Three-Dimensional (3D) Textiles in Architecture and Fashion Design: a Brief Overview of the Opportunities and Limits in Current Practice

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Abstract

Three-dimensional (3D) textiles prove characteristics in structures and performance which can be as attractive as to be the main object of a high number of research and applications in specialist markets (from small medical devices to large engineering structure) where the performance demands are severe ([1] in *J Eng Fibers Fabr.*). Nevertheless, much of the research has come from academia and there are few relatively small companies that, even if have expertise, lack the resources to develop R&D programmes. This prevents to broaden their application and to consolidate their use in new markets ([2] in *Advances in 3D Textiles*, pp 1-18). The paper aims at exploring the potentialities and future implementations of 3D textiles in architecture and fashion design. Both are fields where the demand to balance requirements of environmental sustainability, low time-consuming production and high performance is emerging, in their own respective scale. A set of more than 10 real case studies are collected and analysed with the aim at underlining the potentialities and the limits of 3D textiles in practice. The overview suggests that a more integrated workflow among modelling and simulation tools and bigger effort from industry to enhance manufacturing options and increase the interest on new material systems, bring about new application such as indoor environmental quality (IEQ) or human body protection.

Keywords Three-dimensional textiles · Architecture · Fashion design · Application

1 Introduction

Textile has had a key role in humans' habits evolution. Transforming the hunted animals' skins in fabrics, homo sapiens was able to protect itself from temperature variations creating first prototypes of body envelopes. Later the same fabrics got more volume and hold by wooden structures, they were able to provide temporal spatial comfort for more people, facilitating social activities [3]. In this way, both clothes and

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architecture have been perceived as physiological and psychological extension of social relationships till they can be considered as “our surrogate body without whose support we would immediately perish” [4].

Textile design has been influenced by the technological achievements of a specific historical period. Design processes, fabrication methodologies and cutting-edges materials are consequences of innovations of the several industrial revolutions. The same now, as we are experiencing the 4th industrial revolution and witnessing the paradigm change where ubiquitous computing, embedded systems, and the Internet of Things are bringing to the complete and seamless integration of digital into our built environment [5]. 3D textiles explorations are affected by these achievements widening the applications fields. The case studies and the researches gathered by Chen [6] show how an interdisciplinary approach helps to achieve advances in the production of three-dimensional fibrous structures and how their use has resulted in the creation of novel fabrics and applications. Nevertheless, the application in architecture and fashion design fields is only briefly described. This paper intends to overcome this lack with an overview of the most emerging case studies.

2 Research Method

This paper presents and investigates twenty-two built case studies, which were gathered through a literature research. For this work, unbuilt examples, as well as examples with inadequate documentation, were excluded from the analysis.

The research is limited to the available information on the built case studies, which was mainly gathered from journal articles, conference proceedings, books, web articles as well as from direct contact with authors. Therefore, the presented collection cannot be considered comprehensive, as it excludes the projects, which are not documented in literature, as it is often the case of projects developed by professionals. Moreover, it must be highlighted that, except for case studies developed for research purposes, the released information regarding the design workflow and the performance parameters considered in the optimization process is generally rather limited.

Despite these limitations, the presented collection will be hopefully meaningful and will help to delineate the state of the art of 3D textiles in architecture and fashion design, by briefly describing the design outcomes, as well as the design processes and the 3D textile typology.

3 Case Studies

The case studies are briefly described in the following sections. The first section, named “architectural applications” (Sect. 3.1) collected the projects that refers to the built environment and what concern the AEC market (Architecture, Engineering and Construction). In particular, the projects are categorized by scale application. The second section, named “fashion design” (Sect. 3.2), gathers projects related to the 3D textiles applications in apparel and technical wearable textiles.

3.1 Architectural Applications

3.1.1 Interiors and Furniture Applications

The project Radiolaria exploits the flexibility of warp-knitted spacer textiles to produce lights. The project takes inspiration by the illustrations of the philosopher and zoologist, Ernst Heackel. The designers at Bernotat & Co produce shapes that are stitched in place with fluorescent threads. The design process is totally empirical and did not embed a computational modelling phase [7].

