HYPERLOCAL KNITTING

BUILDING SUSTAINABLE NETWORKS WITH 3D SEAMLESS TECHNOLOGY

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Abstract

Traditional manufacturing models are increasingly unsustainable and vulnerable to environmental and geopolitical challenges. Industry 4.0 principles integrated with cutting-edge 3D knit technology form the basis for the proposed Future Factory Network (FFN). The FFN enables localised production on a global scale, where the physical location of designers and consumers becomes irrelevant; aligning with circular economy principles and offering extensive design options. Produced with near-zero waste, minimal post-processing, and highly customisable, 3D knit products offer an ideal solution for sustainable manufacturing. This research will develop and test a novel manufacturing model that leverages existing resources to adopt slow fashion principles within a scalable, efficient, and agile framework. The FFN model aims to enhance brand sustainability and circular economies through smart manufacturing systems and advanced 3D knit technology. Whilst this model addresses manufacturing processes, the behavioural shifts needed among consumers and stakeholders are intrinsic issues beyond the scope of this research.

Keywords: *3D knit, Industry 4.0, Industry 5.0, Sustainability, Circular economy*

INTRODUCTION

This paper reports on an ongoing doctoral research project in its second year, which explores the intersection of hyperlocal production, 3D knitting, and Artificial Intelligence (AI)-driven processes. The project investigates how the fashion industry can harness digital 3D seamless knit technology for hyperlocal manufacturing to develop sustainable knit products using advanced knitting technologies. This paper presents the research context, outlining the unique methodology that integrates AI to optimise design and material use and introduces the Future Factory Network—a conceptual model for sustainable, site-specific production.

Discussion of the preliminary findings offers insights into this innovative approach, its potential applications and its impact.

3D SEAMLESS KNITTING, INDUSTRY APPLICATIONS AND SUSTAINABILITY

Knitting is the creation of columns of intermeshed loops from a continuous yarn. Flatbed knit machines can produce various outputs, including 3D seamless knit products, shaped (or fully fashioned) panels, and cut-and-sew fabrics. 3D seamless knitting, the focus of this research, minimises or eliminates the need for typical garment construction post-processes by directly engineering near-complete clothes and various products on the knitting machine (Choi, 2005). This technique has evolved from hand-knitted seamless socks in ancient Egypt to advanced technologies offered by manufacturers like Shima Seiki and Stoll, whose patented systems, WHOLEGARMENT® and Knit and Wear®, dominate the market (Pavko Čuden, 2022b; Spencer, 2001).

WHOLEGARMENT® technology streamlines garment production by eliminating the need for linking and reducing waste (Basu & Gupta, 2019; Giglio et al., 2022; Mahbub et al., 2014). Linking is joining individual knit garment pieces together, stitch for stitch, as needed for shaped and cut-and-sew knitting manufacturing methods. Throughout the researcher's experience, there has been an increasing shortage of linkers globally. Factory work is less appealing to younger people than it once was, so fewer of the next generation are learning the skill. WHOLEGARMENT® technology automates garment construction, reducing labour and material waste, thereby aligning with common sustainable production goals (Pavko Čuden, 2022b; Xie et al., 2021). The technology also supports circularity by avoiding mixed-fibre sewing threads needed to sew garments together, complicating recycling.

In conjunction with the knitting machines, Shima Seiki's TOTAL FASHION SYSTEM® offers efficient, sustainable, and flexible production systems that integrate design, virtual sampling, and production management. The TOTAL FASHION SYSTEM®, which enables Just-in-Time manufacturing, which is simply making goods as needed to reduce waste (Swanson & Lankford, 1998), and mass customisation (Sustainability at SHIMA SEIKI, n.d.) for efficient, sustainable, and flexible production (Davis, 1987; Swanson & Lankford, 1998). The technology can align with Davis's (1987) definition of mass customisation by meeting the customer's individual needs anywhere and anytime, with value (Davis, 1987). WHOLEGARMENT® is the selected technology in this research to test a hyperlocal, digitised Future Factory Network (FFN), addressing labour shortages and potentially democratising manufacturing.

