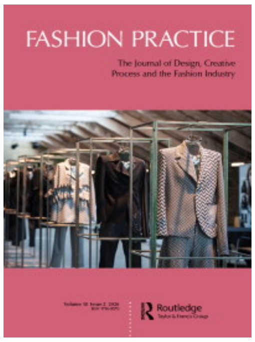

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Fashion Practice

The Journal of Design, Creative Process & the Fashion Industry

ISSN: 1756-9370 (Print) 1756-9389 (Online) Journal homepage: www.tandfonline.com/journals/rffp20

Weaving Technologies and Digital Communications Towards 3D-to-2D-to-3D Near- and Zero-Waste Manufacturing: A Future Fashion Factory Case Study

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Fashion Practice, 2026, Volume 18, Issue 2, pp. 304–337
DOI: 10.1080/17569370.2026.2676857

Weaving Technologies and Digital Communications Towards 3D-to-2D-to-3D Near- and Zero-Waste Manufacturing: A Future Fashion Factory Case Study

Lindsey Waterton Taylor

Lindsey Waterton Taylor has 25 years' experience as a design-engineer in the field of weaving technologies and woven textile design specializing in both 2D, 2D-to-3D and 3D-woven fabrications for varying end applications and industries. She has a keen interest in amalgamating technical function and performance with surface esthetics in varying textile sectors, including 10 years in the composites industry. Over the past 15 years in academia she has focused on technology and software adaptations amalgamating composite material weaving manufacturing processes, with successful commercial projects, for clients diversifying their flat 2D-woven high-performance fabrics (carbon, Kevlar, to polyester, and natural fiber blends) to 3D-woven products, for products within textile sectors, for example: apparel, automative and aerospace.

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Abstract

This research relates to 3D-to-2D-to-3D woven advanced manufacturing. The value in advancing the conventional weaving machine's operational production principles to produce derivative woven products, once valued as an investment for a lucrative return (high-value products) particularly in the composites industry, could then find an opening in tailoring on-loom (conventional weaving machine) fashioning-forms. Thus, opening the application of this exciting approach to using the weave design-engineering principles in conventional weaving machine production/manufacturing in the apparel/fashion sector. Few organizations have the combined knowledge to exploit this opportunity, as typically a team lacks the numerous skills to utilize these 3D-to-2D-to-3D wovens, best done by repurposing the conventional weaving machine's operational production principles that this research proposes. The case study rationale of this research that combines the works of four AHRC-funded Future Fashion Factory industry partnerships is to showcase how the exploration of digital software systems and communication tools where employed in articulating and navigating the inner mindset of an individual's visualization of a 3D-form, alongside the conventional weaving machine's operational production principles, and barriers faced in aligning these with the weave design-engineering remit required for actual production/manufacturing of 3D-to-2D-to-3D. The research methodology employed an action-iterative-design theory toward optimized geometrical forms, utilizing folding and tailored fashioned maquettes; alongside process-parameters, design thinking, on-machine learning, and material agnostic approaches. The synergy of these four projects brought forward key parts, with each a standalone challenge, and concluding results, yet stronger together toward 3D-weaving the future. Leading toward re-engineering weaving parameters and principles, demystifying 3D-wovens for UK weaving mills and their conventional weaving machines operational production principles to diversify in-house technologies toward 3D-to-2D-to-3D wovens to broaden appeal and utilization by future product/fashion/composite design-engineers, alongside deepening the learning of weave design-engineers.

List of Acronyms: FFF: Future Fashion Factory; 3D WIC: 3D Weaving Innovation Center; PoM: Proof of Market; PoC: Proof of Concept; ICP: Innovation Challenge Project; TOS: Twelve Oaks Software Ltd; Op3D: Optima 3D Ltd; WFN: WEFFAN; SME: Small Medium Enterprise; VoSp: Vorteq Sports Ltd; SDW: S. Dawes Weaving Ltd; E.P.CM: Ends Per CM; P.P.CM: Picks Per CM; IP: Intellectual Property

KEYWORDS: 2D- & 3D-Wovens, 3D-Weaving, fabric, composite, near-to and Zero-Waste manufacturing, digital software systems for weaving manufacture

This research relates to 3D-to-2D-to-3D woven advanced manufacturing. This means that product geometry from a physical product (3D) is converted into a 2D-flattened state to then permit translation into a graph template that is a grid system containing the precise number of rows and columns (relating to weaving specifications) to situate the binary code (over or under, like 1s and 0s). This graph template is the 2D-visual communication of how the conventional weaving machine will read the weave file for production/manufacture of a 2D-woven flat fabric. In producing the weave file, the weave design-engineer inputs weave structures that facilitate the woven fabric, once removed from the constraints of the conventional weaving machine, being able to open up into the original product geometry (3D-woven). This principle has been explored in various fields for 35–40 years, but the process has not been successfully exploited for commercial purposes yet due to the complex nature of the 3D-to-2D-to-3D transitions. The value in advancing the conventional weaving machine's operational production principles to produce derivative woven products, once valued as an investment for a lucrative return (high-value products) particularly in the composites industry, could then find an opening in tailoring on-loom (conventional weaving machine) fashioning-forms. Thus, opening the application of this exciting approach to using the weave design-engineering principles in conventional weaving machine production/manufacturing in the apparel/fashion sector. Few organizations have the combined knowledge to exploit this opportunity, as typically a team lacks the numerous skills to utilize these 3D-to-2D-to-3D wovens, best done by repurposing the conventional weaving machines operational production principles that this research proposes. The laborious weaving principles and processes of using conventional weaving machines are still to be overhauled, to permit quantity verification (low-to-high-value products) on investment, or as a solution to onshore manufacturing to shorten the supply chain, to on-demand customization. A core theme that has been evident since 3D-to-2D-to-3D wovens arose in the mindset of UK manufacturing in the early 90's is the digital software systems that encompasses the design-engineered fashioned woven fabric/composite production specifications for conventional weaving manufacture. The communication for understanding or reading of how the simple single woven cloth that on first interpretation of the 2D-graph template housing the weave pattern/structure can become a complex network of two directional interlockings of warp (multilayer) and weft (multilevel) in multilayer-multilevel forms is required. This is to enable all, from weave design-engineer specialist to a non-specialist gain insight into when the multilayer-multilevel woven pattern/structure, as in the 2D-graph template is woven in a 2D-state and once removed from the constraints of the conventional weaving machine can fully become a near-net-shaped tailored 3D-woven product. It must be noted that digital software systems are one aspect of the commercial challenges for 3D-to-2D-to-3D wovens/weaving due to the many stages in developing the 2D-information from the original 3D-form, to produce a replica-interpretation using conventional weaving machines in weaving the required end product, that upon removal becomes the 3D-woven product form.

The case study rationale of this research that combines the works of four AHRC funded Future Fashion Factory industry partnerships is to showcase how the exploration of digital software systems and communication tools where employed in articulating and navigating the inner mindset of an individual's visualization of a 3D-form, alongside the conventional weaving machine's operational production principles, and barriers faced in aligning these with the weave design-engineering remit required for actual production/manufacturing of 3D-to-2D-to-3D. The research methodology employed an action- iterative- design theory toward optimized geometrical forms, utilizing folding and tailored fashioned maquettes; alongside process-parameters, design thinking, on-machine learning, and material agnostic approaches. The synergy of these four projects brought forward key parts, with each a standalone challenge, and concluding results, yet stronger together toward 3D-weaving the future. Leading toward re-engineering weaving parameters and principles, demystifying 3D-wovens for UK weaving mills and their conventional weaving machines operational production principles to diversify in-house technologies toward 3D-to-2D-to-3D wovens to broaden appeal and utilization by future product/fashion/composite design-engineers, alongside deepening the learning of weave design-engineers.

Introduction

3D-to-2D-to-3D wovens have been explored in various fields for 35–40 years (Bally Ribbon Mills 2025). Companies predominantly based in the US, and their true 3D-shape-weaving machines (Taylor 2007) are advanced in their engineering, and in commercial revenue returns on investment for near-net-shape weaving toward near-to and zero- waste manufacturing of woven fabrics/composites. Opportunities within the UK began with pushing the boundaries of jacquard conventional weaving machines that dominate the weaving mills and/or weaving manufacturing landscape, looking toward diversifying product lines. Using conventional weaving machines (typically jacquard due to permitting single warp yarn control for complex weave patterns/structures) were considered, rather than a true 3D-woven profile shaped manufactured route from a highly engineered, yet expensive weaving technology system. The weave pattern (also referred to as structure and/or architecture) evident in compound structures advancing know-how toward complex multilayer multilevel weave architectures informed potential shaped product, or shaped components for product applications incorporating compacted interlocked numerous warp layers (multilayer), with required number of weft levels (multilevel) in woven form. These woven forms, lying flat in a 2D-flattened state on and during the conventional weaving machines manufacturing process, that once removed from the constraints (the tensions on the woven fabric, and warp directional yarns) within the weaving cycle could be opened *via* manual manipulation *via* cutting, pulling, unfolding etc., into a 3D-woven geometry. Hence the 3D-geometries informing the 2D-graph template for the insertion of weave notation, and post-weaving the 2D-woven form transitions into the idealized 3D-woven fabric/composite geometry (Taylor et al. 2015; Schegner et al. 2019).

The principles of weaving in the production of 2D-woven fabrics/composites remain the same today as they were originally formed many, many years ago. Comprising of two directional yarns that interlock at right angles to one another in the warp (0°) and weft (90°) directions, as identified in Figure 1(a), and (d). The surface esthetics of the woven cloth visualized within a 2D-graph template (Figure 1(b)), with a square to notate each intersection of a warp and/or weft on the surface (Figure 1(c) outlined in red). In basic surface design generation, the square is either filled in, representing the warp directional yarn on the surface of the woven fabric/composite, or remaining blank representing the weft directional yarn on the surface of the woven fabric/composite. As conventional weaving machines advanced with associated dobby mechanism in controlling shaft movements, and applicable multiple warp yarn-end control, and jacquard weaving mechanisms for single warp-end control, remaining focused on single 2D-woven fabric/composite construction (Taylor 2018). The 2D-graph template representation shifted in simple surface esthetics of weave patterns between the two main conventional weaving machine types (dobby and Jacquard); simply in the way the warp yarns are controlled, maneuvered up or remaining down during the weaving cycle. The dobby requiring the representation of the surface pattern within the to-be-woven fabrics/composites appearance (referred to as top-down-design) sufficient in the inclusion of squares being filled in (warp over, 1s) or left blank (warp under, 0s). The jacquard requiring a more labor-intensive process of color blocking within the 2D-graph template either a like-for-like visual representation of the intended single cloths surface pattern/figuring or advancing to compound structures (double cloth principles) color blocking to apply the amalgamation of varying weave patterns/structures/architectures within. This enabled the advanced and more complex multilayer and multilevel weave architectures to almost stitch two or more warp layers with weft levels together or remain apart at predetermined locations. Knowledge of generating weave patterns/structures/architectures and lifting plans for single layer woven fabrics/composites and compound structures provides the foundations to designing, producing multilayer-multilevel weave patterns/structures/architectures. Multilayer refers to the many warp yarns that are to interlock with the many multilevel weft insertions – This is to permit the interlocking of 0°/90° warp/weft directional yarns (refer to

