textiles

MDPI

Review

Digital Hybridisation in Adaptive Textiles for Public Space

Katia Gasparini

University of Sassari, 07041 Alghero, Italy; kgasparini@uniss.it

Abstract: Over recent years, many architectural and urban surfaces interact with the environment like a changing skin, adaptable to environmental stimuli. The textile technology appears to be the most suitable to meet the requirement of adaptability to the environment because it can produce changes in shape and colour. Today, this is a possible thanks to textile systems and fibres that are increasingly hi-tech and smart. To make these adaptable systems is a fundamental role in digital technologies and is an important a multidisciplinary approach in every design phase. This article interweaves some of the developments and applications of textiles in urban space design, exploring the possible applications of emerging technology in architectural and urban design. This analysis aims to explore the intersection between the culture, design and technology of textile systems, as well as the role of parametric design and embedded systems in urban space design and transformation. The aim of this article is to spread knowledge on adaptable textile systems as materials for architecture and to do so through practice-based design research. The study frames the contemporary design explorations, in which digital design tools and material expression are major placeholders, with a focus on surface shapes and design experiments exploring the expressiveness of light, colour and movement as design materials. The article reflects on the role of digital design applied to textile systems for urban space as a possible tool aiming at enhancing existing space by surface prototyping.

Keywords: adaptive textiles; urban space; parametric design

Citation: Gasparini, K. Digital Hybridisation in Adaptive Textiles for Public Space. *Textiles* **2022**, *2*, 436–446. https://doi.org/10.3390/textiles2030024

Academic Editors: Fernando G. Branco and Stepan Lomov

Received: 3 May 2022
Accepted: 13 July 2022
Published: 5 August 2022

1. Introduction

As Mies Van der Rohe pointed out, every piece of architecture is linked to its own era and is made visible only with the means of its time in vital tasks. The opposite has never happened (Mies Van der Rohe, 1924) [1].

For this reason, architecture, as a concrete symbol of its time, always has the responsibility to respond to emerging human needs and, at the same time, must adapt to technologies and materials in a continuous evolution. Moreover, in contemporary times, the overwhelming development of the digital sector in the field of design allows you to design architectural and/or urban biomorphic organisms that can develop new functions and integrate the processes of the natural environment, which was unthinkable until a few decades ago. So, the parametric design connected to the emerging technology and materials has revolutionized the design process in the building sector.

Particularly, the scientific research about the emerging materials (reactive, smart, chromogenic, etc.) has led to the implementation of a new generation of fabrics suitable for improving the environmental requirement of architectural surfaces and public spaces. These emerging textiles can be used for temporary and adaptive installations in urban space, or they can be applied to make solar shading systems capable of reacting to environmental stimuli and to improve the performance of building envelopes. In both cases, to get this reactivity, it is possible to act on the material or on the construction system: we can use folding structures operated through mechanical or digital systems or create flexible textile systems that are reconfigured thanks to the innovative material adopted (smart-textile) or thanks to the geometry of the fabric (parametric design).

So, a fundamental design connection is developed between fabric/material, design, mechanical technology and modeling software because the optimal final performance of the textile installation depends on a series of interconnected energy, chemical, biological and mathematical factors.

These are the prerequisites of new research, which is currently ongoing, that explores the intersection among culture, art and technology and, subsequently, defines a method of analysis and categorization of adaptive textile systems for the urban environment, evaluating their potential design and future developments.

2. Research Background

Recent technological innovations have led to the development of a new generation of climate-responsive fabrics in different latitudes, developing the potential to contain energy consumption while improving the comfort of confined environments. To achieve this type of adaptability, it is possible to use folding structures driven by mechanical and dynamic systems or structures that are reconfigured thanks to the innovative material adopted or thanks to the geometry of the fabric used. The process of opening/closing and the variability of this type of structure are particularly interesting for the active control of solar radiation and daylight—both inside buildings and in any open space.