The Maya Breuer's bachelor thesis, supervised by Prof. Dr. Kerstin Zöll and Prof. Dr. Anne Schwarz-Pfeiffer, aimed at developing sound-absorbing textile wall panels, using three-millimetre-thick warp-knitted spacer textiles (Fig. 1a). Based on empirical methodology, the project exploited the flexibility of polyester spacer characterized by an oval-shaped pore on the upper side covered only to get indentations. Later, since the thermoplastic nature of polyester, an ultrasonic welding technology has been used to vary the design of several seams by using different anvil wheels. The project intended to overcome the limitation of traditional textile absorbers having a thickness of just 3 mm and working with three dimensional shapes. She obtained three different kind of prototypes (Fig. 2b) that were tested in reverberation chamber in accordance with DIN EN ISO 354:2003. The results have showed effective sound absorption in the medium-high frequency range (500–5000 Hz) but less in the low-frequency range (125–250 Hz). Their behaviour can be compared to porous sound materials [8] and, for this reason, they could be used in office, hotel lobbies, conference rooms, etc. [9].

The research line developed by prof. Achim Menges and HfG Offenbach, aims at developing an integral computational design process able to embed constraints of making, material characteristics and assembly logics to inform the design process of spacer fabrics [10]. The spacer fabric used for the projects is produced with a pile depth of 10mm (Fig. 2b). The process of sandwich structured composites comprises of the following steps: 1) A transparent resin is applied to the mould allowing to lay up it. 2) Plies of glass fiber are places in the mould and subsequently impregnated with polyester resin to form one-millimetre thin skin. 3) The spacer textile bonded to the sandwich skin by applying resin to the surface and draping the spacer textile over it. The research aims at developing a custom computational tool for design process able to embed both the characteristics of the material system and the constraints of the related manufacturing. The algorithm was set to assess the differential stretch

Fig. 1 Sound-absorbing panels: (a) 3D fabric detail and (b) Overview of the three prototypes ©Maya Joëlle Europa Breuer

Fig. 2 Design process for Lounge Landscape project (a) Customized computational tool for analysing the differential stretch of the spacer fabric (b) 3D warp-knitted spacer fabric (c) Different Lounge Landscape furniture pieces all produced from the same mother mould [10]

and the constraints of the mould manufacturing process given by the limits of the 5 axis CNC mill. A mathematical equation capturing the limits of the material's drape capacity and the manufacturing constraints was developed. In case of Lounge Landscape, the algorithm defines the surface oscillation in Z direction. For the Deichmanske media stations prototypes the algorithm is based on the mathematical definition of a stereographic sphere. The equation's variables were explored through multiple feedback loops integrating the most critical design criteria as the surface ergonomics and aesthetics, the structural stability and, in the case of the Deichmanske media stations, the assembly logics and transport volume (Fig. 2a). The Lounge Landscape has been developed in partnership with the Department of form generation and Materialization of Institute of Computational Design (Stuttgart) and the University of art and Design HfG Offenbach. The prototype applies the process explained above to design and manufacture a seating furniture (Fig. 2c). The algorithm enabled a

morphological evolution of iteratively testing and evaluation parametric variants in relation to structural, ergonomic, and aesthetic design criteria. The final shape was CNC manufactured as “mother mould” facilitating the production of several, individual, geometrically different furniture morphologies.

The Deichmanske Media Stations has been developed in partnership with the Institute for industrial design at AHO University and OCEAN design research network. The Media Stations served as access points for the public Deichmanske Library in Oslo. They enable the access for the library’s audio-visual archive via touch screen (Fig. 3a). The algorithm allows to explore a parametric variant of two intersecting stereographic spheres. The resulting model was coded for CNC milling process to produce the positive moulds, which were finished and prepared to produce negative master plugs. These master plugs were used for the lamination process, during which the spacer fabric was shaped within a composite cloth through a vacuum bag moulding technique. The resulting media station’s overall shape (Fig. 3b) balances specific manufacturing constraints and the particular assembly logics of the material system [10].

Concrete canvas (CC) is a patented product developed by the homonymous company. It is a 3-dimensional spacer fabric-reinforced cement-based composite. CC can be hydrated by spraying or full immersing in fresh or salt water. Once set, the fibres reinforce the cementitious mix, preventing crack propagation and providing a safe plastic failure mode. CC is available in 3 thicknesses: CC5™, CC8™ and CC13™, which are respectively 5, 8 and 13mm thick. The fiber reinforcement prevents cracking, absorbs energy from impact and provides a stable failure mode. CC has excellent chemical resistance, good weathering performance and will not degrade in UV. CC has good drape characteristics and will closely follow the ground profile and fit around existing infrastructure. Unset CC can be cut or tailored using basic hand tools. For these characteristics, the CC has wide applications sectors. In this section we describe the application in furniture scale. The project Folded Concrete Stools (Fig. 4a), developed by the designer Samuel Jennings, overcomes the limits of standardization in furniture design. In this case the CC8 is applied (Fig. 4b). The project has not been developed a digital process (Figs. 5, 6).