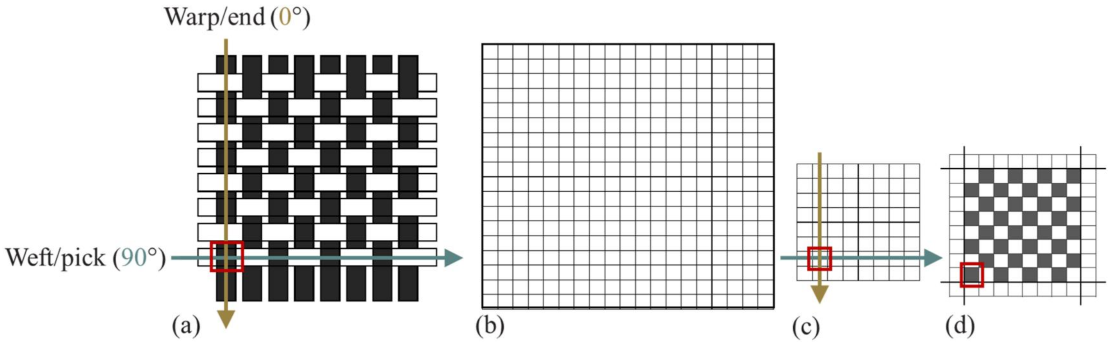

Figure 1
(a,b,c,d). Constructed plain woven fabric/composite (a) is a schematic of the warp and weft yarns representing a woven fabric. The 2D-graph template (b) representing the column for warp direction, row for weft insertion direction, reconfirmed in (c), where the red square, also in (a), (d) shows the point of intersection here, being the warp going over the weft, and therefore showing on the surface of the woven fabric (a). The weave notation in (d) represents the plain weave pattern, and the end requirement of the to be woven fabric, represented in the schematic (a). It is the complete weave notation of plain weave in (d) in the 2D-graph template that is input into the conventional weaving machines digital software system, and additional operational production fi are completed in its hardware system for production/manufacture. Illustrations produced by author and adapted from Taylor 2018).

Figure 1 (a)) in a manner to permit the woven fabric/composite, once removed from the constraints of the conventional weaving machine during the weaving cycle to be manually opened to form a shaped formation. Such as a pocketed woven pattern/structure/architecture, whereby two warp layers and associated weft levels interlock within two layers an area of separation (remaining apart) with a surrounding 'stitched' together seam area to accommodate usability.

The weave pattern/structure/architecture, as it becomes more complex in its multilayer-multilevel interlockings is typically known as the weave architecture. This is the advanced complex generation of a 'pattern' that cannot with ease be generated within a 2D-graphical representation/template (Kovačević et al. 2021), visualizing the top-down surface aesthetic (Figure 1 (a), and Figure 2 (a-c), but requires an additional weave generation system as shown in Figure 2 (d-i) to denote the individual location, the position of each warp (Figure 2 (f) and (h) upon each weft to be inserted, and their interlockings with each other. This is categorized as cross-sectional design-engineering; the completion of plain weave *via* the weft cross-sectional process is shown in Figure 2 (i). A manual cross-sectional process, focusing on the weft direction, as in Figure 2 (i), below was developed by Taylor (2007), leading on from the two warps/wefts layers/levels of the compound structures presented in the works of Goerner (1989). This was in response to the limited number of both commercially available and research institutes software developments that focused solely on isotropic in nature weave architectures applicable to technical textiles/composites sector applications due to their predictive inherent nature; more importantly when woven using carbon fiber a lightweight alternative to their metal matrix counterparts, and a solution to near-net-shaped components with minimal manufacturing waste

(Saboktakin 2019). But in trialing the conventional weaving machine in its ability to weave multilayer-multilevel 2D-for-3D transitioning into a woven shape/product, anisotropic weave architectures with uneven performance characteristics, and complexity of which do not align with ease to predictive software systems employed in the technical textiles/composites field/sector. Therefore, there was limited commercial need for software developers to investigate at this time, (early 2000s) considering time commitment, and cost required in providing a digital software cross-sectional weave generation system, such as the now readily available Technical Weaver, developed by ScotWeave (2007), and 3DWeave Composite developed by EAT: the Design Scope Company (2019).

There are many commercial challenges faced in the success of using conventional weaving machines for the manufacture of 3D-to-2D-to-3D wovens (Chen, Taylor, and Tsai 2011), these include:

- the communication information systems, that encompasses the design-engineered fashioned woven fabrics/composites production specifications.
- digital systems and communication tools to articulate complex woven weave architectures required in the successful transitioning of a 2D-flattened state woven counterpart, comprising of many warps and wefts interlocking at specified locations to transition into the final 3D-woven fabric/composite geometry.
- navigating an individual's inner visualization of the required 3D-woven fabric/composite to meet the demands of the ultimate product/end-user/application.

This AHRC-funded Future Fashion Factory (FFF) case study combines the works of four FFF industrial partner collaborations with the 3D Weaving Innovation Center (3D WIC 2025). The 3D WIC was established as part of a European Research Development Fund (ERDF) project (ERDF: 20R16P00901, during 2017–2020) where the author, the academic lead for 3D WIC delivered 50+ industry facing 3D-to-2D-to-3D workshops. With each FFF projects clear aim(s) and objective(s) (see the bullet points below), there was evidently underlying synergy across the thematic problems each industrial lead wanted to address. The shared synergy is in all the parts, steps and processes that are required in the 3D-to-2D-to-3D weaving-wovens and formulate the shared aim(s) that were to develop an understanding of digital systems, and the skillset required to support design creation of product form using the principles of the weave design-engineering of 3D-to-2D and recognizing and implementing the conventional weaving machines operational production principles for 2D-to-3D in the digital systems concluding file format for weaving. With each FFF industrial project a multidisciplinary team collaborated to improve designer, weave design-engineer, digital software system creator/supplier/

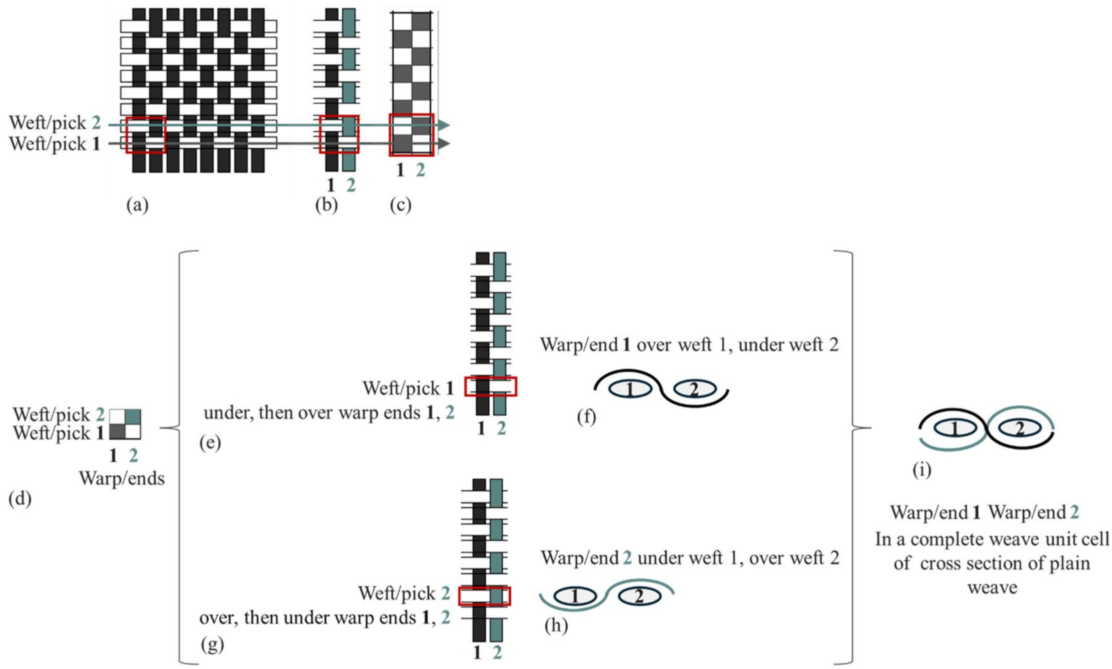

Figure 2

(a,b,c,d,e,f,g,h,i). Constructed plain woven fabric/composite (a) is a schematic of the warp and weft yarns representing a woven fabric, here showing weft/pick insertions 1, and 2. Taking a section to concentrate upon to generate the cross-sectional slice, as outlined in (a-c) x2 warp/ends, and x2 weft/picks are represented in the weave notation (d). The schematic (e) represents the position of warp/ends 1 & 2 when the weft/pick number 1 is inserted. The cross-sectional representation of (e) is presented in (f). The schematic (g) represents the position of warp/ends 1 & 2 when the weft/pick number 2 is inserted. The cross-sectional representation of combining (f) and (h) is presented in (i). (i) is the complete cross-section representing plain weave looking in through the weft/pick direction, representing the positions of warp/ends 1 and 2. Illustration produced by author for this publication.

approaches to their use and manufacturers relationships. This was, is to enable the creative sectors utilization of 2D-to-3D weaving for innovating on-shore product requirements. From minimizing waste materials, reducing the digital software system file formats toward the one necessary for weaving production/manufacture to using the conventional weaving machine, a staple in the UK weaving mills, as a tool for derivative product-design-creation, an explorative technology and principles of use to be more accessible.

To achieve the shared aim(s), the shared objective(s) and goal(s) all four FFF projects looked to:

- Identify opportunities for the use of digital software systems for 3D-design, 3D-weaving/woven manufacturing within the UK toward cost-efficiency manufacturing software tool systems.
- Explore methods of communication to articulate 3D-forms toward 3Ddesign manufacture, and 3D-weaving, 3D-wovens.
- Identify limitations associated to individual manufacturers specifications on weaving machine parameters (the conventional

weaving machines operational production principles) upon the manufacture of 2D-to-3D woven surfaces, and 2D-to-3D woven shaping/shape/product components.
- Enable accessibility to 3D-weave principles and processes for non-specialist designers/companies diversifying manufacturing capabilities and market applications.
- Resource current wasted woven materials in 2D-to-3D weaving-wovens manufacturing process for near- to and zero-waste 3D-wovens (using preexisting 3D WIC and FFF industry project partners conventional weaving machines).

Machines, Materials, and Methods: Aims and Objectives

The four industrial partner projects aligned with identified FFF core research themes, as identified in Table 1, these were: circular economy, late stage customization, aesthetic communication, data driven design/use of AI, and skills and/or education (Almond and Rainton 2025) bringing synergy in addressing different aspects of 3D-to-2D-to-3D weaving-wovens. Table 1 contains detail on each of the individual companies, who they are, alongside project title, project stage: Proof of Market (PoM), Proof of Concept (PoC), or Innovation Challenge Project (ICP), duration, and expected impacts.