Some recent experiments and achievements in the international field allow for an interesting overview of the main parameters that determine the geometry and kinematic behaviour of the components of adaptive shielding based on curved line bending and their effect on the performance of the shielding system. In fact, it is possible to connect the parametric design of an adaptive shielding system with daylight and with energy/light flow modelling software in order to evaluate and improve the performance of the shielding fabric in an interactive way.

A fundamental design connection between the fabric/material, design, mechanical technology and modelling software is thus evident because the optimal final performance of the fabric depends on a series of energy-related, chemical, biological and mathematical factors. Textile fibers seem to be the most suitable material for these applications because they have many appearances and requirements such as translucency, colour, patterning effects and surface texture and tactility [2]. Today, with innovative textile fibers, such as blended fibers, microfibers and nanofibers with a high strength, low weight and better performance than traditional materials [3], it is possible to make a textile that achieves a structural function and has an aesthetic quality. In addition, by combining textile materials with non-textile materials such as sensors, actuators, processors and microsystems [4] and hybrid materials such as microelectronic components and conductive substrates, fabrics may no longer be passive but instead have the capacity to monitor and interact with individuals and their environment. The surface, building system and form are becoming more interconnected and interactive. For this reason, the designers need to work beyond the traditional boundaries of their disciplinary areas [5–7].

Previous research on urban textile installations using emerging technologies also analysed the role of interactivity and the responsiveness of these fabrics [8]. Of the 30 case studies selected internationally, one-third of the projects were built with dynamic systems and interacted with the surrounding environment (Table 1).

The state variations of the textile system were connected to environmental stimuli (movement-wind, sound, light). The concept of adaptivity in this case is assimilated to that of reactivity in architecture. Nicholas Negroponte introduced "Responsive architecture" in the late 1960s. According to him (1975), a "responsive architecture is the natural product of the integration of computing power into built spaces and structures". He also extends this belief to include the concepts of recognition, intention, contextual variation and meaning into computed responses and their successful and ubiquitous integration into architecture [9]. Today, we consider responsive skin to measure actual environmental conditions and to be able to adapt their shape, colour or character responsively, and it is the same for adaptive facades [10].

Table 1. Case studies of urban installations made with textile fibers (natural-artificial-digital/emerging) and different technologies (craftsmanship, digital/emerging, industrial) [11].

Case Study	Year	Place	Material	Design Tools	Technology
URBAN STUDIO ecoc1	2011	Tallin	Artificial	Trad-2D	Emerging
Portal da consciência	2012	Cidade Do México	Artificial	Trad-2D	Industrial
Urban shade	2013	Israele	Artificial	Trad-2D	Industrial
Polymorph	2013	Orléans	Natural	Parametric	Emerging
Entre le rangs	2013	Montreal	Artificial	Trad-2D	Emerging
Fashions fishing rope	2013	Madison Square P.	Artificial	Trad-2D	Craftsmanship
Warde	2014	Jerusalem	Artificial	Trad-2D	Emerging
Aarau bus station canopy	2014	Aarau (Ch)	Artificial	Trad-2D	Industrial
Delirious frites	2014	Quebec City	Artificial	Trad-2D	Industrial
Ephemeral pavilion	2015	Melbourne	Artificial	Trad-2D	Industrial
Icd/itke research pavilion	2016	Stuttgard	Emerging	Parametric	Emerging
Les volumes sourds	2016	Massy (Fr)	Artificial	Trad-2D	Industrial
Urban tree lounge	2016	Milan (It)	Artificial	Trad-2D	Industrial
The giant squid	2016	Azores	Artificial	Trad-2D	Industrial
Lumen	2017	New York	Artificial	Parametric	Industrial
Abwab pavilion	2017	Dubai	Artificial	Trad-2D	Industrial
Teflon pavilion	2017	Amsterdam	Artificial	Parametric	Industrial
Elytra filament pavilion	2017	Vitra Campus	Emerging	Parametric	Emerging
Gaia mother three	2018	Zurigh	Natural	Trad-2D	Craftsmanship
1.78 madrid	2018	Madrid	Artificial	Trad-2D	Emerging
Blue print	2018	Denver	Artificial	Trad-2D	Industrial
Urban inprint	2019	New York	Artificial	Parametric	Emerging
Cobalt muffin installation	2019	Shanghai	Artificial	Trad-2D	Industrial
Into the hedge	2019	Columbus (USA)	Artificial	Trad-2D	Industrial
Eastern lights	2019	Bucharest	Artificial	Trad-2D	Industrial
The catenary and the arc installation	2019	Palma De Mallorca	Artificial	Trad-2D	Craftsmanship
Prismatic	2019	Ghent (USA)	Natural/Ar.	Trad-2D	Industrial
Atomic	2019	Georgetown (USA)	Natural/Ar.	Trad-2D	Industrial
Bending arc	2020	Florida	Artificial	Trad-2D	Emerging
Murmuration	2020	Atlanta (USA)	Artificial	Trad-2D	Industrial

