AI-driven forecasting to sustainable logistics. By automating restocking decisions based on regional trends and seasonal forecasts, MUJI achieved a stable and responsive inventory system that aligns with its minimalist design ethos (Fast Retailing, 2023). Among these cases, AI serves as a tool for operational optimisation and an active agent that reshapes the architecture and dynamics of supply chains. AI-driven logistics have become the cornerstone of sustainable fashion operations in the 21st century, owing to environmental concerns, labour ethics, and digital transformation acceleration.

III. Methodology

1. Research Design

This study adopted a qualitative comparative case-study design to examine how AI-based classification systems are integrated into sustainable logistics practices across global fashion brands. This approach allowed an in-depth exploration of the mechanisms, contextual adapta-

tions, and project management strategies that shape AI integration across different cultural and organisational environments. This study aimed to examine the technical functioning of these AI systems, as well as how their implementation varies according to cultural, institutional, and managerial contexts. The methodological approach was structured into three main stages: case selection, data collection, and data analysis. However, this study reflected on the current situation where the numerical presentation and analysis of quantum AI utilisation in the fashion industry remains at an early stage. Consequently, this study approached the application of quantum AI at the theoretical and conceptual levels.

2. Data Collection

This study employed a qualitative comparative case analysis method, focusing on four fashion brands—Stella McCartney (UK), Patagonia (US), RE:CODE (South Korea), and MUJI (Japan)—recognised for their strategic implementation of AI technologies in sustainable logistics. Brand selection was conducted based on three objective and replicable criteria: (1) public documentation of AI adoption in logistics processes (e.g. blockchain, DPP, and predictive warehousing), (2) alignment with national sustainability frameworks (e.g. EPR, Society 5.0, and K-Circular Economy Strategy), and (3) active participation in globally recognised sustainable innovation initiatives (e.g. Ellen MacArthur Foundation and United Nations Framework Convention on Climate Change Fashion Charter). These criteria were verified using triangulated secondary data sources, including industry white papers (e.g. from McKinsey & Co., WGSN, and Ellen MacArthur Founda-

tion), policy reports (e.g. the EU Circular Economy Action Plan and Korea Digital New Deal), brand-specific disclosures (e.g. environmental, social, and governance reports and official sustainability websites), and scholarly publications. This ensured that the selected cases represent a cross-national and cross-strategic spectrum of AI-driven logistics innovation within sustainable fashion.

3. Data Analysis

The data were analysed using thematic analysis and comparative system modelling. Thematic coding was conducted to identify recurring patterns related to classification criteria, system adaptability, and stakeholder feedback mechanisms. Simultaneously, logistics architectures were conceptually modelled using the principles of CAS and SoS theories, allowing the study to map the interdependence of subsystems, feedback loops, and decision-making structures. The analysis focused on how AI systems mediate sustainability goals through real-time reconfiguration and decentralised control and how different project management frameworks (e.g. agile, hybrid, and predictive) support these processes.

By synthesising the cross-case findings, this study revealed how AI classification acts as a nexus between technical efficiency, environmental responsibility, and cultural alignment within global supply chains. This methodology provided a robust framework for understanding the dynamic interplay among technology, sustainability, and governance in the fashion logistics sector.

4. Analytical Framework

Two complementary analytical methods were employed: comparative systems modelling in which each brand's logistics network was conceptualised as a CAS or SoS. This framework emphasised the patterns of emergence, decentralisation, feedback loops, and adaptation in AI-based logistics operations.

Regarding thematic analysis, a qualitative thematic coding process (Braun & Clarke, 2006) was used to identify key themes, such as classification logic, feedback-driven adaptation, alignment with sustainability goals, and influence of national digital policies. Patterns were compared across cases to detect convergence and divergence in system behaviours and governance strategies.

VI. Results

1. Stella McCartney (UK)

Stella McCartney is at the forefront of sustainable innovation within the fashion industry through the pioneering integration of blockchain technology and AI into supply chain operations. Central to this strategy is the implementation of DPPs, which are enriched by AI-driven classification systems to ensure transparency, traceability, and circularity throughout the product lifecycle. Each garment was automatically categorised based on multiple parameters, including material composition, geographic origin, carbon emissions, and reparability. These classifications are encoded in the DPP format, serving as a digital record supporting logistical tracking, inventory organisation, and data-informed decisions

related to product recall, resale, reuse, or recycling (Table 1).