In today's industry application, the Shima Seiki TOTAL FASHION SYSTEM® currently operates within a single manufacturer. The Future Factory Network (FFN) proposes expanding the system into a decentralised network of "Design Hubs" and local manufacturing sites. This approach could reduce freight costs, lead times, environmental impact, and geopolitical risks by enabling responsive production closer to consumers—making import tariffs and potential geopolitical crises like the COVID-19 pandemic less impactful to supply chains.

Sustainability improvements in the manufacturing industry are essential, and seamless 3D knitting provides significant advantages over traditional manufacturing methods. It reduces waste, eliminates labour-intensive post-processing, has a lower carbon footprint, and, in applications outside of apparel, can produce flat-packed, lightweight products (Cerulo et al., 2022; Pavko Čuden, 2022a). The textile industry contributes 8% of global greenhouse gas emissions and generates significant waste, with 33% of the 100 billion garments produced annually ending up in landfills within a year (Khan et al., 2023; Quantis, 2018).

Whilst 3D seamless knitting has vast potential to reduce waste, designing requires highly skilled specialised programming to maximise the technology's technical capabilities (Peterson & Ekwall, 2007). The development of AI to assist with programming could significantly enhance communication of design and enable knit programming capabilities, allowing users with minimal experience to create effective and appealing knit programs for production with shorter lead times and fewer resources dedicated to sampling (Scheidt et al., 2020), this will be explored further later in the paper. The proposed FFN has the potential to address the need for specialised skills and reinforce its commitment to sustainable and efficient production, balancing the advantages of WHOLEGARMENT® technology integrated with technological innovation and ethical manufacturing practices.

Integrating Industry 4.0 technologies, explored later in the paper, can improve collaboration throughout the FFN supply chain, making it possible to scale slow fashion principles. Slow fashion is an alternative to fast fashion, aiming to slow resource extraction while meeting essential needs and representing a "future vision" for the fashion industry (Aakko & Koskennurmi-Sivonen, 2013; Cataldi, 2013). Cataldi (2013) proposes deconstructing the 'fast fashion' sector into more specialised fashion industries, such as slow fashion, which has many business models, including recycling, resale, reuse, and repair of garments. Although slow fashion businesses still operate for profit (Pucker, 2022), they are more socially and environmentally conscious and strive to have a positive impact.

For slow fashion to be a sustainable, scalable fashion model, collaboration is critical, and interconnectedness strengthens the actors through the guidance of similar principles (Cataldi, 2013). An interlinked local system of designers, consumers, and supply chain workers can create connections throughout the fashion life cycle, offering a philosophy similar to slow fashion except at scale (McRobbie, n.d.). Sustainable systems, like the proposed FFN, care for internal and external systems, from work culture to external society's well-being – necessitating the shift from the technological advances of Industry 4.0 to Industry 5.0, driving innovation in knitting, delivering benefits for the environment, industry, work culture and society (Maiti et al., 2022; Pavko Čuden, 2022b; *Sustainability at SHIMA SEIKI*, n.d.).

INDUSTRY 4.0, 5.0 AND 3D SEAMLESS KNIT

The transition from Industry 4.0 to Industry 5.0 represents a critical opportunity for the knitting industry to align advanced automation with sustainability and human-centric principles. The FFN proposes reconfiguring existing Industry 4.0 technologies into a globally adaptable, sustainable manufacturing model that could transform the knit manufacturing industry.

Industry 4.0's integration of cyber-physical systems (CPSS), Internet of Things (IoT), and AI has revolutionised manufacturing by enabling smart, interconnected production environments (Ahuett-Garza & Kurfess, 2018; Pavko Čuden, 2022b) (Ahuett-Garza & Kurfess, 2018; Pavko Čuden, 2022). IoT refers to internet-connected objects with built-in intelligence capable of communicating, exchanging data, making decisions, triggering actions, and delivering services. It emerged from IT processing power, cloud computing, and data analysis advances. In the textile industry, IoT is primarily linked to Radio-Frequency Identification (RFID) for tracking and tracing (Zizic et al., 2022). Industry 5.0 builds on this foundation by emphasising worker well-being, resilience, and sustainability, fostering a more balanced manufacturing ecosystem (European Commission. Directorate General for Research and Innovation., 2020; Ivanov, 2023; Maddikunta et al., 2022).