3. Methodology

The research originates from the author's previous research [11–13] on reactive and colourful systems for architecture and urban space. Through the analysis of some of the most recent and innovative case studies and the recent scientific literature, this article lays the foundations for research on the potential of new technologies and materials for the design and implementation of urban adaptive textile installations.

The topic requires a multidisciplinary research and design approach, the key components of which are parametric design, electronics and mechatronics, textile design, emerging technologies and materials [5,6,14].

In order to achieve the predefined objectives, the research process has been developed as follows:

- Review of the textile in urban space (Section 3.1);
- The role of parametric design and the additive manufacturing (Section 3.2);
- The adaptivity of the textile (Section 3.3);
- Multidisciplinary and research. Three case studies (Section 3.4).

3.1. Textile Design and Urban Space

Textile architecture has ancient origins, dating back to 40.000–44.000 BCE, ranging from the period of the pre-historic age and continuing into contemporary times [4]. Currently, this field of application is witnessing noticeable developments day by day, being linked in more recent times (in the 20th century) to the studies and experiments on kinetic architecture by Buckminster Fuller. Additionally, Frei Otto (1925–2015) was inspired by nature and sought to mimic biological structures in terms of both form and function (biomimicry), inspiring forms based on aquatic microbiological organisms (planktons) and studying the principles of natural structures such as spider webs, plants, vertebrates, etc. He also applied these principles to textile architecture; hence, he produced more innovative forms supported by cable nets, tensioned membranes and pneumatic structures, thus anticipating the current parametric design [15]. In the 21st century, the modeling of textile surfaces was linked to parametric design by big names in architecture. The term "parametric design" mainly referred to computational design systems—in other words, systems capable of modeling, simulating or replicating shapes and patterns using a computer. The term was applied as early as the 1960s by architect Luigi Moretti (1906–1973) and by mathematician Bruno De Finetti (1906–1985). Traces of this design method can be found in the work of Zaha Hadid (1950–2016), Gregg Lynn, ONL and many others. Basically, information technology has given designers the instruments to analyze and simulate the complexity of nature and apply it in the shaping of buildings and in urban organization [16].

The analysis of a significant sample of case studies about urban installations showed that they were built with textile systems made by different materials and technologies. This reveals that there was a fundamental design connection between the fabric/material, design, mechanical technology and modeling software because the best final performance of the fabric depends on a number of energy-related, chemical, biological and mathematical factors [8].

Why use textiles for urban installations instead of traditional rigid building systems? This is mainly for their requirements of: being lightweight, being flexible/foldable, having a high tensile and tear strength, having a variety of transparency levels and recyclability. Additionally, this is because they can meet the requirements of the facades and users related to: daylight level control, glare control and solar heat, gaining thermal insulation, ventilation management sound and pollution control [17].