3.1.2 Facades Application

The project 4dTex developed by the Textile Lightweight Construction Division of the Frankfurt Research Institute (FRin) focuses on dynamic components constructions in

Fig. 3 Deichmanske media stations project (a) Deichmanske Media Stations Multi-component shell during assembly (b) Detail of composite spacer fabric structures. [10]

Fig. 4 Folded concrete stool (a) Folded concrete stool overview © Concrete Canvas Ltd 2021 (b) Folded concrete stools detail. Source: <https://www.innerdesign.com>

combination with spacer textiles. The movement mechanisms for opening and closing as well as for the control of viewing and incident light from spacer textiles aimed at developing robust and low-maintenance components for facades. When closed, they can also temporarily reduce energy loss or the heating up of the rooms behind them. The project investigates the controllable daylight management of spacer textiles used as moveable elements on the macro level, and movements in the textile structure itself at meso level. The empirical and experimental methodology can be summarized in the following steps: 1. Experimental investigations with spacer textiles on 1:1 scale. 2. Research on folding technologies. 3. State of art on textile folds on architectural scale. 4. Evaluation of movement mechanisms at both macro and meso levels. Several strategies are explored in terms of opening management (macro level), of transparency, translucency, and opacity management (meso level), of thermal properties management, passive and active use of solar energy management, air filtration, sound insulation and water extraction management. The results demonstrate the potential of spacer textiles in the solar protection field but, at the same time, it underlines the need to embed the time-consuming production process in a digital computational tool [11].

Fig. 5 Concrete canvas shelter (a) Internal view (b) External view © Concrete Canvas Ltd 2021

Fig. 6 Concrete Canvas for structural refurbishment: (a) State before installation (b) State after the installation © Concrete Canvas Ltd 2021

For non-structural façade systems, textile-reinforced concrete (TRC) is a composite material made of open-meshed textile structures and a fine-grained concrete. Comparable to steel reinforcement, the textile fabric bears the tensile forces released by the cracking of the concrete. Thus, the application of TRC leads to the design of filigree and lightweight concrete structures with high durability and high-quality surfaces [12]. One of the first applications of TRC for the cladding of a building was the ventilated façade of the extension to the laboratory hall of the Institute of Structural Concrete at RWTH Aachen University in 2002. The upper part of the façade is clad with $2.68 \times 325 \times 25$ mm panels consisting of a fine-grained high-strength concrete and two layers of alkali-resistant glass fiber near the concrete surface. The panels were cast in a lamination process in horizontal position. The main disadvantages of this very simple yet labour-intensive production process are difficulties in the exact positioning of the textile-reinforcement layer. The panels were fixed to the wall with standard loop and aluminium fixing devices at four anchorage points each [13].

3D textiles with cement matrix are also applied for outdoor cladding and for filtering solar radiation. The spin-off Textudo, from Politecnico di Milano, is working on an innovative production process that consists in impregnation and then formation through localized and/or distributed compression and traction deformation without the need to create customized moulds or formworks [14]. The applications go from outdoor cladding to filtering solar radiation [15].

The “Textile phonemic crystals” project, funded by AiF project Gmbk, aims at implementing noise protection panels [16]. The interlacing in the stitch formation causes crossing points with specific porosity, necessary to provide good sound absorption properties. The project focuses on spacer textiles as photonic crystals. The pile yarns provide an intrinsic periodicity that can be modified to improve sound insulation of low frequency. The textile design takes in account the lowest possible influenceable frequency range and to achieve the lowest possible frequency while maintaining media transparency, the possibility to embed a filling material studies and technical and economic evaluation. The possible application can concern the sound protection of residents living near main traffic arteries and motorways, worker in the vicinity of noisy machinery, vehicle users etc.