The two PoM projects, one for the duration of 3 months, and one for the duration of 6 months shared an initial aim of navigating the current state of the art in association to technologies and software relating to 3D-weave manufacturing processes. Initially, the partnership with Twelve Oaks Software Ltd (TOS (2025)) was broad in scope, focusing on technologies that manufactured product outputs in 3D-form (such as 3D-printing/additive manufacturing). However, navigating synergy with the three other industrial project partners, including the second PoM project with industrial partner Optima 3D Ltd (Op3D (Optima 3D Ltd 2025)) and with consideration to the duration of 3 months permitted the inception of the project with TOS to take a positioning into 3D-weaving-wovens using conventional weaving machines. Aligning to the research within the author's experience in the field of commercially available software in the field of both 2D-weaving-wovens and 3D-weaving-wovens. TOS are a Small Medium Enterprise (SME) of software experts specializing in tailored digital products, and business driven bespoke systems. Providing consultancy and a collaborative approach in the design and implementation of software. Specializing in creating "situation-appropriate software" and systems to co-ordinate in-hand technologies and desktop systems (android, iOS, macOS, Windows) (TOS 2025). Op3D mechanical engineers with a diverse background in machine engineering with a focus on conventional weaving machines for predominantly the technical textiles and composites industry. Op3Ds' scale of machine engineering varies from product sampling to manufacturing technologies, with emphasis on varying weft-

Table 1. FFF industry project partners, stage of technological development and alignment with the FFF core research themes. Table produced by author for this publication.

	LITAC-3D WIC FFF Industrial Project Partners							
	Twelve Oaks Software Ltd. (TOS)		**Vorteq Sports Ltd.** (VoSp)		**Weffan** (WFN)		**Optima 3D Ltd.** (Op3D)	
Project Titles:	**Future design manufacture: Developing new models and systems for 3D design to manufacture.**		**Get weaving: Engineering 2D-to-3D fabric structures.**		**On-loom fashioning for off-loom 3D woven garments.**		**Animated concepts and robotic motions-mechanisms for seamless 3D shape weaving manufacture.**	
Project Stage of Technological Development:								
Project Stage: Proof of Market (PoM)	√						√	
Project Stage: Proof of Concept (PoC)					√			
Project Stage: Innovation Challenge Project (ICP)			√					
Project Duration	3 months		12 months		12 months		6 months	
Expected Impacts:								
Development of new products					√		√	
Development of new processes	√		√		√		√	
Increased use of research infrastructure	√		√		√		√	
Reduced costs and/or increased production efficiency			√		√		√	
Improved quality of products and/or services					√		√	
New business models					√			
Alignment with FFF Core Research Themes (at least one primary and one secondary)								
	Primary	Secondary	Primary	Secondary	Primary	Secondary	Primary	Secondary
Circular economy					√		√	
Late-stage customisation			√		√		√	
Aesthetic communications		√						√
Data-driven design / use of AI	√		√			√		
Skills and/or Education	√		√	√	√		√	

yarn insertion mechanisms (shuttle and shuttleless mechanisms) within variable height shedding geometries in the weaving cycle.

As separate entities to one another, TOS and Op3D aims differed in how the ultimate commercial impact, the innovation outputs were to address different aspects of 3D-weaving-wovens and 3D-manufacture, which was still a requirement of TOS aims. These aims were:

- TOS, to:
  - Prove end user needs of systems intended to shorten supply chains and support the reshoring of UK manufacturing via digital systems for 3D-to-2D-to-3D fabrics/composites.
  - Develop understanding of a digital thinking, developing a new skillset and understanding of the product development processes required for 3D woven garment production.
  - Explore the systems required to support the re-designing of designer-manufacturer-consumer relationships (for 3D manufacturing and 3D-to-2D-to-3D fabrics/composites.
- Op3D, to:
  - Scope the market in terms of shedding geometries to aid 2D-to3D weaving of shapes.

- Understand the limitations of the conventional weaving machines warp-0° and weft-90° interlockings in multilayer-multilevel weave architecture.
- Establish the variables needed in conventional weaving machines electronic electrical mechanics/mechatronics for differing shedding geometries in height permitting traditional weaving of warp (0°) and weft (90°) on-loom interlocking's' with the amalgamation of alternative directional interlockings, for example weft directions to the warp of: ±30°/±45°/±60°.
- Have an appreciation of digital design-engineering systems in the design-engineering and production/manufacture of seamless 3D-woven shapes/parts during the conventional weaving machines weaving cycle.
- Establish derivatives of 3D-shapes/parts for alternative shaped profiles toward zero-waste material manufacturing.

The remaining two of the four FFF industrial project partners, aimed to produce actual woven fabrication in the form of 2D-wovens with 3D-surface characteristics and 3D-woven shaped fabric/composite at an entry point stage of a PoC, and ICP, both 12 months in duration (as detailed in Table 1). The PoC was in collaboration with WEFFAN (WFN). The ICP was in collaboration with Vorteq Sports Ltd (VoSp). Both were challenging, in terms of pushing the boundaries of conventional weaving machines to create 2D-to-3D woven fabric/composite forms.

WFN revolutionizes garment production *via* the aims for an ambitious near-to-zero fabric and resource waste by engineering with existing UK automated textile weaving infrastructure to eliminate production steps from the supply chain. Using existing industry and research institute weaving infrastructure will promote low-cost adoption, near-shore manufacturing building demand-driven, and transparent, sustainable production. WFN aim(s) were to develop a process in which apparel components (pockets, belt-loops, zip area accommodation) could be created, if not all the apparel silhouette, in the form of 3D-woven trousers as a demonstrator in this PoC partnership; toward their pioneering a 3D-woven garment production system that weaves out waste (WEFFAN 2025).

The ICP in project partnership with Vorteq Sports Ltd (VoSp) aims were in the acquisition of knowledge for in-house know-how capabilities of double cloth woven-construction (consider tubular woven forms) and weaving production toward manufacturing capabilities of prototyping on-demand. Developing skill set in design-engineering weave notation of specific aerodynamic weave designs using highly extensible, high elongation to break elastane yarns on conventional weaving machines to undertake in-house prototyping developments for a quicker turnaround of R&D. In consideration to 3D-woven surface characteristics associated to aerodynamic wovens. VoSp a R&D company specializing in the production of high-end aerodynamic skinsuits for athletes to ensure cutting edge performance (Vorteq Sports Ltd 2025). A team of fabric specialists and engineers on board to test prototypes in the wind tunnel at the Silverstone Sports Engineering Hub ensuring VoSp can be at the forefront of UK innovation in manufacturing and testing of sportswear, speed-wear.

The four industrial partner objectives were to:

- TOS:
    - Thorough background, literature review of digital systems and software for 2D-weaving-wovens, and 3D-weaving-wovens.
    - Tap into the specific UK manufacturing and creative industry expertise to identify the needs and demands of users (designers and manufacturers) to inform the development of digital systems for this specific UK industry.
    - Via a collaboration of multidisciplinary skills through industry focussed workshops informing about the technical capabilities of 3D-weave technologies and how they can be shared more easily to improve and streamline those systems through digital tutorials.
    - A collaboration of multidisciplinary skills through industry focussed workshops informing about the technical capabilities of 3D-weave technologies and how they can be shared more easily to improve and streamline those systems through digital tutorials.
- Op3D:
    - Thorough background, literature, patent review of weaving technologies focusing on shedding geometries; variable shedding systems relating to 0°/90° with ±30°/±45°/±60° directional yarn interlocking's'.
    - Theoretically test adaptation/modification to weaving principles of motions and mechanisms on conventional weaving technologies.
    - Develop animated 360° of demonstrators' to adapting conventional weaving technologies for variable shedding mechanisms.
    - CAD/CAM requirements for the control systems required in weave notation, and weave production toward manufacture of variable shedding systems.
- WFN:
    - Through iteration processes, experimental weaving during one cycle on-weaving technology using 3D WIC's multi-shuttle jacquard weaving technology, and a rapier

jacquard weaving technology housed in a local Lancashire mill, S. Dawes Weaving Ltd (SDW (2025)).
  - Developing innovation through shuttle path configurations at 3D WIC, to deconstruct and re-engineer at SDW, for rapier weft pathways in-conjunction with appropriate weave notation.
  - Whole apparel components using rapier weaving-technology within commercialization of experimentations to strengthen outputs.
  - Fashioning components: pockets, belt-loops, zip area accommodation through iterative weave notation experiments for multi-shuttle weaving technology production toward efficient manufacturing (near-to and zero- waste).
- VoSp:
  - To create three simple geometric surface patterning's to allocate stitch/tied down intersection-points of the warp and weft within a series of compound weave structures, based upon the principles of double cloth (compound structures (Goerner 1989)).
  - Through iterative design-produce-test concluding geometric surface patterning's with a number of fabric setts (Ends Per CM (E.P.CM), Picks Per CM (P.P.CM)).
  - To produce defined standard wind tunnel swatch test specimens using VoSp Optima 3D rapier jacquard technology.
  - To produce optimized innovative fashioned swatches using 3D WIC multi-shuttle weaving technology.
  - Trialing 3D-surface height characteristics toward aerodynamic optimization.
  - To establish skill set of highly specialized principles and processes of weaving highly extensible, high elongation to break elastane yarns on conventional weaving jacquard technologies, using both rapier and shuttle weft insertion mechanisms.

The developing methodologies forming the framework for each research deliverable to be measured against for future reproducibility included the iterative process, on-machine learning for future de-risk manufacturing, material learning through iterative principles. The iterative principles (Simonsen and Hertzum 2010) are proven to support practical/experimental works in using conventional weaving machines, digital software systems and communication tools, fabric/composite 2D- and 3D-design-engineering, both on-conventional weaving machines and off-conventional weaving machines. Table 2, encompasses all tangible parts to the practical components of the projects, including commerciality of manufacturing through utilizing the conventional weaving machine(s): type: dobby, jacquard, weft insertion mechanism (shuttle or shuttleless), and applied to workshops with targeted attendees from within the field of end-user of: digital systems, and communication tools for 2D-weaving/wovens and 3D-weaving-wovens.

The three 'stage-level' categories of PoM, PoC and ICP were to differentiate the market level entry points of the associated aims and aligned objectives, these form the Innovation Summary within Table 3. For ease, the market level (PoM, PoC, ICP) and associated details are also within Table 3, of all four FFF industrial partnered projects with 3D WIC.

Additionally, competitor analysis strengthened the rationale to why these FFF projects were and remain innovative with consideration to potential Intellectual Property (IP) outcomes, evidenced in Table 4. It also provides insight to synergies across the FFF project partners, for example it highlights that the aerodynamic surface qualities of the fabric requirements of VoSp is new to the 3D WIC, in terms of product requirements. But requires known knowledge and transfer of knowledge from the 3D WIC to VoSp of weaving expertise for production/manufacturing outputs using the latest in jacquard conventional weaving machines.