Some recent experiments and achievements in the international field allow for an interesting overview of the main parameters that determine the geometry and kinematic behavior of the adaptive shading components based on curved line bending and their effect on the performance of the shielding system. In fact, it is possible to connect the parametric design of an adaptive shielding system with daylight and with energy/light flow modelling software in order to evaluate and improve fabric performance interactively. Parametric design allows for emphasis to be placed on the progressive evolution of the shape and texture of textile shielding.

Despite these factors, the first results related to the study of the design tools and technologies involved prove that there are very few case studies designed with parametric tools or made with emerging technologies (9 out of 30). Emerging technologies and parametric design (6 out of 30) are not widely used. Artists and designers seem to prefer industrial manufacturing (18 out of 30) (Table 1). Projects made by industrial or craft technologies are not interactive; on the contrary, the use of emerging technologies is linked to the adaptability of the system or fabric.

3.2. Parametric Design and Additive Manufacturing

Parametric design tools are flexible, adaptive and accurate in solving complex problems in architectural and urban design. In the field of architecture, there are several digital tools that perform different functions. The connection between these different tools is timely via plug-ins, and most of them are multi-hybrid platforms capable of performing various tasks, such as modelling, simulation and evaluation [18].

Parametric design versus conventional design methods applies mathematical variables to easily solve complex geometric problems and create advanced design models in an automated process.

Therefore, the aim of parametric design is to establish direct relationships between the elements of the project through codes/algorithms. In this way, the project changes into real time, reducing the amount of iteration needed to obtain optimized results [19,20]. It then allows you to investigate the geometry and behaviour of the fabric, from the knitting and weaving of individual yarn to large-scale fabric structures. In addition, the contextual use of computational design tools and simulation and modelling software integrated directly into the design process obtains excellent results from the point of view of solar and acoustic shielding.

These programs have extended the possibilities of developing complex forms inspired by nature, minimising implementation times and improving both the quality and performance of the textile installation. Such techniques have been used to produce several famous works of contemporary architecture and urban installations, including the Olympic Watercube in Beijing, China, 2008, and the installations of Jenny Sabin and Janet Echelman.

Parametric design is connected to the use of digital systems for additive-AM manufacturing (Industry 4.0) in different sectors and to the use of innovative materials (Figure 1).

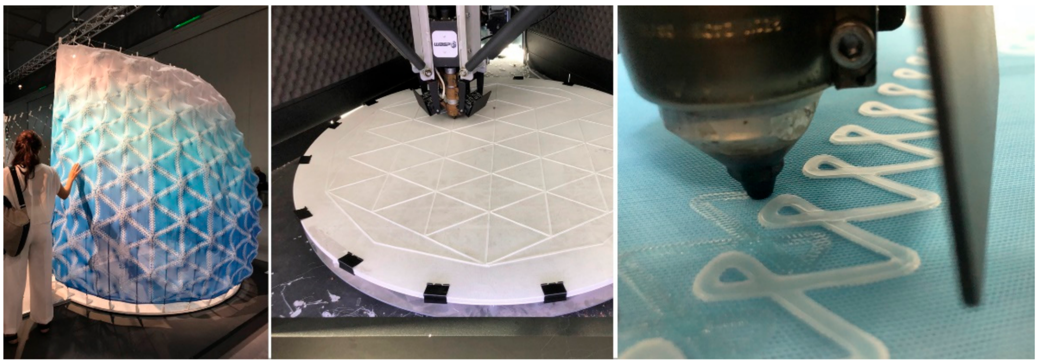

Figure 1. Textile created by a team of architects and designers from the Milan Polytechnic and the NUMEN institute in collaboration with the companies ShapeMode and DeltaWASP (ph. @3dwasp e www.3dwasp.com accessed on 26 February 2022).

At present, the materials used in 3D printing are synthetic materials (polymers) and, in some cases, are minerals for Selective Laser Sintering (S.L.S.). We have witnessed the creation of objects with materials called "liquid stone", for example, or with materials of a mineral origin. AM has recently found its way into the textile industry. There are interesting experiments in fashion design thanks to the designer Iris Van Herpen or the Kinematic dress produced with the sls by Nervous System Design. However, these are experiments that use only synthetic materials and not natural fibres or anything like them.