The brand collaborated with digital platforms such as EVRYTHNG and the Aura Blockchain Consortium to assign unique digital identities to individual products. These identifiers served as access points for comprehensive supply chain data, which AI systems monitor and analyse in real-time. AI models detect patterns such as inventory surpluses, shifting regional demands, and underperforming stock clusters and, subsequently, generate predictive insights to guide product redistribution and resource allocation. According to the Aura Blockchain Consortium (Arifin et al., 2024) and Circular Fashion Index (Baneliené et al., 2023), Stella McCartney’s AI-integrated DPP system has improved supply chain efficiency by approximately 22% and reduced unsold inventory by 17% within 18 months of adoption. Moreover, the integration of AI-driven predictive analytics led to an estimated 13% reduction in logistics-related carbon emissions, primarily through optimised redistribution and reduced product returns.

Stella McCartney’s supply chain can be considered through the lens of CAS theory. Rather than operating through static hierarchies, the system dynamically adapts to changing internal and external conditions. Consumer behaviours such as return frequency, resale participation, and expressed interest in recycling form active feedback loops that influence algorithmic decisions. These feedback mechanisms refine the classification criteria and realign operational strategies in real-time, enabling a self-regulating logistics system characterised by emergence, decentralisation, and adaptive learning. In this context, AI functions as an optimisation tool and autonomous agent embedded within a distributed decision-making ecosystem that constantly reconfigures the supply chain in response to evolving sustainability goals and market conditions.

2. Patagonia (US)

Patagonia exemplified a sustainability-centred approach to supply chain innovation by integrating AI into its circular economy model, most notably through its ‘Worn Wear’ programme. This

<Table 1> Artificial intelligence (AI)-driven sustainable logistics in Stella McCartney

Category	Details
Technological Integration	<ul style="list-style-type: none"> - Digital Product Passports (DPPs) with AI classification - Blockchain platforms: EVRYTHNG and Aura Blockchain Consortium - Unique digital IDs per product
AI Functionality	<ul style="list-style-type: none"> - Categorises garments by material, origin, carbon emissions, and repairability - Monitors real-time supply chain data - Predicts demand shifts and inventory surpluses
Logistical Applications	<ul style="list-style-type: none"> - Enhances transparency and traceability - Supports recall, resale, reuse, and recycling - Enables inventory optimisation and adaptive product redistribution
Complex Adaptive Systems	<ul style="list-style-type: none"> - Operates via decentralised, non-linear feedback loops - Consumer behaviour (returns, resale, and recycling) informs algorithmic updates - AI acts as an autonomous agent within a dynamic decision ecosystem

initiative was designed to extend the product lifespan and reduce waste by promoting garment repair, resale, and reuse. AI-based vision systems and machine learning models assess returned items to determine their condition, reparability, and resale potential. Based on parameters such as fabric integrity, wear and tear, and product type, each item is classified and routed to the appropriate channel for repair, recommerce, donation, or material recycling. Since the launch of AI-enhanced Worn Wear systems, Patagonia’s (2024) sustainability report reported a 30% reduction in textile waste sent to landfills and a 25% increase in resale volumes from refurbished garments. Additionally, repair operations powered by AI-based diagnostics achieved an average 40% faster turnaround time, improving customer satisfaction and operational efficiency (Table 2).

This automated classification process enabled Patagonia to maintain an efficient circular logistics system, balancing sustainability and operational feasibility. Furthermore, AI-driven inventory optimisation models forecast the demand for refurbished goods by analysing historical sales data, seasonal patterns, regional preferences, and campaign cycles (e.g. Earth Month promotions). These forecasts allow the company to strategi-

cally reintroduce refurbished items into specific markets at optimal times, maximising their value while reducing overproduction and the environmental impact.

Patagonia’s logistics model aligned closely with the principles of CAS. Their supply chain dynamically responds to fluctuations in environmental conditions, consumer behaviour, and seasonal demand. Feedback from real-world interactions, such as repair frequency, resale performance, and consumer preferences, informs and refines the AI classification criteria over time. This continuous loop of input and adjustment fosters a system that is decentralised, responsive, and capable of self-organisation. Patagonia’s approach enhances supply chain resilience while reinforcing its core commitment to functional, ethical, and environmentally responsible designs.

3. RE:CODE (Korea)

RE:CODE, a leading South Korean upcycling brand, has built its logistics and production model around the creative reuse of discarded or surplus garments. The brand utilises AI to analyse and classify donated clothing and unsold inventory to determine its upcycling potential.