The integration of automation within Industry 5.0 does not seek to replace human labour and creativity, but rather to enhance the human experience by removing repetitive and labour-intensive tasks. One example is to enable designers to focus on innovation, especially with 3D knit seamless products, which can be advanced in technical complexity. The advanced technology can leave designers at the mercy of the programmer's willingness to experiment (Taylor & Townsend, 2014), and AI can potentially help overcome these limitations. For instance, AI-driven tools can assist in automating the creation of technical specifications, such as tech packs for complete garment knitwear. This optimisation allows designers to conceptualise and iterate creative ideas more freely while ensuring that these ideas are technically feasible and aligned with production requirements. AI models trained with diverse design scenarios and costing frameworks can offer real-time suggestions, improving the efficiency of design-to-production processes (Grosso & Boselli, 2022). Such integration fosters a symbiotic relationship between human creativity and machine efficiency, where AI supports designers by streamlining complex technical details, ultimately enhancing their capacity to meet market demands without compromising the artistic and ethical dimensions of fashion design. This human-technology collaboration aligns with the core values of Industry 5.0, reinforcing creativity rather than constraining it (Adel, 2022; Kazancoglu et al., 2023).

By integrating AI and machine learning, the FFN seeks to support decentralised decision-making, enabling hyperlocal production that adapts to market demands and geopolitical challenges (Li et al., 2021; Zizic et al., 2022). The FFN aspires to leverage these advancements to scale slow fashion principles, offering on-demand, localised manufacturing.

Technologies like Shima Seiki's WHOLEGARMENT® and a range of "smart technology" such as "Smart Bobbins", which are elaborated on later in the paper, streamline production, reducing lead times and the necessary resources while enhancing flexibility and circularity (Pavko Čuden, 2022b; Simonis et al., 2016). Smart Factories, exemplified by the Shima Seiki Factory Boutique, demonstrate the potential for customised, sustainable production using existing technologies (Peterson et al., 2011). Complemented by advanced software for design visualisation and automated production used within smart factories, environmental impact and efficiency are reduced.

The FFN's reliance on automation could enhance efficiency and create new job opportunities in high-labour-cost regions by reviving local industries. Labour shortages have severely impacted the U.S. manufacturing sector. In 2020, there were over 600,000 stable manufacturing jobs on the job market. As noted earlier, Australia is experiencing the retirement of older workers before their skills have been passed on, causing great worry to stakeholders (Stevick, 2023).

By combining human ingenuity with robotic systems, Industry 5.0 ensures innovation supports societal well-being and environmental sustainability, aligning the textile industry with modern economic and ecological goals (Adel, 2022; Kazancoglu et al., 2023).

ARTIFICIAL INTELLIGENCE, KNIT PROGRAMMING AND 3D SEAMLESS KNIT

Since its inception in 1955 by Stanford Professor John McCarthy, AI has evolved from creating intelligent machines to a broader discipline focused on developing machine intelligence. Contemporary definitions describe AI as intelligence generated through mathematical modelling, enabling machines to process signals, make decisions, and reduce human error (Hassani et al., 2020; Manning, 2020; Wang et al., 2024). AI classification is based on its capacity to emulate human thought and emotion, encompassing categories such as AI-enabled machines and technology-focused approaches (Hassani et al., 2020; Joshi, 2019). This research will primarily use generative AI, though integrating additional AI technologies could further enhance its outcomes if there were increased resources.