The methodology framework sought to address key challenges, and in line with manufacturing outputs, for industry, as well as design practitioners in the field of textiles, woven textiles for fashion/apparel silhouettes and components of and/or for. Their success can stem from the previous works of 3D WIC lead academic and authors' industrial experiences and research background works in wovens that need to function, as well as consider surface structure and esthetics. Although, surface esthetics remain outside the scope of work as these can be applied later. The aim was to achieve 3D-to-2D-to-3D woven components, whether as a whole, such as an apparel item (trousers, shirts), or components within apparel/sportswear applications that can cross over into technical textiles/other fabrics/composite applications. Action- (Bhandari, Palokangas, and Ojanen 2025) iterative- design research (Cronholm and Göbel 2022) was explored toward optimized geometrical forms, utilizing folding and tailored fashioned maquettes in line with origami principles (Xu et al. 2022). Alongside process parameters as a method (Kongprasert, Brissaud, and Butdee 2012), in relation to iterative design methodology, with design-engineering thinking, together with on-machine learning, and material agnostic approaches. Leading toward re-engineering weaving parameters and operational production principles, demystifying 3D-to-2D-to-3D-wovens to broaden appeal and utilization by future product/fashion/composite design-engineers, some of whom may not have weave knowledge. An incremental journey of iteration, cycle of trials, changes, edit and adaptability toward design-engineering, and repeat toward optimized 3D-form/3D-shape/3D-product. Linking practice, design and manufacturing to problem solutions these four

Table 2. Machine, digital software systems, materials & methods: Conventional weaving machine utilized, including the number of layers-levels associated to the woven structure within each industry-led project. Table produced by author for this publication.

	FFF Industrial Project Partners: 3D-to-2D-to-3D weaving/wovens				
	Applicable to:				
Conventional Weaving Machine and Associated Weft Insertion Mechanism:	**Twelve Oaks Software Ltd.** (TOS)	**Vorteq Sports Ltd.** (VoSp)	**Weffan** (WFN)	**Optima 3D Ltd.** (Op3D)	**3D WIC**
Mageba multishuttle conventional weaving machine with Staubli Unival 100 Jacquard (x4 shuttles, single pick)	NA	✓	✓	✓	✓
Optima 3D multishuttle conventional weaving machine with Bonas Jacquard (x4 shuttles, double pick)	NA				✓
Bonas Rapier Jacquard conventional weaving machine (x1 rapier, single pick)	NA		✓		✓
Optima 3D rapier Jacquard conventional weaving machine (x1 rapier, single pick)	NA	✓		✓	✓
Jacquard conventional weaving machine: general to specialised operational production parameters	✓				✓
	Applicable to:				
Conventional Weaving Machine(s) Digital Software Systems and Communication Tools, Using:	**Twelve Oaks Software Ltd.** (TOS)	**Vorteq Sports Ltd.** (VoSp)	**Weffan** (WFN)	**Optima 3D Ltd.** (Op3D)	**3D WIC**
Engineered paper maquettes (3D-to-2D geometry flattening)	NA	✓	✓		✓
Non-specialised software (Excel, PowerPoint, Miro)	✓	✓		✓	✓
Specialised software (ScotWeave, 3D Weave Composite)	✓		✓		✓
Machine software (Staubli Bonas, Mageba, Optima 3D Ltd)	✓	✓		✓	✓
	Applicable to:				
Materials Consideration to Support the Tailoring / Fashioning Weave Design- Engineered Fabric(s)/Composite(s):	**Twelve Oaks Software Ltd.** (TOS)	**Vorteq Sports Ltd.** (VoSp)	**Weffan** (WFN)	**Optima 3D Ltd.** (Op3D)	**3D WIC**
Yarn type	NA	✓	✓	✓	✓
Layers-levels: 1	✓	✓	✓	✓	✓
Layers-levels: 2	✓	✓	✓	✓	✓
Layers-levels: 3>	✓	NA	✓	✓	✓
Weft shuttle path configurations	NA	✓	✓	✓	✓
Weft rapier pathways	NA	✓	✓	✓	✓
	Applicable to:				
Methods Applicable to Shape or Surface of the Near-to and Zero- waste Production / Manufacturing of 3D-to-2D-to-3D Woven:	**Twelve Oaks Software Ltd.** (TOS)	**Vorteq Sports Ltd.** (VoSp)	**Weffan** (WFN)	**Optima 3D Ltd.** (Op3D)	**3D WIC**
2D-to-3D fabric(s)/composite(s) end shape	NA	NA	✓	✓	✓
2D-to-3D fabric(s)/composite(s) surface characteristics	NA	✓	NA	✓	✓
2D flattened state geometries within the total weaving width	✓	✓	✓	✓	✓

independent FFF projects capturing the industrial landscape of weaving manufacturing within the UK and what is required in: 3D-weaving the future.

Discussion on Outputs: Digital Systems and Communication Tools

There are two forms of digital software systems, and each communicates aspects of the weaving process, principles and in the design-engineering generation for, simply referred to hardware and software. The work carried out under the project scope of TOS identified associated digital

Table 3. PoM, PoC, And ICP: market level and associated details in line with state-of-the-art background review. Table produced by author for this publication.

	FFF Industrial Project Partners: 3D-to-2D-to-3D Weaving / Wovens				
	Applicable to:				
Market Level and Associated Details (PoM, PoC, ICP):	**Twelve Oaks Software Ltd.** (TOS)	**Vorteq Sports Ltd.** (VoSp)	**Weffan** (WFN)	**Optima 3D Ltd.** (Op3D)	**3D WIC**
Proof of Market (PoM)	√			√	
There is not a proven market, or there may be an emerging market	√		√	√	√
Range of competitors to be determined	√		√		√
State of the art, background / literature review	√		√	√	√
Proof of Concept (PoC)			√		
Requiring a series of defined experimentations to demonstrate feasibility of design		√	√		√
Apply experimentations within a manufacturing set-up, and research infrastructure towards commercialisation validation		√	√	√	√
Validate methodology for reproducibility		√	√	√	√
Innovation Challenge Project (ICP)		√			
Designed to address a specific need within the organisation		√			√
To establish methodology for reproducibility of identified parts		√			√
To develop skill set of production know-how towards innovative manufacturing processes		√			√
	Applicable to:				
Innovation Summary:	**Twelve Oaks Software Ltd.** (TOS)	**Vorteq Sports Ltd.** (VoSp)	**Weffan** (WFN)	**Optima 3D Ltd.** (Op3D)	**3D WIC**
Digital Systems	√	√	√	√	√
3D-to-2D-to-3D weaving fabrics/composites	√		√	√	√
3D-woven shaped product form		√	√		√
3D surface characteristics for aerodynamic woven fabrics/composites		√			√
Near- zero- waste manufacturing		√	√	√	√
Advancing conventional jacquard weaving technologies		√	√	√	√
Adaptation/modification to conventional jacquard weaving technologies				√	√
On-machine learning towards digital system(s) optimisation		√			√
On-machine learning for 3D-geometry informed 2D-weaving of shaped/products/forms		√	√		√
Material agnostic approaches towards optimised 3D-to-2D-to-3D weaving-wovens		√			√

software system information relative to the research infrastructure, the conventional weaving machines within the 3D WIC. The conventional weaving machines identified in Table 2, are manufactured with pre-determined hardware (engineered by the machine manufacturer) that enables the conventional weaving machine to become operational, in terms of the machine can be turned on and ready to receive a design-engineered weave notation in a suitable file format. For example, the hardware for the Staubli jacquard conventional weaving machine UNIVAL 100 is the most sophisticated in the field of jacquard harnesses for technical textiles, particularly 3D-weaving-wovens from the 2D weaving principle that are the multilayer-multilevel weave architecture fundamentals. The individual movements of the single warp yarns are controlled by the actuators (JACTUATOR). Each actuator works individually and communicates directly with the JC7U controller, the predetermined hardware with integrated digital software systems (Staubli 2025). This permits precise warp control height within the shedding geometry; and is also relative to the work carried out with Op3D. In order for the JC7U controller hardware to be able to 'weave', it needs to receive, either *via* manual input, or uploading of a digital file from

Table 4. Market, competitor analysis applicable to the identified FFF industry project partners and the 3D WIC, together with expected intellectual property (IP) generation. Table produced by author for this publication (EE Exclusives 2025).

	FFF Industrial Project Partners: 3D-to-2D-to-3D Weaving / Wovens				
	Applicable to:				
Market Analysis Concluding in Lack of Competitor(s) within the Applicable Field to the Industry Project Partner: (x3 relative competitors and/or researchers within the field)	**Twelve Oaks Software Ltd.** (TOS)	**Vorteq Sports Ltd.** (VoSp)	**Weffan** (WFN)	**Optima 3D Ltd.** (Op3D)	**3D WIC**
MagicLeap: https://www.magicleap.com/	√				√
Mircrosoft HoloLens: https://learn.microsoft.com/en-us/hololens/	√				√
XR Stories: https://xrstories.co.uk/	√				√
Velotec: https://www.velotec.cc/		√			
Bioracer: https://shop.bioracer.com/the-most-tested/		√			
Sobike: https://sobike-active.com/pages/about-sobike		√			
Unspun: https://www.unspun.io/?srsltid=AfmBOorox2EdAEvPQXZnKSEwnQQEf2B5szLSQkJEWwJoYvAdIe_LasGI			√		√
Kelly Konings: https://scandinavianmind.com/kelly-konings-designer-on-why-3d-and-whole-garment-weaving-is-here-to-stay/			√		√
EE Exclusives: https://www.ee-exclusives.com/3d-woven-garments-developments/			√		√
VegaTM: Unspun: https://www.unspun.io/vega			√	√	√
Bally Ribbon Mills: https://www.ballyribbon.com/				√	√
3D Weaving: High end technical fabrics: https://3dweaving.com/				√	√
	Applicable to:				
Expected IP Generation:	**Twelve Oaks Software Ltd.** (TOS)	**Vorteq Sports Ltd.** (VoSp)	**Weffan** (WFN)	**Optima 3D Ltd.** (Op3D)	**3D WIC**
Cost-effective software system	√			√	√
Advanced in-house skills for on-demand R&D/product manufacture		√			√
Near- zero- waste design know how towards catalogue of apparel components / whole garments (future brand collaborations)			√		√
Adaptive animated 360° mechanical demonstrators for future conventional jacquard weaving technology modification know-how				√	√

external software the weave notation. Once this is input, the second stage before production/manufacture is to use the integrated digital software within the hardware that comes with the weaving machine that is partnered and positioned underneath the jacquard harness. Remaining with the machines in Table 2, the Staubli Unival 100 jacquard at the 3D WIC is partnered with the Mageba multi-shuttle, multi-beam warp let-off system (Mageba 2025). Therefore, the Mageba also has hardware with integrated digital software systems, which is to control the weaving parameters, the conventional weaving machines operational production principles of this machine in conjunction with the jacquard. Both hardware systems are closed systems that cannot be adapted to deviate from the specifications pre-set by their respective manufacturers – A key conclusion from both TOS and Op3D.