The most current materials used for AM textile structures are usually not flexible enough to provide adequate comfort for daily use. Natural textile fibres on a cellulosic or protein basis would be ideal to provide environmental comfort even in shielding or urban installations. Some researchers try to use wool as a printing material to overcome the limit of plastics, but in this case, the process is related to the needling of wool yarn to produce 3D shapes and precisely do not present 3D printing using polymer deposition. Since wool and cellulose fibres have no melting point, their direct use for 3D printing by melting is not possible; only solution-based methods could be a solution for them [21]. Moreover, it is a question of understanding how suitable these natural materials would be for outdoor use. Emerging 3D printing technologies are also being developed to be used for innovative methods aimed at multi-material printing to produce complex structures, bio-printing with various soft and biocompatible materials, optimising AM technology with higher speeds, improved resolution and lower costs and combining AM with traditional production [21].

In the projects analysed in Table 1, the use of parametric design to define the shape of the installations often corresponds to the construction of steel cable structures (i.e., Portal Da Consciência) or aluminium objects covered by recycled polymeric material (i.e., Urban Shade, Abwab Pavilion, Prismatic). More broadly, the textile surfaces are made with polymeric materials (PTFE, ETFE, nylon, etc.); only one case mentions cables in carbon-fibreglass (ICD/ITKE Research Pavilion), or we can find a generic "composite material" cited. Only Jenny Sabin's design mentions a smart yarn of the hydro-chromic type (i.e., Lumen), or she used ceramic 3D printing in the Polymorph project.

3.3. The Shape of Adaptive Textiles

Textiles in architecture, as in interior and fashion design, are commonly thought to be materials without their own shape—to be sewn and "adapted" on building systems or on people.

The chemical research applied to the creation of new yarns (derived from smart materials, nanotech, etc.) has allowed for the design and production of seemingly endless solutions of fabrics with different behaviours and functionalities in relation to the different environments and surfaces of application and interaction.

In theory, the fabric is a light and easily transportable semi-finished product; it can be made with a range of different yarns, currently with recycled materials and with the so-called "neomaterials" inserted in the current vein of the circular economy, which have a great potential to be a sustainable choice for architecture.

In the field of solar shielding and textiles for installations and small urban pavilions—that is, in any kind of architectural project that uses traction instead of compression—fabrics are designed to follow a predetermined shape, whether they are natural tissues or if they are the result of the research on polymers and nanostructured and layered materials. In the "tensile" architecture, the fabrics are stretched until the resulting shape becomes practically rigid. This is done to avoid deformation due to the wind load. What if we allow for movement in the fabric? What happens if the wind becomes a design variable to decide the expression of the textile architectural form? This means that it can be adaptive to the construction system or that the materials have to be adaptive.

An adaptive system reacts to its environment, inhabitants or the objects within it. A common motivation for designing adaptive systems is to save energy resources. However, many systems fall into the paradox of using a lot of energy, both through the operational phase and the maintenance. Adaptive systems often rely on numerous actuators and require a continuous power supply to operate [11–13,22]. Some examples of this are the experiments on dynamic and adaptive architectural facades built in the last 20–30 years, which nevertheless have remained experiments with little success, from the Institute du Monde Arabe in Paris to the more recent Al Bahar Towers and their responsive facades. This is due to the cost of the construction, the management and the operational problems over time due to the complexity of the system [11–13].

Today, in the textile design field, Jenny Sabin's process design for the Lumen project is interesting. The form-finding software package used is a custom C# plug-in for Rhino that implements dynamic relaxation—a mathematical formulation for solving for equilibrium states of structures. The Rhino geometry from the Jenny Sabin Studio was used to construct an analysis model and loading corresponding to the weight of the knit structure, and wind pressure was applied. While running the model, element lengths were adjusted to regularise the net, minimising the number of distinct cell sizes. Based on the model output, additional edge ropes were added to increase the tensile capacity of edges under high tension. The anchorages were then sized according to the forces [23].