Hassani et al. (2020) classify IoT applications into internal and external platforms, with machine learning (ML), a subset of AI, playing a critical role in enhancing IoT's capabilities. IoT refers to internet-connected objects with built-in intelligence capable of communicating, exchanging data, making decisions, triggering actions, and delivering services. It emerged from IT processing power, cloud computing, and data analysis advances. In the textile industry, IoT is primarily linked to Radio-Frequency Identification (RFID) for tracking and tracing, such as the referenced earlier, RFID "smart bobbins" enable operators to respond immediately to yarn changes without relying on manual checks or sensor triggers, saving up to 20% in reset time while reducing skill level variability and boosting international competitiveness (Zizic et al., 2022). IoT technology, in conjunction with ML, enables AI to function intelligently by learning from its environment; for example, it can be particularly valuable in predicting the properties of knitted fabrics. Artificial Neural Networks (ANNs), a common ML tool, effectively model the complex relationships between yarn, machine type, and knit structure, forecasting fabric attributes like handle, drape, and comfort (El Naqa et al., 2015; Singha et al., 2022). ANNs rely on input, hidden, and output layers to filter complex data, and their efficiency can be further improved using fuzzy logic (FL) to manage variable parameters (Alibi et al., 2013; Yildirim et al., 2018). There is incredible potential in using AI to predict machinery failures and faulty products, reducing waste and extending the life of equipment whilst enhancing the workers and designers through human and technology collaboration (Banjanović-Mehmedović & Mehmedović, 2022). Incorporating other advanced AI techniques, such as long short-term memory (LSTM) models, offers significant potential for automating knit programming. LSTMs can process sequential data and generate knitting codes based on design specifications, reducing the need for highly specialised programming skills (Scheidt et al., 2020) and bridging the gap between designers and programmers. Workflow and increased efficiency are possible by reducing sampling lead times and minimising waste from unapproved samples. However, designers still require a foundational understanding of 3D knitting technology to fully exploit its capabilities and streamline the design-development process (Smith & Moore, 2020).

Current training for industrial knitting machines, such as those offered by Shima Seiki, remains segmented between design and programming. Using AI to integrate these disciplines could foster technical designers capable of navigating both creative and technical aspects of knitwear production (Taylor & Townsend, 2014). Tools like design compilers, which translate high-level design elements into machine-ready instructions, hold promise for democratising knit programming and accelerating innovation in the industry (McCann et al., 2016).

Innovative AI-driven intelligent development and manufacturing systems can enhance sustainable design, development and manufacturing strategies by adopting mass customisation concepts (Grosso & Boselli, 2022) as seen in slow fashion. AI's ability to optimise and design production processes that can cater for customised and personalised products at a mass scale greatly benefits consumers, society and the environment. This research proposes a model that enables slow fashion principles to be competitive with fast fashion without compromising ethics or sustainability goals through the uptake of advanced AI technologies combined with the capabilities of 3D knitting machines. Reducing the design and development bottleneck and leveraging AI tools to make better design and technical decisions streamline the process. All whilst upholding high ethical and sustainability standards and rapidly responding to consumer demands.

3D SEAMLESS KNITTING, HYPERLOCAL, SLOW AND FAST FASHION

As consumers become increasingly aware of their impact on the environment and consumption, slow fashion becomes an increasingly important movement. Slow fashion emphasises sustainability, quality, and respect for natural resources and labour. This philosophy aligns with Shima Seiki's WHOLEGARMENT® technology, which supports zero waste, traceability, and durable garments (Aakko & Koskennurmi-Sivonen, 2013; Maffei & Villari, 2011). By enabling community-focused production and shortening supply chains, WHOLEGARMENT® technology creates local "hi-tech craft workshops" (Langvik, 2022), bridging the gap between traditional slow fashion values and the demand for faster, more efficient production.

The Future Factory Network (FFN) takes this further, leveraging 3D seamless knitting technology within an alternative manufacturing framework. The precision and flexibility that 3D seamless knitting offers are required for on-demand production, reducing waste and eliminating labour-intensive processes like linking. By decentralising production through a network of manufacturing hubs, the FFN promotes Just-In-Time manufacturing and mass customisation, striking a balance between the responsiveness of fast fashion and the ethical, sustainable principles of slow fashion (Cerulo et al., 2022; Pavko Čuden, 2022b). In the FFN theoretical framework, raw materials, like yarn, are stored and only used once an order is placed, ensuring no unsold product stock, while in this case, keeping the yarn available for new styles. This hyperlocal approach allows quick responses to market demands.

Hyperlocal manufacturing plays a pivotal role by producing goods closer to the consumer, the FFN reduces freight costs and environmental impact, reinforcing slow fashion's emphasis on local economies and minimal waste (Nawaz & Nayak, 2015; Ozdamar Ertekin & Atik, 2015). Concurrently, the FFN is highly likely to be able to respond and adapt rapidly to market demands, which aligns with the agility of fast fashion. The FFN can then be an offering for a sustainable alternative manufacturing model without sacrificing efficiency.