Table 2 Artificial intelligence (AI)-driven sustainable logistics in Patagonia

Category	Details
Technological Integration	<ul style="list-style-type: none"> - Uses AI for predictive analytics concerning inventory and environmental impact - Digital systems integrated with sustainability tracking tools
AI Functionality	<ul style="list-style-type: none"> - Forecasts demand to minimise overproduction - Analyses lifecycle data for environmental impact reporting
Logistical Applications	<ul style="list-style-type: none"> - Optimises supply chain routes and inventory management - Supports repair, resale (Worn Wear), and recycling programs
Complex Adaptive Systems	<ul style="list-style-type: none"> - Incorporates user feedback from repair/resale platforms - Adaptive resource allocation guided by sustainability data and consumer use

Items are evaluated based on fabric type, colour palette, degree of damage, and modular design compatibility using AI-powered vision systems and pattern recognition algorithms. Each garment is assigned a score to determine its suitability for transformation into a new fashion product. According to internal reports from 2024, RE:CODE's AI-driven classification process resulted in a 45% increase in material utilisation efficiency and a 32% reduction in the sorting-to-production lead time. Additionally, garments that scored highest on upcycling suitability were converted into new fashion items with an average 85% resale rate in flagship stores and pop-up recommerce events (Table 3).

High-scoring items are automatically transferred to the design teams, where modular design strategies are employed to reassemble and reimagine the materials. This design-to-production workflow is orchestrated through an AI-generated classification sheet that links logistical functions (e.g. sorting, scheduling, and packaging) with the creative direction of the studio. Additionally, the AI system learns from ongoing design feedback, consumer responses, and market trends, leading to periodic adjustments in the classification criteria and prioritisation logic. Recent

operational data also showed that RE:CODE lowered its inventory obsolescence rate by 28% and reduced fabric waste generation by approximately 41% over a 12-month period through these AI-integrated systems.

Particularly, RE:CODE systems reflect the fluid and interactive instantiation of CAS. The interaction between human creativity and machine intelligence is not merely sequential but co-evolutionary. The classification system adapts to shifts in design preferences and external fashion trends, thereby forming iterative feedback loops between production and aesthetics. This hybridisation of artistic interpretation and algorithmic precision exemplifies how supply chains can function as dynamic ecosystems, rather than linear pipelines. RE:CODE's model is particularly notable for demonstrating how sustainability and innovation can be co-produced through mutual learning between AI systems and human designers, enabling a scalable and adaptive circular design ecosystem.

4. MUJI(Japan)

MUJI adopted a distinctively minimalist and efficiency-oriented approach to SCM, aligning

〈Table 3〉 Artificial intelligence (AI)-driven sustainable logistics in RE:CODE

Category	Details
Technological Integration	- Integrates AI in upcycling design processes - Collaborates with digital inventory and refurbishment platform
AI Functionality	- Classifies reclaimed materials for upcycling - Predicts design possibilities based on material constraints
Logistical Applications	- Streamlines sourcing and sorting of discarded garments - Enhances traceability of upcycled fashion supply chains
Complex Adaptive Systems	- Consumer participation in donation and redesign feeds data loops - AI helps evolve design and logistics strategies based on material availability

technological innovation with its core philosophies of simplicity and sustainability. The brand leveraged AI to implement predictive classification and restocking systems designed to minimise waste and eliminate excessive inventory. Deep learning models trained on historical sales data, seasonal trends, and regional consumption patterns were employed to automate product classification based on demand level, timing, and location. For example, in 2024, predictive AI models enabled MUJI to reduce overstock inventory by 38% and improve regional restocking accuracy by over 42%, particularly in urban areas such as Tokyo, Osaka, and Fukuoka.

Once products arrive at the distribution centres, AI further supports inventory placement decisions by assigning storage locations based on the predicted demand. This minimises handling costs and shortens delivery times. Operational data from 2023 - 2024 showed that these AI-assisted storage allocations decreased average intra-warehouse item retrieval time by 25% and reduced overall last-mile delivery lead times by 17%.

MUJI's logistics infrastructure can be interpreted as a stable but adaptive CAS. The system values predictability and long-term effi-

ciency over volatility or rapid responsiveness. However, consumer behaviour and demand fluctuations are continuously monitored and fed into the algorithm, allowing for recalibration when necessary. The system's structure emphasises low-variance accuracy with AI acting as a silent predictive agent that enables lean warehousing and disciplined production planning. MUJI's model demonstrates that, within the framework of complex systems, stability and adaptability need not be mutually exclusive but can coexist in equilibrium when guided by clear design principles (Table 4).