3.1.3 Structural Applications and Temporary Structures

The research developed by Prof. Luling at Frankfurt University of Applied Science, in partnership with Zukunft Bau, focusses on foamed spacer fabrics [17]. The research has been developed through experimental pavilion structures built by the students. They worked with three-dimensional textiles such as textile sleeves or spacer fabrics. Foam filled spacer fabrics were used for load-bearing structures such as: a shell structure produced according to Heinz Isler's principles, a folded structure with foamed folds and a modular dome. To make the dome, open, pyramidal modules made of 30 mm thick spacer warp-knitted fabrics were folded and upended, making them stable like a hat. The modules were then joined together by foaming predefined voids between them.

The aforementioned Concrete Canvas can be applied also for temporary shelters. The company provide Concrete Canvas Shelters TM made by 13mm thick polyester spacer fabric. They are hardened shelters that require water and air for construction. The air needs to inflate the plastic layer to lift the structure until it is self-supporting. The shelter is then pegged down with ground around the base. The layer is hydrated by spraying with water (also sea water can be used). After 24 hours, the structure is ready to use. Access holes can be cut to allow to integrate installation of services. For this reason, the solution has operational and financial advantages. The systems allow to cover 25sqm or 50sqm by two people in less than 24 hours.

Concrete canvas is also applied for structural refurbishment. In August 2018, CC8TM (8 mm thick) was chosen to reline a reinforced concrete salt storage area at the Fortischem chemical plant in Novaky, Slovakia. The Sodium Chloride used to produce Hydrochloric acid at the plant had badly corroded the concrete over time and was attacking the reinforcement steel. Contractor Ekoflex installed 2000m² of CC8 bulk rolls with a team of 5 in 10 working days. The works were carried out in hot and dusty conditions due to the large concentration of salt dust remaining within the facility. Prior to the installation, the walls of the area were cleaned and made smooth with mortar cement to fill cracks and any potential voids. The installation itself involved relining the walls, which were near vertical and up to 8m tall in some places. The lower section of the walls, in direct contact with the salt once filled, was lined with a double layer of CC8 to avoid any degree of salt ingress as shown in Fig. 9. The CC was fixed to the substrate using a Hilti nail gun and x/cr 58 nails. For structural purpose, 3D spacer fabrics can be also applied with epoxy resin and cementitious grout [18]. The research demonstrates the high structural performance for beam repairing.

3.1.4 Infrastructure

The Concrete Canvas (CC), with appropriate adaptations, is applied also for infrastructural applications. Details are provided of slope protection and ditch lining examples. The first were carried out by CET & Hourie V and Rousse, in 2019, to provide erosion protection to a stretch of slope alongside the Pan Arab Highway in Bekaa region of Lebanon. At the highest point, the slopes measure approximately 25m. In preparation for the installation, any large, protruding sharp rocks, tree stumps, roots and vegetation are removed to prevent damage to the material's PVC membrane backing during installation, and to prevent the development of void space beneath the material. A 5mm thick spacer fabric in cement-based composite has been applied as shown in Fig. 7. A specific digital modelling process has not been adopted.

Fig. 7 Concrete Canvas for slope protection purpose: (a) 5 mm-thick Concrete canvas detail (b) Concrete canvas application phase © Concrete Canvas Ltd 2021

In 2017, Hammond ECS carried out a lining of a dilapidated channel on the grounds of Teorchy Comprehensive School (South Wales). Among several considered solutions, a spacer 8 mm thick with cement composite was adopted as shown in Fig. 8. This helped to install 10 times faster than traditional methods and to mitigate any requirement for maintenance and risk of further degradation of the channel in the future.

Besides these examples, an interesting field of research pushes to apply 3D textile-based composite in structural joints. They can be made in several ways, but those most relevant to FRP bridges are woven fabrics consisting of thick multilayers linked by threads in the Z-direction either flat or made in more complicated 3D shapes, hollow multilayer fabrics containing voids. Braids may also be used like demonstrated by Chen and Hearle [19].