The integration of Industry 5.0 principles further enhances this relationship. Smart Factories like the Shima Seiki Factory Boutique demonstrate how automation and advanced technologies can scale slow fashion principles. The integration maintains the speed and flexibility of fast fashion whilst operating sustainable and ethical supply chains, fostering resilience and adaptability in shifting market demands (Adel, 2022; Kazancoglu et al., 2023).

METHODOLOGY

This research takes a practice-based approach, leveraging AI and smart technology. It aims to automate tasks where possible and improve the efficiency of the design and development process by utilising a range of low-cost or free AI tools. The developed knit products will demonstrate the flexibility and capability of 3D seamless knit technology, specifically the Shima Seiki WHOLEGARMENT SWG-XR machine owned by UTS.

The process begins with the selection of appropriate technologies, identifying and selecting AI tools that are either low-cost or free, and focusing on those that can automate repetitive tasks and increase efficiency. Leveraging the Shima Seiki WHOLEGARMENT SWG-XR machine and suite of Shima Seiki products, seamless knit products will be created and refined through virtual simulations to ensure they meet the desired specifications before being produced.

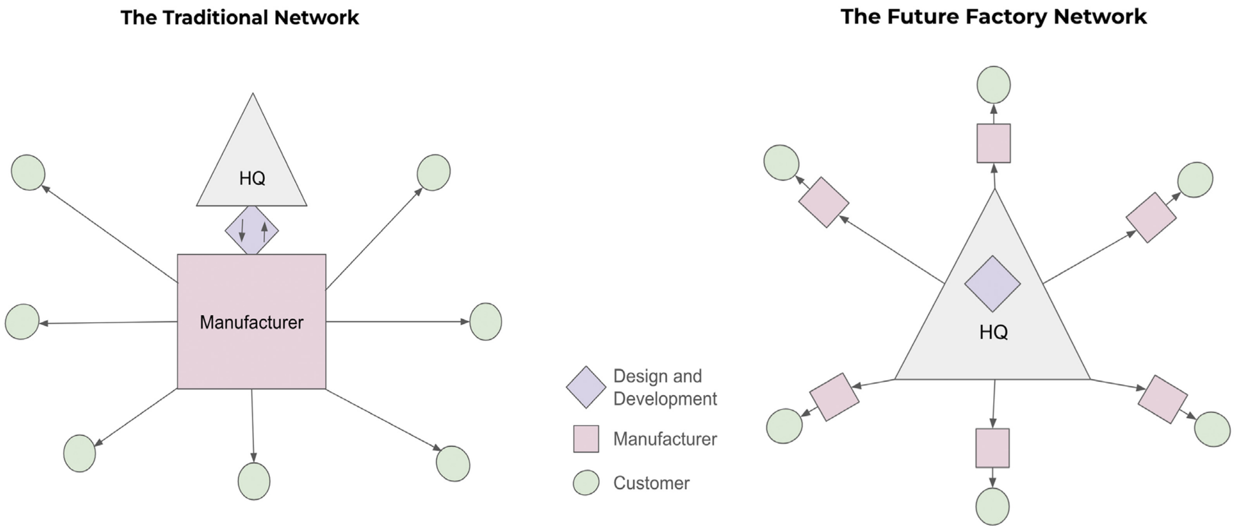

Fig. 01

The Future Factory Network (FFN) simulation aims to explore the feasibility and efficiency of a networked production environment involving Knovus and UTS, utilising their combined advanced programming skills and knit product development expertise. The FFN simulation consists of setting up a mock network connecting Knovus and UTS and integrating knit development expertise from both locations. Testing of the FFN model will include experiments to investigate the communication and coordination between the two locations. The researcher will test the production capabilities of the FFN with overseas networks, considering lead times, costs and environmental footprint.

Evaluating the technology and system requirements needed to support the FFN will be critical to the simulation. The evaluation will involve assessing the hardware, software, and communication tools necessary to establish and maintain an efficient FFN and determining the environmental impacts and the overall model through simulation with an overseas partner. The researcher will develop a rubric for evaluating the success of the experiments identifying optimal parameters for designing a system that capitalises on AI within the FFN. After the research has concluded, the researcher will exhibit the results from the experiments as a series of artefacts and samples.