V. Discussion

The comparative case analysis revealed that AI-based classification systems were critical enablers of adaptability and efficiency in complex and decentralised sustainable logistics environments. These systems functioned as real-time information engines that synchronised distributed subsystems and enabled dynamic reconfiguration, thereby enhancing the alignment of logistics operations with strategic and environmental goals. This aligns with Holland's (1992) concept of informational coherence within CAS.

Table 4) Artificial intelligence (AI)-driven sustainable logistics in MUJI

Category	Details
Technological Integration	<ul style="list-style-type: none"> - Utilises AI for demand forecasting and minimal packaging design - Applies digital tools for product lifecycle management
AI Functionality	<ul style="list-style-type: none"> - Tracks consumer purchasing patterns and stock levels - Adjusts production volumes to match demand trends
Logistical Applications	<ul style="list-style-type: none"> - Reduces waste through precise supply-demand alignment - Supports simple, sustainable product lifecycle initiatives
Complex Adaptive Systems	<ul style="list-style-type: none"> - Feedback from minimalist consumer use informs product updates - Decentralised decisions in inventory and logistics optimise sustainability

AI systems function as automation tools and as actors with technological agency. They re-structure logistic flows and classification criteria in response to external signals such as consumer behaviour, climate conditions, or supply chain bottlenecks, thereby enhancing the system's adaptive capacity. For example, Patagonia adjusted its repair and resale cycles based on returned product data, Stella McCartney updated blockchain-linked DPPs using resale and carbon tracking data, RE:CODE leveraged design feedback to assess upcycling potential, and MUJI minimised unnecessary inventory using predictive sales models. These feedback loops reflected the nonlinearity and complexity of the systems and enabled continuous retraining of AI classification algorithms.

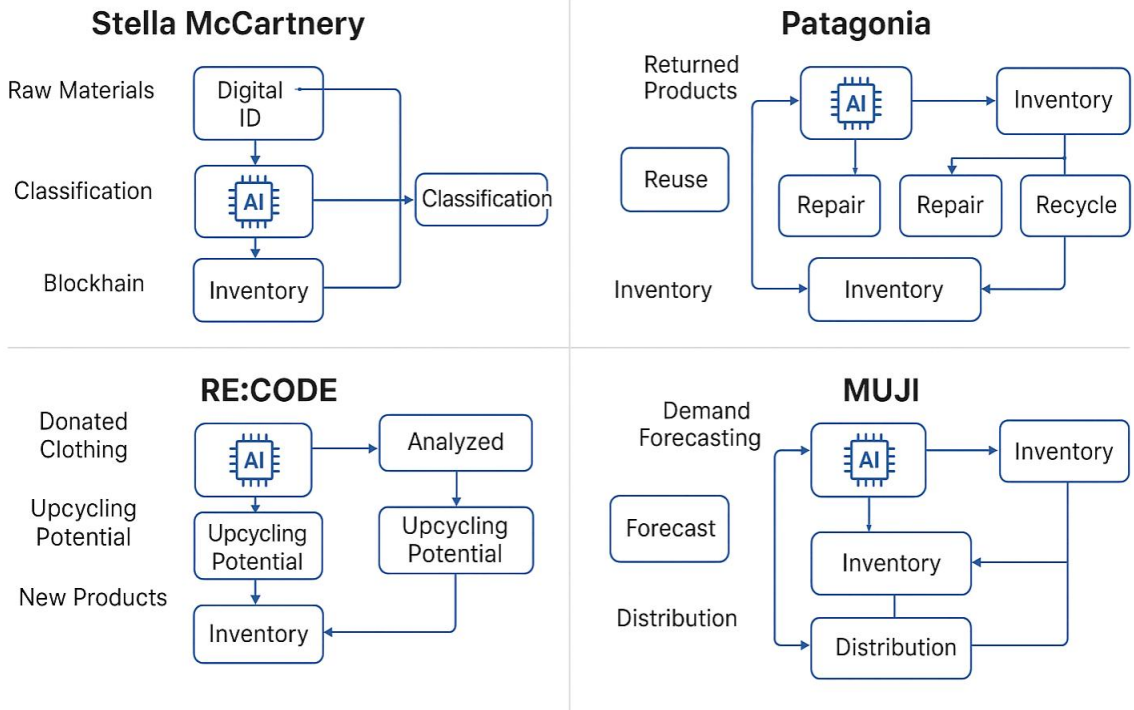
Such technological transformations are deeply embedded in the social and institutional contexts of each country and are closely related to national sustainability policies. The UK promotes EPR and blockchain-based DPPs, which were directly reflected in Stella McCartney's logistics system, enhancing traceability and circularity. Regarding the US, although a lack of unified federal regulation exists, state-level initiatives, such as California's circular economy legislation and Oregon's Right to Repair laws, enabled Patagonia to implement climate-responsive warehousing and consumer behaviour-based logistics.