3.2 Fashion Design and Technical Apparel Applications

A clear understanding of how fashion design is conceived today is provided. The Oxford English Dictionary defines *fashion* the act of “make, build, shape. Said both of material

Fig. 8 Concrete canvas for ditch lining purpose: (a) Concrete canvas application phase (b) Final result © Concrete Canvas Ltd 2021

and of immaterial things”¹. It refers to the matter to present itself that it usually is linked to “apparel or personal adornment”. And if we think that each historical period has its own common social code to recognize and to label one’s appearance, we can say that fashion refers also to “a prevailing custom, a current usage”¹. So, what is the current emerging usage in fashion design? According to “The Future of Fashion: From Design to Merchandising, How Tech Is Reshaping the Industry”² the main trends are: 1) In terms of design process, the digitalization will enable to push towards a mass personalization of the product. 2) The advancements in manufacturing process will overcome the idea of seasonal apparel (at least for fast fashion brands), it will facilitate the integration of new manufacturing processes like 3D printing, and it will allow to develop fully-fashioned apparel. 3) The integration of technology in apparel will extremize the idea of connected clothes. This will also enable research on more performative and more sustainable yarns. For these reasons, the research on the application of 3D textiles in fashion design have considered also researches that put attention on material performance and optimization process. According to the purpose of this paper, the case studies have been categorized by the application body area: head, upper and lower limbs, bust, hands and feet.

3.2.1 Head Area Applications

The needs to prevent workplace injuries have increased the demand for protective garments. Garments protecting against mechanical injuries are manufactured from yarn characterised by very high resistance to cuts but with low comfort in working conditions [20]. 3D knitted fabrics can combine high level of comfort and mechanical behaviour [21, 22]. The research project developed by the German Institute for textile and fibre research Dekendorf (DITF) is investigating the development of body protection systems also for everyday life or for leisure activities. The researchers are working on a pomelo fruit inspired system to achieve a very effective cushioning system. The cushioning mechanism is technically reproduced by integrating a pressure-stable spacer fabric in a foam medium. In head protection, the damping behaviour was improved by up to 30% by reinforcing the EPS rigid foam with spacer fabric. The project concerns also the development of back protectors³.

3.2.2 Bust and Total Body

The study, developed by the Institute of Textiles and Clothing in Hong Kong Polytechnic University, investigates the application of warp-knitted spacer fabrics as a substitute for conventionally used foam inserts for body protectors in horse-riding. Thermal manikin test method and Transplanar water transport tester support the usability of warp-knitted spacer fabrics in impact-protective clothing [23].

Also, big fashion brand companies are funding research on the application of 3D textiles. Uniqlo, in partnership with Shima Seiki Mfg., Ltd., has applied the concept of Wholgarment in the fast fashion context [24]. Like already demonstrated [25], the project underlines how the manufacturing process can lead to new design aesthetic. The

¹ Fashion, Source: OED Online. Oxford University Press. Source: <https://www.oed.com/view/Entry/68389>

² The Future of Fashion: From Design to Merchandising, how tech is reshaping the industry. CB Insights; 2020. Source: www.cbinsights.com

³ Foam-filled spacer fabric for body protection - DITF. Source: <https://www.ditf.de/en/index/current/press-releases/detail/foam-filled-spacer-fabric-for-body-protection.html>

Fig. 9 Design process of 3D Knit project. (a) Apex 4 software screenshot Source: www.shimaseiki.com (b) Woman's 3D Knit Extra Fine Merino Ribbed Boat Neck Long Sleeve Sweater. Source: Uniqlo shop online

machine overcomes the traditional process to knit separately the products (front, back, right and left, collar) by knitting the fabric in a spiral, following a knitting program entered the design system, in a fully automated process. Thanks to the integration of the realistic fabric simulator “APEX 4” (Fig. 9a), the design exploration expands to new unpredictable sample solutions. The first result is cotton or fine merino 3D knit dress with comfortable fit that follows the body, from neck down to the shoulder (Figs. 9b, 10).

3.2.3 Upper and Lower Limbs Area Applications

Dow Corning's Active Protection System is a “smart” textile that remains soft and flexible until it is struck by high-impact force, in which case the material instantly stiffens to help protect against injury. When the collision has passed, the material immediately becomes

Fig. 10 Aps fabric for protection purpose. APS fabric colour typologies Source: Dow Corning

Fig. 11 3D shoe design process from digital to prototype (a) 3D weaving structure modelled in Weavecraft environment. [26] (b) Production phase. [27] (c) 3D weaving shoes samples. Source: www.virtualtextilesresearchgroup.com

flexible again. The active ingredient in the fabric is a dilatant silicone coating, which is a shear thickening fluid (STF). The viscosity of this coating increases with the rate of shear, therefore defining it as a smart material as it responds to changes within its environment. The Active Protection System is breathable and flexible for outstanding comfort and freedom of movement, and it can be stitched directly into garments, eliminating the need to insert and remove components. It is bulky and it opens creative and fashionable design possibilities. The washable fabric can be layered to provide customized levels of protection for specific areas, and it integrates easily into existing manufacturing processes.