The interoperability is the main inhibitor to reducing the number of hardware-software input stages before weaving can commence. This results in the conventional weaving machine being almost obtuse to non-specialists. TOS identified inhibitors to weave accessibility for design-practitioners/product-designers/other industries that could benefit from the use of 2D-wovens and/or 3D-wovens. TOS concluded: operating hardware, typically that associated to the production/manufacturing operation of the conventional weaving machines and design, weave notation, weave geometries within independent digital software systems analysis from fashion and textile design perspective shows that the missing features, requirement of specialist, expertise skills (in specific steps), bespoke and confidential features in-software all contribute to reduced interoperability for current users, as well as limited adoption of conventional weaving machines, and 3D-to-2D-to-3D principles and processes to wider audiences/end users. As an example to the many digital software system stages/step sequences in generating various file formats required before confirmation in the hardware, the conventional weaving machine for production/manufacture, it was found that virtual fashion software Clo3D (Clo3D 2025), amongst a few others, and Lectra Design Concept 3D Tech Tex (Lectra 2025) used within the automotive industry, are two of the limited number of design digital software systems for the communication of 3D-geomteries, and the potential to flatten into a 2D-format. The 2D-format still is not within the 2D-graph template, representation required to input the woven notation in its entirety; accounting for every warp and weft point of intersection in its simple format of a single-layer design file. When in production, this 2D-graphical representation needs to be accompanied by design parameters of weft-yarn insertion information, and if converting to a multilayer multilevel 3D-weave notation, how many layers and levels there are. The virtual fashion digital software systems, when considering 2D-to-3D have features to enable physics-based simulation, digital processing of 'real' fabrics, and their associated geometries when in product form; seams, folding, pleating requiring application of force (user input) to generate lines that alter meshed patterns. Design Concept 3D Tech Tex is based on parametric designing and requires lengthy human input to obtain a small component of a fashion form, such as the bra in the work of Shi et al. (2023), with a screenshot of the parametric structure to apply the 3D-geometery to in Figure 3. This digital software system has a flattening feature that can translate the 3D-geometries into a 2D-flattened state design, relative to the intended 3D-product geometries. However, this is mostly, still an experimental digital software system as those seeking methods/software/communication tools to input, transform-flatten, to apply weave notation too still require other design-steps, file formats to interpret the 2D-flattened design of the 3D-geometires into a 2D graph template, for the insertion of weave pattern/weave architecture (single cloth, double, cloth and multilayer-multilevel). Furthermore, the conventional weaving machine's operational production principles and associated parameters still need to be input into the hardware software system, and a step at the moment remaining with a specialist operative.

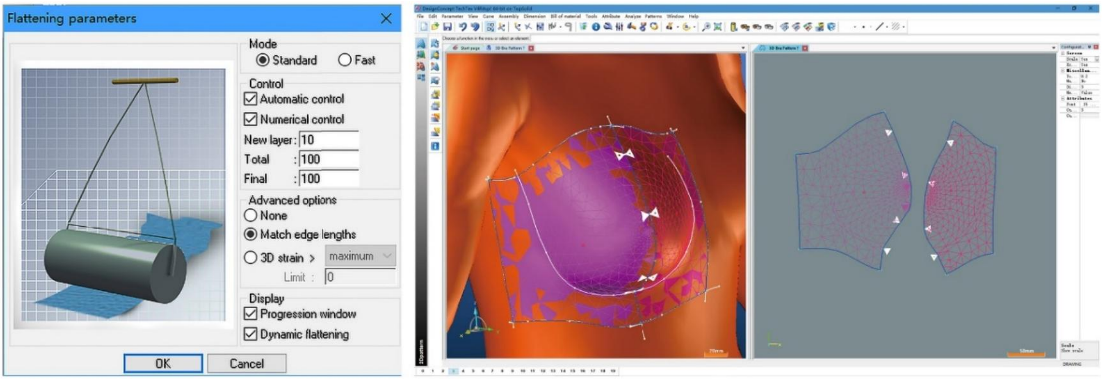

Figure 3
3D-bra geometry application using parametric calculations toward flattened conversion (Shi et al. 2023).

Software for 2D-input is more readily available, including ScotWeave (2025), Pointcarrè (2025), NedGraphics (2025). Each permitting the input of top-down weave notations, fabric/composite details associated to warp and weft, colorways and machine type, and operational production principle specifications for the concluding design file format. To use effectively these still require the end user to have a basic understanding of weave to input information that can be read appropriately by the associated hardware toward production-manufacture. Skill set includes basic understanding of weave type, weave documentation, weave to fabric specifications, weave to manufacture specification. These will also generate animated visualization interpretation of final details input but is in the 2D-flattened state. Software with 3D-capabilities, cross-sectional design input, and visual interpretation from 2D-top-down input include ScotWeave Technical Weaver (ScotWeave 2007) and EAT 3D Composite; with the latter employed by 3D WIC.

TOS also confirmed findings by previous works by the author, the academic lead at the 3D WIC in relation to industrial collaborations, open source, such as TEXGEN (2025) permit plug-ins/extensions, then there is C++, friendly wizard graphical user interface, as well as a next level, more complex Python interface (for more advanced users, to give complex commands in scripting), and visualization toolkit to render 3D-geometries. These options can all be exported to other digital software systems *via* appropriate file formats for further information input or further rendering processes such as those linked to finite element modeling for optimization of the warp and weft intersections within complex 3D-geometries. Weavecraft (Wu et al. 2020), designed by a team with textile and apparel background, contains visible UI and UX (features) elements that can ease 'softer', textile and apparel approaches. Special attributes: slice editor, stenciling with input blocks, weft operations, simulation and easy correction, continuous weft recognition automised, toward automatic structure synthesis for 3D-woven relief. Lastly, an intuitive user friendly AdaCAD, (The Atlas Institute 2025) a computational design tool that is browser based, blends features from traditional weaving software (such as ScotWeave, Pointcarrè) with circuit design tools (Friske, Wu, and Devendorf 2019) to enable multilayers to be generated *via* input of basic fabric/composites parameters required as a pre-requisite toward a layering process of the final visualization, as evidenced in the lattice structure by Meiklejohn (2023).

Table 5 formulates the commercial challenges gathered on project inception. VoSp realized at project inception the importance of digital systems, both in R&D production, toward manufacturing outputs, but also in the communication between those with basic (minimum) weave knowledge and those at an advanced level, subject specialist. The project collaboration required visual interpretation of fabric analysis, and re-formatting identified weave architecture(s) within compound structures (relative to the tube). Given VoSp were wishing to acquire knowledge and skillset toward accessibility of 2D-weaving-wovens toward 3D-surface characteristics lending themselves to aerodynamic test and validation the incorporation of non-specialist software was agreed upon. Simply, Excel graphical representation, a software standard in most businesses, but also an aid toward sense checking and subject grasp, and development of weaves applicable to 2D-to-3D surface contours, and toward further relevant complex weave architectures requiring bi-directional stretch and recover. This also provide an easy solution to archiving identified fabric analysis weaves, and weave architectures that may support 3D-surface forms for future R&D prototyping. Excel, as a foundation to weave learning, sense checking and communication is a default to the industry facing workshops delivered by 3D WIC. A business software staple, that provides a solution to communication, editing, interpretation and validation becoming slightly more complex when using shape functions to determine weft insertion shuttle paths, and weft rapier (shuttleless) insertion routes to accommodate tailoring on loom components and/or fully fashioned apparel silhouettes. This format was exploited further by WFN. Communication between WFN, 3D WIC and S Dawes Weaving was simplified in electronic, digital software system files of clearly documented weave architectures, alongside jacquard color blocking. With the 12-month duration of VoSp and WFN projects, excel defined the first part of the developmental stages toward designs that would follow the action- iterative- design research. As both projects progressed the introduction to specialist software at 3D WIC was introduced and was the first part of the methodology framework incorporating process parameters, on-machine learning and material agnostic approach. Design-engineering thinking informed the production-trials of on-machine learning toward test swatches to validate weave notations, and full fabric/composite making particulars.

The technical specification of yarn type gathered through fabric analysis and market research enabled VoSp to address the innovation

Table 5. Commercial challenges faced by the four FFF industry project partners gathered by the 3D WIC pre-industrial partner collaboration, and on project inception. Table produced by author for this publication.

	FFF Industry Project Partners: 3D-to-2D-to-3D weaving/wovens				
	Applicable to:				
Commercial challenges faced when utilising conventional weaving machines, and those industry project partners who achieved success (indicated by a tick) overcoming these:	**Twelve Oaks Software Ltd.** (TOS)	**Vorteq Sports Ltd.** (VoSp)	**Weffan** (WFN)	**Optima 3D Ltd.** (Op3D)	**3D WIC**
Communication information systems (digital software systems) for design-engineering of fashioned fabrics/composites	√	√	√	√	√
2D-flattened state transitioning to 3D-woven fabric/composite geometry	√	√	√	√	√
Digital software systems and communication tools as vision articulation and control towards 2D-flattened woven notations	√	√	√	√	√
Digital software systems and tools as vision articulation and control for non-specialist end users	√	√	√	√	√
	Applicable to:				
At the outset of the individual project inception, commercial challenges:	**Twelve Oaks Software Ltd.** (TOS)	**Vorteq Sports Ltd.** (VoSp)	**Weffan** (WFN)	**Optima 3D Ltd.** (Op3D)	**3D WIC**
Identifying opportunities for the use of digital systems for 3D design manufacture within the UK towards cost-efficiency manufacturing software tool systems	√	NA	√	NA	√
Exploring methods of communication to articulate 3D-forms towards 3D design manufacture, and 3D-weaving, 3D-wovens	√	√	√	√	√
Limitations associated to individual manufacturers specifications on weaving machine parameters upon the manufacture of 2D-to-3D woven surfaces, and 2D-to-3D woven shaping/shape/product components	NA	√	√	√	√
Accessibility to 3D weave principles and processes for non-specialist designers/companies diversifying manufacturing capabilities and market applications	√	√	√	√	√
Resource waste into manufacturing process for near- to zero- waste 3D wovens (using pre-existing LITAC-3D WIC and industry weaving technologies)	NA	√	√	√	√

challenge in defining expertise growth, on machine-weaving technology specifications for both compound structures, and high-stretch yarns. Gaining control of the weaving process, design stages (*via* the digital software system(s)) for design production (using the conventional weaving machines and associated operational production principles) enables, the speed-wear fabric specialists and fabric/composite testing engineers to quickly and effectively adapt the surface and texture of fabrics, and finalization of. By altering the woven fabrics surface such as smoothness and texture, peaks (height) and valleys (in-fabric plane) and surface pattern geometries enables the design and design for production of bespoke fabrics tailored to individual athletes. Each athlete requires different fabric surface structures to act with differing aero capacities depending on their surface shape and geometric size, and repetition as well as their sporting discipline.