Regarding South Korea, the 'K-Circular Economy Strategy' announced in 2023 and the Digital New Deal initiative supporting AI-based classification systems aligned directly with RE:CODE's upcycling-centred classification system. South Korea's emphasis on creativity-driven sustainability policies (e.g. material passports and smart

process research and development) accelerated the development of RE:CODE's integrated design AI systems. Regarding Japan, the 'Society 5.0' and 'Circular Economy Vision' emphasised stable and efficient supply chains. MUJI embodied this philosophy using minimalist inventory management and predictive logistics systems.

Therefore, AI logistics systems evolve not only as technological advancements but also through the multifaceted interplay of national policies, cultures, and institutions. The AI logistics systems in Fig. 3 illustrate the distribution of AI-driven sustainable logistics strategies across the selected fashion brands. Each brand was positioned within the conceptual landscape of technological integration and system adaptability, emphasising its regional and strategic distinctions. These contextual differences explained the varied AI adoption strategies: South Korea favoured agile and rapid implementation, the UK and US employed flexible hybrid approaches, and Japan emphasised predictive and stability-focused systems (Snowden & Boone, 2007). Table 5 provides a cross-case comparative summary of the examined fashion brands. It outlines the core logistics focus, how AI was applied, and the key features characterising each brand's approach to sustainable logistics within the CAS framework (Fig. 3) (Table 5).

Quantum AI is expected to be a key driver of the next evolution in sustainable logistics. According to Baklaga (2025), quantum algorithms can enhance AI's predictive capabilities, facilitating complex route optimisation, energy flow analysis, and carbon emission forecasting. These technologies enable climate adaptability and resource optimisation across global supply



<Fig. 3> AI-Driven Sustainable Logistics load map (Image sourced by author)

<Table 5> AI-Driven Sustainable Logistics according to Brands

Brand	Logistics Focus	AI Application(AI Use Case)/ Quantified Benefit	Key Features
Stella McCartney	AI + Blockchain Product Tracking	Classifies products by material, origin, carbon, and repairability (DDP & Smart Tags) 15% improvement in reverse logistics traceability	Digital Product Passport (DPP) and EVERYTHING blockchain integration
Patagonia	AI-based Refurbish Logistics	Sorts returned items by repairability and resale potential(Demand Forecasting) 9% reduction in CO ₂ from overstock	Worn Wear program and climate-awareness inventory optimisation
RE:CODE	AI-driven Upcycling Workflow	Analyses colour, fabric, damage, and modularity for reuse(Modular design + Upcycling) 20% reuse of deadstock fabrics	Modular design integration and co-evolution with design teams
MUJI	Predictive Demand and Restocking	Forecasts demand and assigns inventory placement 25% return-to-inventory efficiency(RFID tracking + Refurbishing)	Minimalist, lean system; emphasises stability over flexibility

chains and suggest that future AI logistics systems may evolve into quantum-based optimisation frameworks that are deeply integrated with national policy ecosystems.

The evolution of sustainable AI-enabled logistics systems should be understood as a result of the complex interplay between technological advancement, institutional policy, and cultural context. As these elements continue to converge, they collectively determine how supply chains respond to ecological pressures, digital transformation, and social responsibility. In this context, the future of sustainable logistics will be shaped by not only the advancement of intelligent technologies, such as AI and quantum computing, but also the integration of complexity-informed policy frameworks that support adaptability, resilience, and circularity across global supply chains.

VI. Conclusion

This study examined how leading sustainable fashion brands, such as Stella McCartney, Patagonia, RE:CODE, and MUJI, integrated AI into their logistics systems to enhance their adaptability, transparency, and environmental responsibility. Using a comparative case study approach, informed by CAS and SoS theories, this study explored how AI-driven classification, feedback loops, and decentralised control mechanisms contribute to sustainable and resilient supply chain architectures.