This methodology tests the parameters and possibilities of a Future Factory Network by leveraging AI and advanced manufacturing technologies. The simulation between Knovus and UTS will provide insights into the technological and system requirements for efficient and innovative knit product development. The experiments conducted within the FFN will help identify the optimal parameters for designing a flexible and customisable production system that can operate in hyperlocal settings. Documentation of observations on environmental impact and lead times will be made, although thorough research on these aspects is beyond the scope of this study.

DISCUSSION AND CONCLUSIONS

This research demonstrates the potential of integrating advanced knitting technologies, such as Shima Seiki's WHOLEGARMENT® and TOTAL FASHION SYSTEM®, within a hyperlocal manufacturing model to address critical challenges in the fashion and textile industries. The proposed FFN aligns with previously discussed sustainability goals, leveraging Industry 4.0 and 5.0 principles to reduce waste, improve efficiency, and localise production. By decentralising manufacturing through a network of design hubs and local production sites, the FFN presents a sustainable alternative to traditional supply chains, often fraught with environmental and geopolitical vulnerabilities.

As highlighted earlier, the textile industry significantly contributes to global carbon emissions and waste. The FFN's emphasis on Just-In-Time manufacturing and mass customisation provides a pathway for reducing these impacts, supporting circularity, and minimising overproduction. Technologies such as WHOLEGARMENT® allow the creation of knitted products without linking, thereby addressing labour shortages and reducing material waste. The findings could underscore the benefits of shifting towards a decentralised, hyperlocal model that enhances sustainability and revitalises local economies by bringing production closer to consumers.

A key area of research in this study is the role of AI in democratising knitwear production. A critical component is that AI-driven tools, such as generative design and machine learning algorithms, can streamline the programming of complex knit products, bridging the gap between designers and programmers. In the researcher's experience as both a programmer and a designer, the right combination of shared skills offers tremendous potential; there are many ways to program the same product with varying production efficiencies, and AI offers great prospects to find optimal outcomes. The integration could improve communication and reduce the time and cost associated with sampling, allowing for more efficient design iterations. These tools align with the FFN's model by enabling non-experts to use advanced knitting technology, expanding access to sustainable manufacturing practices.

Despite these advancements, several challenges remain. While the FFN will present a robust framework for sustainable production, its scalability and integration into existing global supply chains require further exploration. Balancing local production with global demand and the complexities of managing decentralised networks will offer additional research opportunities. Additionally, while AI has shown promise in enhancing knit programming, its full potential has yet to be realised. Future studies could investigate the development of more sophisticated AI models capable of automating the entire design-to-production workflow, further reducing the reliance on specialised skills.

The research also points to gaps in applying Industry 5.0 principles within the textile industry. While Industry 4.0 has focused on automation and efficiency, Industry 5.0 introduces a more human-centric approach, emphasising sustainability and worker well-being. Integrating these principles within the FFN offers a unique opportunity to create a balanced manufacturing ecosystem that prioritises technological innovation, sustainability and ethical practices. Future research could explore how this balance can be maintained as the FFN model is scaled, ensuring that the benefits of automation do not come at the expense of human labour and creativity.

Finally, this study highlights the potential of hyperlocal production to revolutionise the fashion industry by offering a sustainable alternative to manufacturing models. By focusing on localised, on-demand manufacturing, the FFN could reduce the environmental impact and enhance supply chain resilience. However, further research is needed to fully understand the implications of this model, particularly in terms of its economic viability and ability to meet diverse consumer needs. This ongoing research will continue to refine the FFN model, contributing valuable insights into developing a more sustainable and adaptable textile industry.

In conclusion, this research demonstrates the transformative potential of combining 3D seamless knitting, AI, and hyperlocal production within a decentralised manufacturing framework. Further exploration into the remaining gaps is needed to realise the Future Factory Network's potential. By doing so, this work aims to contribute to a more sustainable, efficient, and ethical future for the global fashion and textile industries.

CAPTIONS

[Fig. 01] Traditional supply chain model vs. proposed Future Factory Network Model, Author: Chircop (2024), "Diagram of Future Factory Network next to current supply chain network model"

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