Referring to WFN, 3D-weaving garments merged two manufacturing processes: woven fabrics/composites and garment manufacturing. By simultaneously creating the structure of the garment in the weaving of the fabric, eliminating steps in the supply chain, reducing production steps, time, costs, and, most importantly, waste; outside of the FFF project(s) became part of quantifiable research with WFN as Project Lead, and the author, academic lead of the 3D WIC as Co-lead on an UKRI, Innovate UK Research programme: Resource Efficiency for Material

Manufacturing (2025) project (UKRI: 10064069, 2023–2024). Therefore, the use of Excel between the two project partners and sub-contractor S Dawes Weaving, sense check was vital to make the most of the weaving manufacturers weaving technology down-time to accommodate woven-fabric/composite manufacturing. In practice iterative design stages toward final outcomes came *via* cyclic processes, and overlapping of further cyclic processes toward prototyping, testing, analyzing, refining product/process. Based on the results of the last test, this cyclic process with new additions and/or edits toward the next iteration of the design-engineered weave notations, specifications for further manufacturing of the next test pieces. Machine changes, through on-machine learning based on those in Table 2, works harmoniously with iteration processes toward the optimal solution, and meaningful analysis. This ensured the data captured could be used effectively within the constraints of the PoC 12-month timeline, and time in weaving each test piece, toward final 2D-to-3D wovens.

Discussion on Outputs: Design-Engineered Conventional Weaving Machines

3D-weaving using conventional weaving machines, entails three directional yarn interlockings in the length, width, and depth of the fabric plane. This does not only offer a manufacturing solution to both bespoke and high-volume requirements that can minimize labor intensive post-fabrication product manufacturing methods, but also makes it possible to manufacture with reduced pre-consumer waste processes. It is difficult to adapt existing weaving systems, digital software systems, conventional weaving machines. There are limitations upon flexibility to vary geometries, including but not limited to pre-determined and fixed warp density, warp and weft directional mechanisms-motions, standard let-off, take-up during weaving, shedding geometry and digital software system capabilities. When dividing the total E.P.CM (total number of warp-yarns, also referred to as ends within a CM) amongst the required number of warp-layers for the 3D-woven shape the warp density, the E.P.CM decreases within each warp-layer. This reduces stability and product functionality. The individual warp yarn control, shedding system affects the achievable height above/below the true warp line (2D-fabric/composite plane). This ability to ascend/descend from a central point (fabric plane) optimizes the weft directional interlocking routes and complex tailoring of. Variable let-off and take-up mechanisms are required to permit out-of-the-fabric-plane weaving. In conjunction with Op3D, a shared IP approach was taken with the 3D WIC for a theoretical digital-design-engineering-system proposed, in the form of animated 360° test adaptation/modification to weaving principles of motions and mechanisms on the conventional weaving machine (in this instance a jacquard machine). The developed animated 360° of demonstrators were adapted to conventional weaving machines operational production principles for variable shedding mechanisms. Remaining with simple weave notation systems (under and over, the weave pattern) a series of sequence step-step-stepping of warp yarn allocating to reallocation within the 2D-woven fabric/composite plane toward specifications for future works in the field of robotic prototype for flexible weaving of multifarious woven textile products was employed. Supported by digital software systems for design-engineering of the weave (variable file formats) and conceptual digital software systems (for the animated 360° test adaptation/modification), the Op3D PoM for weave manufacturers, woven cloth end-users requiring seamless, fully integrated on-loom production of 3D-woven forms (preforms/shapes), and reiterations of once removed from the constraints of the conventional weaving machine. This solution will enable diversification of existing woven product lines with consideration to sustainable manufacturing and future proofing customization for a 3D-weaving futures, 0.4 industrial revolution. A breadth of machine engineering, conventional weaving machine principles to the amalgamation of varying digital directional weave yarn interlocking's for manufacturing complex woven preforms (shapes) were brought together through this partnership. With trials on Op3D in-house rapid prototyping rapier weft insertion weaving technology, with open surrounding area of the reed/beat-up mechanism to permit additional theoretical add-on systems toward alternative control mechanics of electrical electronically controlled systems. The PoM timeline reduced opportunity for physical demonstrator(s), however the theoretical background review, including patent searches in line with the animated 360° test adaptation/modification reinforced both market needs, and no start-of-the-art to match the aims and objectives of this FFF PoM project. The review of terminology, digital software, and hardware systems, machine mechanics and electronic control systems of the Op3D project deliverables, alongside the TOS, PoM generated the first generation of a lexicon, which can be seen in Table 6.

Discussion

Although, with each industrial partner (TOS, Op3D, WFN, and VoSp) having their own clear aim(s) and objective(s) to be met, the synergy across the four projects leads us back to the beginning in that we are seeking to push the boundaries of conventional weaving machines operational production principles for 2D-to-3D weaving-wovens, and to simplify, make accessible the digital software systems required in converting 3D-to-2D, and understanding 2D-woven to 3D-woven. As the conventional weaving machines currently dominate the textile weaving mills/manufacturing landscape within the UK this will provide a basis for upgrading existing facilities (rather than installing new facilities) to enable 3D-to-2D-to-3D-woven production. As research with the four industry partners commenced, we knew of existing limitations at the outset (Table 6) which can be simply articulated as below:

- digital software systems currently available can converse with a differing file format, but one file format only, for example a PDF of a design generated in Photoshop can be interpreted by specialist weave software for those designs to be produced on a jacquard conventional weaving machine. However, not commercially viable, when generating an excel document of weave notation within its 2D-graph template ready for generating the breadth of information required for 3D-to-2D-to-3D (Taylor 2007; Shi et al. 2023) as a form of sense checking; this is a standalone, independent file format, yet to be challenged commercially.
- Current 3D-weave software is great for visualization of geometry if the weave pattern/structure is known. Leading to the requirement of a specialist weave design-engineer.
- In-house teams would need a wide-ranging set of skills and knowledge to adapt existing digital software systems, file formats into the final file format for production/manufacturing, and additional training would be required.
- To translate 3D-product into flattened 2D-geometries for inputting the weave notation (pattern/structure/architecture) which in turn would allow the development of manufacturing parameters for 3D-woven production/manufacture is a transition requiring both basic weave skills, for 2D-weaving-wovens, and an advanced skill set for 3D-weaving-wovens.

There remain many step sequences, stages from inception to production/manufacture, both manual interventions and digital software systems approaches, with concluding hardware information parameters. In its simplest form:

- Step 1: product inception, desired 3D-output, 3D-product geometries (digital and/or manual specifications).
- Step 2: 3D-to-2D flattening through folding (manual), paper engineered maquettes at reduced scale, unwrapping of 3D-geometries via digital/software systems to reconfigure into a 2D-state.
- Step 3: layer (warp) and level (weft) calculated total against total E.P.CM and P.P.CM (this is to account for the total number of warp-yarns in a CM, also referred to as end(s), and E.P.CM, and to account for the total number of weft-yarns in a CM, also referred to as pick(s), and P.P.CM).
- Step 4: manual identification of weft insertion toward path configurations for shuttle positioning (in-out-return), or shuttleless, rapier pathways for integrated seam allowances.
- Step 5: digital software system input in weave software for 2D-jacquard color blocking.
- Step 6: weave generation (can be done manually by pen(s), graph notation paper), input into digital software systems, such as

Table 6. Lexicon generation outcome from Op3D, and TOS, and 3D WIC FFF project partnership. Table produced by author for this publication.

Lexicon:

Weave Terms:	Conventional Weaving Machine Classification:
Notation	Jacquard
Graphical representation	Dobby
Weave unit cell	Single-end control
Common Denominator	Multiple-end control
Lifting plan	Shuttle
Weave: pattern, structure, architecture	Shuttleless (rapier)
Top-down	Let-off
Face of the fabric	Take-up
Cross-sectional	Shedding
Slice	Weft insertion
Repeat	Continuous weft
Long-hand	Beat-up
Short-hand	Cloth fell
Colour blocking	Back beam(s)
E.P.CM	Creels
P.P.CM	Front beam
D.P.CM	Fabric beam
Fabric Sett (Density)	

Excel (2D-graph template representation for sense checking weave pattern/structure/architecture), and/or straight into specialist weave generation software (e.g., ScotWeave, 3D Weave Composite).

- Step 7: weave drop-in, allocation of weave pattern/structure/architecture within the 2D-jacquard color blocking of step 5.
- Step 8: if specialized 3D-weave software available, convert 2D-weave structures (top-down) to cross-sectional slices. Adjacent borderline float length checks from slice-to-slice of each cross-section required in the 2D-jacquard color block.
- Step 9: file transfer to hardware integrated digital software systems, input machine production/manufacturing operational production principles and associated parameters, full woven fabrics specification details.
- Step 10: weave

The detailed steps 1–10 represent a snapshot of the various steps in generating 3D-geometries toward flattened 2D-geomteries to the aligned and produced intended 3D-woven. These are summarized *via* the findings from all four FFF industry facing projects, and inline with the research undertaken, and continues to be developed in the 3D WIC in

Table 7, below. In Table 7, a more simplified version of overstep sequences 1–8, with consideration toward accessibility of 2D-weaving-wovens and 3D-weaving-wovens for non-specialists, and specialists from skills required, to current solutions, to remaining gaps requiring future research. This also reinforces the iteration that is inherent in the weave design-engineering steps. With consideration to 2D-weave digital software systems - understanding of basic weave/weaving principles and specialist terminology, need to know weave structures/understand visual and structural differences, good understanding of the yarn, the loom, and the fabric that is possible is still at a subject specific knowledge level that requires further future research into a lexicon of weave architectures applied within identified product ranges, from apparel, automotive to aerospace applications. In accessing 3D-weave digital software systems - on top of general weave knowledge, understanding of 3D-weave structures, building blocks, layers-levels (schematic views of cross-sections in the weft and warp directions) a greater subject specific knowledge on machinery, weaving technologies remains.

Conclusion

Structured iterative design practice and process machine and material learning have strengthened each of the partners knowledge base and opportunity to continue to mature toward aspects relative to 3D-weaving in the future. Alternative communication tools for information input, as well as output representation visualization to render the 3D-woven post-forming process continues to be a challenge. Although with parametric design generation (Shi et al. 2023) for application of 3D-surface, 3D-shape *via* alternative market systems, there is a need for physical attributes in shape/product forming in real-time simulation, and as an end product (Meiklejohn, Hagan, and Ko 2022) are vital. New ways of thinking about waste within the design process to manufacture, as in the work of WFN and others aligning to sustainable goals, and material and manufacturing resilience remains. With the latest in design-practitioners, Toit (2024) taking this approach in utilizing production (manufacturing) constraints as design inspiration, within a reconfigured design process for woven garments, amalgamating textile design with garment design and skillsets. The validation of the mixed methods framework was through the lens of each FFF industrial project leads defined problem. The combination of method types/approaches was established due to the common challenges in the field of 3D-to-2D-to-3D weaving-wovens as discussed in the introduction. Developing research process and tools, conducting and reviewing research, data analysis, with a focus on developing understanding of a digital thinking, developing a new skillset and understanding of the product development processes required ultimately for 3D-weaving-woven production/manufacture. Exploring the systems required to support the re-designing of design-engineer-manufacturer-consumer relationships. The success of the FFF

Table 7. Processes simplified overstep sequences 1–8, & accessibility by specialists and non-specialists *via* the: step, skills required, current solutions and identified gaps for future research. Table produced by author for this publication.