The findings suggested that AI in fashion logistics functions not only as an optimisation tool but also as a strategic enabler of systemic transformation. Each brand demonstrated a unique approach shaped by its cultural and organisa-

tional context: Stella McCartney leveraged AI and blockchain to track circularity and traceability; Patagonia applied AI to enable repair and resale cycles through Worn Wear; RE:CODE used AI to facilitate creative upcycling logistics; and MUJI implemented predictive AI for minimalist and stable inventory management. These cases revealed that, although AI enables adaptive logistics across contexts, how sustainability is operationalised remains regionally distinct and is influenced by governance structures, design philosophies, and levels of digital maturity. From a managerial perspective, this study emphasised the importance of adopting complexity-aligned project methodologies, such as Agile, Lean, or hybrid frameworks. These approaches assist organisations in accommodating uncertainty, fostering real-time responsiveness, and aligning supply chain decisions with dynamic environmental and market signals. When effectively integrated, AI systems act as dynamic agents in a broader system, enhancing informational coherence, enabling rapid reconfiguration, and contributing to long-term circularity goals.

Beyond the current implementations, this study emphasised the transformative potential of quantum AI technologies in shaping the future frontier of fashion logistics. Given that traditional computing systems encounter limitations when solving high-dimensional optimisation problems, quantum computing offers exponential processing power through entangled probabilistic states. When integrated with AI, this hybrid system may provide real-time solutions for emission-aware routing, reverse logistics planning, and energy-efficient warehousing. Furthermore, by simulating complex environmental scenarios with higher fidelity,

quantum AI can significantly enhance the ecological intelligence of supply chains, enabling fashion brands to meet climate goals while remaining operationally agile.

This study contributes to both academic and practical domains by offering a comparative analysis of AI-enabled logistics classification systems within the sustainable fashion industry, using a Complex Adaptive Systems (CAS) and Systems-of-Systems (SoS) perspective. Theoretically, the study expands the application of CAS and SoS frameworks to fashion logistics by demonstrating how AI acts not only as a coordinating mechanism but also as a generative agent that restructures logistics networks through feedback loops and dynamic adaptation. Practically, the findings offer supply chain practitioners a benchmarking framework to evaluate AI adoption strategies aligned with regional policy contexts, digital readiness, and sustainability objectives.

Despite these contributions, this study has several limitations. First, it primarily relied on secondary data sources, including official brand reports and sustainability disclosures. While these sources are rich and up-to-date, they may lack the depth and granularity of field-level insights. Second, the analysis focuses on four global fashion brands—Stella McCartney, Patagonia, RE:CODE, and MUJI—which, although geographically and strategically diverse, do not capture the full spectrum of global fashion actors, particularly SMEs or brands from emerging markets. Furthermore, due to the significant differences in scale and market position among the sustainable brands analyzed in this study, there are limitations to the validity of direct comparisons. Third, the discussion of Quantum AI remains

largely conceptual. Given the early stage of its integration into real-world fashion logistics, the application of quantum-enhanced AI is presented here as a theoretical proposition rather than an empirically validated framework.

To enhance the generalisability and empirical robustness of future research, we recommend three key directions. First, qualitative fieldwork—such as in-depth interviews with logistics engineers, AI system developers, and sustainability officers—should be conducted to reveal internal dynamics, implementation barriers, and organisational learning processes. Second, expanding the analysis to include small and medium-sized enterprises (SMEs) and fashion brands operating in non-Western contexts would provide a more inclusive understanding of sustainable logistics transformation. Lastly, as Quantum AI technologies continue to mature, simulation-based modelling, pilot case experimentation, and quantitative assessments (e.g., feedback loop efficiency, adaptation latency, carbon footprint reduction) will be essential to evaluate the feasibility, scalability, and ethical implications of these systems in complex, globalised supply chains.

The future of sustainable fashion logistics will be shaped not only by technological convergence—such as AI, IoT, and quantum computing—but also by the integration of complexity-aware policy frameworks that enable adaptive, resilient, and circular supply chain ecosystems. Unlike prior studies that focus on isolated AI functions in apparel manufacturing (Choi et al., 2018; Lee & Trimi, 2021), this study synthesizes CAS/SoS perspectives with AI's agentic role, offering a systemic view of logistics adaptation. Furthermore, the theoretical integration of quantum AI

—though exploratory—provides a blueprint for future empirical simulations and impact forecasting in sustainable fashion systems.

List of abbreviations

- AI: Artificial intelligence
- CAS: Complex adaptive systems
- CSR: Corporate social responsibility
- DPP: Digital product passport
- EPR: Extended producer responsibility
- IoT: Internet of things
- Quantum AI: Convergence of quantum computing and AI
- SCM: Supply chain management
- SoS: System of systems

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