AIRLOCK® Spacer Technology helps firefighters maintain a high level of protection against heat without the burden of weighty, cumbersome clothing that does not breathe. A heat-stable and chemically inert spacer is applied to the GORE-TEX® moisture barrier, creating an insulating cushion of air. This lightweight innovation offers thermal protection, a matching reduction of heat stress, and optimum freedom of movement [25].

3.2.4 Hands and Feet Area Applications

The project “3D shoe”, developed by T.E.A.M, inc., RISD textile department of Rhode Island School of Design and Cornell University, aims at exploiting the specialized nature of 3D weaving to create complex shapes. For this purpose, a new tool, Weavecraft [26], has been developed to give designers a way to visualize, collect and design weave structures as spatial architectures and provides a path for creating complex 3D-woven objects [27]. The process has been applied to design 3D shoes as shown in Fig. 11.

In the same research field, warp-knitted polyester spacer fabrics are used as cushioned insoles to reduce the impact forces on feet associated with running [28]. The middle layer is made up of polyester monofilament yarn and the two outer surfaces of the fabric were made from polyester multifilament yarns. The comfort properties of spacer fabric have been studied by measuring air permeability, water vapor permeability, and thermal properties with respect to fabric porosity. The experimental result shows that the vertical gap of the two outer surface layers and the horizontal pore size of the face surface decide the permeability and conductivity properties of the spacer fabric. It is found that the 3.1-mm thickness spacer fabric with hexagonal net structure proves to have good air and water vapor permeability and comparatively lower thermal conductivity.

4 Discussion

The information regarding the main features of the case studies is summarized in Table 1 for architecture field and in Table 2 for fashion design field. Besides the “application” category, the architectural case studies have been further classified in accordance with their performance typologies. The table collects information regarding the three-dimensional textile typologies, the design process developed, the binder embedded in the composite as well as regarding the procedures used in the designing process.

5 Architecture and 3D Textiles

The collection of case studies shows a great degree of variation with respect to their function and profiles: from building to infrastructure scale. Most of the case studies are developed by academic institutions and only few are developed by companies. In the first case, the projects are developed in partnership with specialized companies in 3D textile production, thus helping to explore new application fields and enabling innovative approaches. Also, most of the described case studies are developed by using an empirical method or have not specified digital design process. Empirical approach is still common even if the digital processes are very advanced in the examples in which are adopted. Regarding the 3D textiles, among the several typologies 6), polyester knitted spacer fabric is mainly used for architectural purpose. In fact, it allows to achieve several typologies of from structural to environmental performances. This is also possible thanks to the integration of different binders. In fact, if the specific project requires high mechanical performance, concrete or resin is applied to the composite. Instead for environmental performances, the projects prefer to use the intrinsic characteristics of the spacer composites as well as to exploit the integration of foam.

6 Fashion Design and 3D Textiles

The gathered case studies in fashion design (Table 2) concern wider application field that embeds also technical apparels, active protective systems as well as sportive clothes. Beside the body area application categories, the table collects the case studies specifying material system, 3D textile typologies, binder, performance, and design process. The projects are mainly developed by fashion brand companies or advanced composite manufacturers. In any case, academic institutions have an important role. The using of digital tools is not so common but, in those cases, it enables advanced process and allow to achieve high performance. In particular, the main performances that emerge from the collected case studies are thermal insulation, wearability, and impact protection. For the first performance the projects demonstrate as 3D spacer fabrics can achieve high thermal properties and wearability by using only intrinsic characteristics. Otherwise, it is combined with binder like foam or silicone material to achieve mechanical performance. 3D weaving typology can be an alternative solution.