	Accessibility by specialists and non-specialists via the: step, skills required, current solution, and identified gaps: future research			
PROCESS simplified overstep sequences 1-8:	**Step**	**Skills Required**	**Current Solution**	**Identified Gaps: Future Research**
1. Garment design / product geometries	Conventional garment / 3D-scanned shape / Desired 3D-form / 3D-product geometries.	Apparel / fashion design and development (pattern cutting, fabric and manufacturing knowledge, spatial sense, cut-and-sew pattern pieces).	Physical / digital apparel / fashion development. Paper patterns /paper maquettes / digital patterns (Lectra, Gerber) / Virtual fashion (Clo3D, BrowzWear, etc) / alternative 3D software (Lectra Design Concept) 3D-scan a form. 3D-model a form.	Simultaneous workflow of 3D-garment to 2D-pattern, incorporating multilayer-multilevel system, and shuttle, shuttleless weft insertion pathways.
2. Converting 3D-geometries to 2D-form and transference to graph template	Pattern reappropriation to flat fold / design from folded thinking / origami / flattening of 3D-form without considering traditional cut and sew patterns.	Core pattern cutting skills, understanding of 3D-form creation through 2D-shapes.	Physical / digital apparel / fashion development - core pattern design-engineering, for example using origami principles or flattening along desired cutlines / or folding and analysing multilayers-multilevels of folded desired product pattern assembly on lightbox.	Simultaneous workflow of 3D-garment / 3D-product to 2D-pattern, and multilayer-multilevel system, and shuttle, shuttleless weft insertion pathways. Visualization of 3D-multilayer-multilevel form in exploded view, spatial interactions.
3. Multilayer-multilevel weave conversion	Flat folded panels for multilayer-multilevel weave conversion - mark edges and seams, yarn attributes (can be in step 5 too). Transforming multilayer-multilevel weave theorisation into 2D-grid template to house the weave pattern and prepare for colour blocking associated to jacquard conventional weaving machine design. Colour blocking - pairing a coloured section of pattern to a specific unit of a weave pattern / structure.	General understanding of 3D-weaving, and how it manifests in 'edges, seams and layers (warps), and levels (wefts)', colour blocking and binding mapping (stitching in the multilayer-multilevel). Knowledge on the function of each weave pattern /structure for each colour block. Beginner - intermediate user of Photoshop / Excel to work on colour blocking, weave pattern / structure drafting. Hand sketching.	Physical / digital apparel development towards visualization of multilayer-multilevel system of weave patterns / structures Hand sketching cross-sections of weave patterns / structures, and shuttle and / or shuttleless weft insertion pathways. Use of photoshop and Excel for colour blocking, surface pattern / structure of weave to cross-sections of weave patterns / structures, and shuttle and / or shuttleless weft insertion pathways.	Simple plug-in, add-on, or use of AR, VR to permit adaptation, amendment to features within the 2D-to-3D product requirements, including belt loops, pockets, and seams and their connection between multilayer-multilevel weave pattern / structure configurations towards weaving 2D-form for conversation to 3D-product geometries.
4. 3D check unfolding 2D-to-3D	Check if unfolded 2D-to3D version looks right through fabric and whole garment simulation (homogenous fabric simulation).	Affinity to digital fashion / pattern software - general intermediate user level - able to interact with 2D-layers to unfold into 3D-product form.	Virtual fashion tool with 3D-simulation (for example Clo3D) – Ability to unfold pattern pieces to assign to the folding of the product within the 2D-conversaion process (graph template).	Digital tool (animation / simulation) to interactively unfold multilayers-multilevels (physics-based simulation, self and inter-collision, python/games software).
5. layers to weave structures (3D-to-2D)	List of 3D-weave blocks (input via cross-section or existing library). Colour blocked visual input to system, and assignment of blocks to colour. Designate repeat, period or wraparound weft. Yarn specification (can be step 3 too). 3D-modelling, possible adjustment on yarn level (weft or warp position). Near-unit cell physics-based simulation to see more realistic result.	Intermediate understanding of 3D-weave structures and multilayer-multilevel system. Intermediate to even advanced user of 3D-weave software, understands 3D-weave and weave terminology, CAD and CAM relations, yarn and weave behaviour, hardware operations.	Adjustment of manual colour blocking using Excel / Photoshop, 3D-weave software operations (see software list above).	Library of structures and weave colour blocks - automatic conversion of colours to weave structure and / or drag and drop model.
6. 3D check - micro or macro scale (2D-to-3D)	Combined approach to simulate yarn layers-levels within schematic / 3D software (ScotWeave Technical Weaver, EAT 3D Composite) within required 3D-garment / 3D-product geometries and design features (belt loops, pockets, seams)	Affinity to digital software, general intermediate user level.	Knowledge of warp/weft yarn locations in multilayer-multilevel simulation / position / orientation (CAD / manual).	Full or combined product simulation using warp/weft yarn locations in multilayer-multilevel orientation for 3D-fabric / 3D-product simulation.
7. weave	Finalize and set up to final file format. Send to conventional weaving machine (Jacquard).	Intermediate understanding of conventional weaving machinery, ready to weave files (weave documentation). Intermediate or supervised use of weave hardware/software controller.	Skilled knowledge, or supported by skilled operator, apply operational production principles to file format for production / manufacture.	3D-weave software with extensive control over several factors on the conventional weaving machines operational production principles.
8. Off-conventional weaving machine post-weave processes	If needed: cut / sew / treatment / decoration / dye / heat shrink etc., to enhance 2D-to-3D formation.	Depends on process - mainly product development skills / apparel manufacturing / manual operation.	Cut and sew manufacture processes, general apparel / fashion / product development methods.	Eliminate material waste or incorporate within the weaving of the 3D-products design features.

project partnership WFN and 3D WIC led to a successful application to UKRI for: resource efficiency for materials and manufacturing, celebrating innovation in UK manufacturing (UKRI 2025). With a focus toward near zero manufacturing and data driven confirmation of innovating through weaving for onshore manufacturing aligned not only to thematic area of FFF, but to the materials and manufacturing vision 2050 (Innovate UK, UKRI 2023).

We can conclude that each FFF project was innovative, and has generated new knowledge, and insight to take forward toward, either as step for change in the process of 3D-to-2D weave design-engineering, and how to use the various digital software systems (those for file generation and those aligned to the hardware of conventional weaving machines), or as part of the production/manufacturing utilization of conventional weaving machines (jacquard) operational production principles for 2D-to-3D weaving-wovens, or to form externally funded research proposals, such as the UKRI, Innovate UK (2025) research, successfully awarded and completed:

- Resource efficiency, cost effective solutions of derivative fabric/composite shapes/product forms to the typical norm of a woven length of fabric for cut-and-sew manufacturing processes.
- Minimizing waste through, interpreting waste as a design feature within the generation of weave notation for production/manufacture, toward near-to and zero- waste weaving processes.
- 3D-geometry alterations with on-weaving technology add-ons toward tailoring for the 'right-fit', 'off-loom ready-to-wear', 'on-demand manufacturing of high-value engineered 2D-to-3D near-net shaped forms'.
- Variable shedding geometries in association to complex on-loom engineering following the principles of origami, but controlled through additional mechanisms and motions for weaving fully-fashioned, seamless 3D-wovens in- and out- of the fabric plane.

Key stakeholders within the FFF four industry partners internal teams are to be part of future research projects. These are in association with the lead academic of the 3D WIC, and author of this FFF case study in supporting commercialization of all aspects of the 3D-to-2D-to-3D weaving parameters-principles-processes, and in pushing the boundaries of conventional weaving machines operational production principles. These developed, and in development research proposals are advancing upon the conclusions from each of the FFF project partnerships, and then how all four FFF partnerships helped form the concluding Lexicon in Table 8.

The research proposals are in the field of:

Table 8. Concluding lexicon generation outcome from Op3D, TOS, WFN, VoSp, and the 3D WIC FFF project partnerships. Table produced by author for this publication.

Lexicon:

Weave Terms:	**Conventional Weaving Machine Classification:**	**3D-Woven Structures & Shapes:**	**Design-engineering 3D-to-2D** (3D original product geometry to 2D graph template for the location of the weave pattern/structure):
Notation	Jacquard	Solid	3D-geometries
Graphical representation	Dobby	Hollow	Paper maquette(s)
Weave unit cell	Single-end control	Nodal	Colour blocking
Common Denominator	Multiple-end control	Shell	Weave directional zone
Lifting plan	Shuttle	Beams: I, T, H, Pi	Shuttle paths
Weave: pattern, structure, architecture	Shuttleless (rapier)	Tube(s), tubular, bifurcated, trifurcated	Shuttleless path
Top-down	Let-off	Anisotropic	Seams
Face of the fabric	Take-up	Isotropic	Origami
Cross-sectional	Shedding	Multilayer	Multilayer
Slice	Weft insertion	Multilevel	Multilevel
Repeat	Continuous weft	Spacer	
Long-hand	Beat-up	Drop-stitch	
Short-hand	Cloth fell	Orthogonal	
Colour blocking	Back beam(s)	Angle-interlock	
E.P.CM	Creels	Honeycomb	
P.P.CM	Front beam	Cellular	
D.P.CM	Fabric beam	Dome	
Fabric Sett (Density)		3D-surface	

- Digital hardware system manufacturers: in-built, electrical, electronic mechanisms and motions of conventional weaving machines (jacquard to the underlying machines weft insertion mechanism), circumnavigated to be adapted/altered.
- Digital software system developers: weave notation, weave design-engineering, top-down, cross-section and conventional weaving machine operational production principles parameters as a base toward requiring future add-ons.
- Alternative digital software systems toward add-ons for physical forces applied in the off-conventional weaving machines to aid the 2D-woven to 3D-shape/product forming process.
- Innovative use of robotics and AI vision systems in the field of commercialization of conventional weaving machines for production/manufacture of 3D-to-2D-to3D woven textiles for various end products and applications.

The synergy of these four projects brought forward their unique research aim(s), objective(s) and goal(s) yet interconnect with each other due to the many variables associated with the weaving process. So although each FFF industry partner had their standalone challenge, and concluding results, they were/are stronger together toward 3D-Weaving the future. This can be achieved *via* the collaboration of multidisciplinary skillsets, team dynamics through industry focussed workshops informing about the technical capabilities of 3D-weaving using conventional weaving machines and how they can be shared more easily to improve and streamline those systems through digital tutorials, and access to open sources, or alternative digital software systems.

Acknowledgements

1. **Twelve Oaks Software Ltd** (Proof of Market, Call 3): Future design manufacture: Developing new models and systems for 3D design to manufacture.
   Company Principal Investigator: P. Jervis, MD
   Academic Principal Investigator: Dr. S., Postlethwaite, Royal College of Art
   Academic Co-Investigator: Dr. L, W., Taylor, University of Leeds, LITAC-3D WIC
2. **Vorteq Sports Ltd** (Innovation Challenge Project, Call 4): Get weaving: Engineering 2D-to-3D fabric structures.
   Company Principal Investigator: R. Lewis, MD
   Academic Principal Investigator: Dr. Lindsey Waterton Taylor, University of Leeds, LITAC-3D WIC
3. **WEFFAN** (Proof of Concept, Call 4): On-loom fashioning for off-loom 3D woven garments.
   Company Principal Investigator: G, Audren, MD
   Academic Principal Investigator: Dr. Lindsey Waterton Taylor, University of Leeds, LITAC-3D WIC
   Sub-contractor: S Dawes Weaving Ltd.
4. **Optima 3D Ltd** (Proof of Market, Call 4): Animated concepts and robotic motions-mechanisms for seamless 3D shape weaving manufacture
   Company Principal Investigator: S. Cooper, MD
   Academic Principal Investigator: Dr. Lindsey Waterton Taylor, University of Leeds, LITAC-3D WIC

Disclosure Statement

No potential conflict of interest was reported by the author.

Funding

The four industry-led research projects received funding from Arts and Humanities Research Council Future Fashion Factory – Digitally Enabled Design & Manufacture of Designer Products for Circular Economies (Award Reference: AH/S002812/1).

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References

Almond, K., and S. Rainton. 2025. "Future Fashion Factory: Developing an Ecosystem to Support Sustainable Change." *International Journal of Fashion Design, Technology and Education* 18 (1): 134–146. https://doi.org/10.1080/17543266.2025.2454669.

Bally Ribbon Mills 2025. About us. Website by ThomasNet RPM. Accessed February 2025. https://www.ballyribbon.com/about-us

Bhandari, Kajal, Jaako Palokangas, and Ville Ojanen. 2025. "Applying Design Sprint Method to Create a Minimum Viable Product with Machine Vision." In *Digital Transformation and Business Sustainability, From Theory to Practice*, edited by Getika Jain, and Malahat Ghoreishi, 14. London: Routledge.

Bioracer 2025. About Bioracer. Accessed February 2025. https://shop.bioracer.com/the-most-tested/

Chen, X., L. W. Taylor, and L. Tsai. 2011. "An Overview on Fabrication of Three-Dimensional Woven Textile Preforms for Composites." *Textile Research Journal* 81 (9): 932–944. https://doi.org/10.1177/0040517510392471.

Clo3D 2025. About CLO. Accessed February 2025. https://www.clo3d.com/en/company/about-clo

Cronholm, Stefan, and Hannes Göbel. 2022. "Action Design Research: Integration of Method Support." *International Journal of Managing Projects in Business* 15 (8): 19–47. https://doi.org/10.1108/IJMPB-07-2021-0196.

EAT: the Design Scope Company 2019. About EAT. Accessed January 2025. https://www.designscopecompany.eu/en/company/about-eat

EE Exclusives. 2025. EE Labels Label Factory Exclusives Accessed February 2025. https://www.ee-exclusives.com/3d-woven-garments-developments/

Friske, M., S. Wu, and L. Devendorf. 2019. "AdaCAD: Crafting Software for Smart Textiles Design." CHI '19: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems, Paper No.: 345, Pages 1–13. https://dl.acm.org/doi/10.1145/3290605.3300575. https://doi.org/10.1145/3290605.3300575.

Goerner, D. 1989. *Woven Structure and Design, Part 2 - Compound Structures*. Leeds: British Textile Technology Group (BTTG), WIRA Technology Group.

Innovate UK, UKRI. 2023. Materials and manufacturing vision 2050. Accessed February 2025. https://iuk-business-connect.org.uk/wp-content/uploads/2023/03/Innovate-UK-Materials-and-Manufacturing-Vision-2050.pdf

Innovate UK, UKRI. 2025. Reimagining Materials and Manufacturing Together. Accessed February 2025. https://ow.ly/JpqZ50V5YtS

Kelly Konings 2025. Scandinavian MIND. Accessed February 2025. https://scandinavianmind.com/kelly-konings-designer-on-why-3d-and-whole-garment-weaving-is-here-to-stay/

Kongprasert, N., D. Brissaud, and S. Butdee. 2012. "A Methodology for the Selection of Manufacturing Processes Based on the Design of the Manufacturing Matrix." *Asian International Journal of Science and Technology in Production and Manufacturing Engineering* 5 (2): 65–77.

Kovačević, Stana, Snježana Brnada, Irena Šabarić, and Franka Karin. 2021. "Limitations of the CAD-CAM System in the Process of Weaving." *Autex Research Journal* 21 (3): 225–233. 2019 https://doi.org/10.2478/aut-2019-0077.

LECTRA (Design Concept 3D Tech Tex). 2025. Who we are. Accessed February 2025. https://www.lectra.com/en/discover-lectra

Mageba 2025. Our Machines. Accessed February 2025. https://www.mageba.com/en/textile-machines/looms.html.

MagicLeap 2025. From Vision to Reality. Accessed February 2025. https://www.magicleap.com/

Meiklejohn, E. 2023. "Lattice Structures". AdaCAD. Accessed February 2025. https://docs.adacad.org/docs/learn/examples/lattice-tutorial/.

Meiklejohn, E., B. Hagan, and J. Ko. 2022. "Rapid Sketching of Woven Textile Behaviours: The Experimental Use of Parametric Modelling and Interactive Simulation in the Weaving Process." *Computer-Aided Design* 149: 103263. volume https://doi.org/10.1016/j.cad.2022.103263.

Microsoft 2025. Microsoft HoloLens. Accessed February 2025. https://learn.microsoft.com/en-us/hololens/.

NedGraphics 2025. NedGraphics: CAD/CAM Textile Design Software. Accessed February 2025. https://nedgraphics.com/

Optima 3D Ltd. 2025. Optima 3D Ltd Composite Weaving Solutions. 2025. Accessed February 2025. https://www.optima3d.co.uk/

Pointcarre 2025. Textile CAD software. Accessed February 2025. https://www.pointcarre.com/

Saboktakin, Abbasali. 2019. "3D Textile Preforms and Composites for Aircraft Structures: A Review." *International Journal of Aviation, Aeronautics, and Aerospace* 6 (1): 1–41. https://doi.org/10.15394/ijaaa.2019.1299.

Schegner, Philipp, Monireh Fazeli, Cornelia Sennewald, Gerald Hoffman, and Chokri Cherif. 2019. "Technology Development for Direct Weaving of Complex 3D Nodal Structures." *Applied Composite Materials* 26 (1): 423–432. 2018 https://doi.org/10.1007/s10443-018-9734-9.

ScotWeave 2007. ScotCadTextiles Technical Weaver. 2007. Accessed January 2025. http://scotweave.com/products/technical-weaver/

ScotWeave 2025. Digital Tools for Weave Designers. Accessed February 2025. https://www.scotweave.com/

S. Dawes Weaving Ltd. 2025. Versatility in High-End Weaving. Web Design by Fruity Llama. Accessed January 2025. https://www.sdawes-weaving.co.uk/

Shi, Yuyuan, Lindsey Waterton Taylor, Vien Cheung, and Abu Sadat Muhammad Sayem. 2023. "Scan2Weave: Connecting Digital Anthropometry with 3D Weaving Technology." In *Digital Fashion Innovations*, edited by Abu Sadat Muhammad Sayem. 83–96. Boca Raton: CRC Press. https://doi.org/10.1201/9781003264958.

Simonsen, Jesper, and Morten Hertzum. 2010. "Iterative Participatory Design." In *Design Research: Synergies from Interdisciplinary Perspectives*. Edited by Jesper Simonsen, Jørgen Ole Bærenholdt, Monika Büscher, John Damm Scheuer. 16–32. London: Routledge. http://www.routledge.com/books/details/9780415572637/.

Sobike 2025. About Sobike. Accessed February 2025. https://sobike-active.com/pages/about-sobike

Staubli 2025. Jacquard machine UNIVAL 100 for technical fabrics. Accessed February 2025. https://www.staubli.com/global/en/textile/products/jacquard-machine/technical-fabrics-3d-weaving-unival-100.html

Taylor, Lindsey Waterton. 2007. "Advances in the Manufacture of 3D Preform Reinforcement for Advanced Structural Composites in Aerospace." *DTI Global Watch Technology Mission: Dissemination Report*. DOI: URN 06/1218.

Taylor, Lindsey Waterton. 2007. "Design and Manufacture of 3D Nodal Structures for Advanced Textile Composites." PhD diss, University of Manchester.

Taylor, Lindsey Waterton. 2018. "Woven Fabrics." In *Textile and Clothing Design Technology*. Edited by Tom Cassidy, and Parikshit Goswami, 147–196. Boca Raton: CRC Press. Taylor & Francis Group.

Taylor, Lindsey Waterton, and Xiaogang Chen. 2015. "Nodal Three-Dimensional Woven Textiles." In *Advances in 3D Textiles*. Edited by Xiaogang Chen, 99–122. Cambridge: Woodhead Publishing.

TEXGEN 2023. Main Page. Accessed February 2025. https://texgen.sourceforge.io/index.php/Main_Page.

The ATLAS Institute Research and Innovation Office 2025. "AdaCAD. University of Colorado Boulder." Boulder, CO: Regents of the University of Colorado. Accessed February 2025. https://www.colorado.edu/atlas/adacad.

3D Weaving. 2025. High End Technical Solutions. Accessed February 2025. https://3dweaving.com/

3D Weaving innovation Centre (3D WIC). 2025. European Research Development Fund. University of Leeds. Accessed February 2025. https://3dweaving.leeds.ac.uk/

Toit, Ilkhe Du. 2024. "A Reconfigured Design Process for Woven Garments: Production Constraints as Design Inspiration." Master's thesis., Aalto University.

Twelve Oaks Software Ltd 2023. About Us. Accessed February 2025. https://www.twelveoaks.software/about-twelve-oaks-software/

Unspun 2025. 3D Weaving from Yarn to You. Accessed February 2025. https://www.unspun.io/?srsltid=AfmBOorox2EdAEvPQXZnKSEwnQQEf2B5szLSQkJEWwJoYvAdIe_LasGI

Unspun 2025. Meet Vega™. Accessed February 2025. https://www.unspun.io/vega

Velotec 2025. Velotec Speedwear. Accessed February 2025. https://www.velotec.cc/

Vorteq Sports Ltd 2025. Engineered Sporting Innovation. Accessed February 2025. https://vorteqsports.co.uk/

WEFFAN 2025. 3D Weaving the Future of Garment Production. Accessed February 2025. https://weffan.co/

Wu, Rundong, Joy Xiaoji Zhang, Jonathan Leaf, Xinru Hua, Ante Qu, Claire Harvey, Emily Hotzman, et al. 2020. "Weavecraft: An Interactive Design and Simulation Tool for 3D Weaving." *ACM Transactions on Graphics* 39 (6): 1–16. Article 210: https://doi.org/10.1145/3414685.3417865.

XR Stories. 2025. XR Stories Accessed February 2025 https://xrstories.co.uk/

Xu, Qiaoli, Longxin Gu, Gui Liu, Zhuoran Liu, Dongdong Lu, and Zhaoqun Du. 2022. "Design, Preparation, and Characterisation of Auxetic Weft Backed Weave Fabrics Based on Miura Origami Structure." *Textile Research Journal* 92 (7-8): 1126–1134. https://doi.org/10.1177/00405175211050534.