Table 1 Overview of the architectural projects, gathering relevant data on material system, 3D textile, binder, and design process

Application	Typology	Partners	Year	3D textile material	3D textile typology	Binder	Primary performance	Design process typology	Source
Furniture	Lounge chair	Academic institution + University	2009	glass fiber	10 mm depth 3D warp-knitted textile	resin	ergonomics; multi functionality	digital	[10]
	Media Station	Academic institution + University + design firm studio	2009	glass fiber	3D warp-knitted spacer textile	resin	multi functionality; structure	digital	[10]
	Lamp	Design firm studio	2013	polyester	knitted-spacer fabric	none	lighting	empirical	[7]
	Chair	Designer	2013	polyester	8 mm warp-knitted spacer	patented cement	support	empirical	innerdesign.com
	Acoustic panel	University + company	2018	polyester	warp-knitted spacer textiles	none	sound absorption	empirical	[8, 9]
Structural applications and temporary structures.	Temporary pavilion	Academic institution	2016	polyester	15 mm thick spacer	resin	structural	digital	[17]
	Dome	University + company	2016	polyester	30 mm warp knitted spacer	PU based foam	mechanical	empirical	[17]
	Structural refurbishment	Building company	2018	polyester	8 mm warp-knitted spacer	patented cement	structural	empirical	Concretecanvas.com
	Temporary shelter	Company	2019	polyester	13 mm thick spacer	patented cement	force protection; insulating; fire resistant	empirical	Concretecanvas.com

Table 1 (continued)

Application	Typology	Partners	Year	3D textile material	3D textile typology	Binder	Primary performance	Design process typology	Source
Facades	Ventilated facade	University + company	2007	alkali resistant glass	0.89 mm2 (2400 tex) and 0.45 mm2 (1200 tex) spacer	concrete	thermal insulation	not specified	[12, 13]
	Movable shadowing system	University + company	2018	polyester	warp-knitted spacer textiles	none	daylight management	empirical	[11]
	cladding system	Spin off	2019	polyester	3d spacer fabric	cement	daylight management	digital	[14], [15]
	Textile photonic crystals	Foundation + Company	2019–2021	not specified	not specified	material and foam	sound insulation	not specified	[16]
Infrastructure	Ditch lining	Building company	2017	Polyester	8 mm polyester + PVC backing	patented cement	erosion control	empirical	Concretecanvas.com
	Slope protection	Building company	2019	Polyester	5 mm polyester + PVC backing	patented cement	erosion control	empirical	Concretecanvas.com

Table 2 Overview on fashion design applications, gathering 3dimensional textile typologies, material system, binder, primary performance, and design process

Body area category	Typology	Partners	Year	3D textile material	3D textile typology	Binder	Primary performance	Design process typology	Source
Hands and feet	shoe	Academic Institution University	2019	polyester	3D weaving	none	damping resistance	digital	[27]
	shoe		2014	polyester	warp-knitted polyester spacer fabrics;	none	air permeability, water vapor permeability, and thermal properties	Empirical	[28]
Bust and total body	jacket	University Brand company	2013	polyester	spacer fabric	foam	thermal properties	Empirical	[23]
	Balloon-Sleeve Sweater, Boat-Neck Sweater, Balloon-Sleeve Dress		2020	wool, cotton	3d knitting spacer fabric	none	comfort and wearability of daily staples	Digital	[24]
Head Upper and lower limbs	helmet	Public foundation University	2018	not specified	spacer fabric	EPS foam	damping resistance	Not specified	[20]
	jacket		2018	not specified	spacer fabric	none	fire resistance, heat stress reduction, movement comfort	Empirical	[25]
	jacket	Brand company	2007	nylon	spacer fabric	silicone material	comfort and impact protection	not specified	Dow Corning

7 Conclusions

This paper intends to give an overview on current application of 3D textiles in architecture and fashion design. In particular, the paper aims at underlying potentialities and the limits in current practice. Both are fields in which the technological achievements are affecting processes and final products. In terms of design process, the development of powerful digital tools allows to improve both the simulation and prediction of complex behaviour. The gap between real and virtual is decreased since these tools allow to control the whole process from design phase until the manufacturing one. Moreover, these tools are conceived as user-friendly for those that usually work with complex geometry system such as architects and textile designers. In addition, they improve the interoperability of the design process by smoothing the exchange of information between the operators of the several steps and, moreover, by enhancing the control of the performance enabling the scalability in terms of applications. In fact, most of the case studies demonstrate that the application of 3D textiles in both architecture and fashion design are led by the increased demand to achieve high performance results. The current practice focuses on mechanical and environmental performances mainly. Particularly advanced are the applications that exploit the micro-climate controlling features of 3D fabrics at apparel scale. This is scaled up to the architectural scale but still at very early stage. With a continuous and interdisciplinary exchange between textile designer, fashion designer and architects, it is possible to make economically and ecologically sustainable the usage of 3D textiles at architectural scale.

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Data Availability Statement The authors declare that all data supporting the findings of this study are available within the article.

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