The adaptivity of the material seems to be the most feasible method, even if, currently, the experimentation in this sense is limited to smart materials, which, in the textile sector, tend to be chromogenic materials. Materials that change shape (shape memory) have not yet found an application on a large scale. In any case, we always remain in the field of synthetic materials, not natural materials.

A project recently presented at the Expo in Dubai, on an experimental basis, is the SIKKA fabric project. The project is based on the innovative combination of rigid materials and flexible materials; 3D printing has been realised on fabric. The prototyping process involves 3D printing with FDM technology (3D pellet printing) on elastic fabric. The fabric, without the tension, generates the selective deformation of the plane and extremely complex surface curvatures. The composite fabric is then bent, cut and/or laminated to achieve further aesthetic and functional effects [24].

3.4. Multidisciplinarity and Research

Multisciplinarity in design and research allows you to optimise the performance of the most advanced systems in any environment. For this reason, the skills currently involved in the design of adaptive textile systems include electronic, spatial and material engineering for the construction component, art and design for the interaction between form and function and the study of biology—because environmental systems are similar to living beings—as an extension of nature and its multiple biological parameters. Citing the Japanese architect Toyo Ito, one could argue that "since architecture has always served as a means of adapting to the natural environment, contemporary architecture must function as a means of adapting to the computer environment; architecture today must become a media dress" [25].

The textile fibres currently used offer unique characteristics such as translucency, colour, patterned effects, texture and the tactility of the surface. With the development of new textile fibres, such as mixed fibres, microfibers and nanofibers with a high strength, low weight and high performance compared to conventional materials [3], it is possible to make fabrics with better structural functions and aesthetic qualities.

In addition, by combining textile materials with non-textile materials such as sensors, actuators, processors and micro systems [4] and hybrid materials such as microelectronic components and conductive substrates, tissues become active and acquire the ability to monitor and interact with individuals and their environment [5,6,14].

At present, the most advanced and well-known applications can be seen in the following two projects: that by Jenny Sabin and Janet Echelman in collaboration with Arup and HygroSkin Pavilion by Achim Menges in collaboration with the Institute for Computational Design, University of Stuttgart.

3.5. Case Studies

3.5.1. As If It Were Here, Janet Echelman, 2015

The temporary installation (2015, 6 months) was made for the Boston Rose Kennedy Greenway and involves a multidisciplinary approach between art, engineering and architecture. This is a confirmation of what has been said previously about the close relationship between structural and parametric design and art at the time of approaching fabrics, both shielding and artistic.

In open spaces, the factors involved in design are related both to the performance of the materials involved and to the study of shapes.

The latter must reflect the creative part and respond to the mechanical and dynamic stresses resulting from the size, texture and environmental stress.

A partner of the project is the company Arup, which has followed the engineering and construction of this sculpture of fibreglass of about 2000 square meters. The sculpture was installed about 110 m above the Rose Kennedy Greenway in Boston and extends up to 180 m between three skyscrapers.

The form of the installation echoes the history of the urban space on which it stands. The three voids recall the "Tri-Mountain" that was razed to the ground in the 18th century. The colourful bands are a nod to the six lanes that once swept the neighbourhood, before the Big Dig allowed for the reclamation of space for urban pedestrian life. The sculpture is composed of hand-woven ropes that form an interconnected network of over half a million knots. When any of its elements move, every other element is affected. It appears to be a monumental drape in scale and strength, but it is delicate as lace, which reacts fluidly to the wind and time that is always changing.

Its fibres are 15 times stronger than steel but incredibly light, making the sculpture able to adapt directly to three skyscrapers as a soft drape on architecture with sharp contours.

The artwork incorporates the elements of dynamic light that interact with the changing wind thanks to an embedded system that, according to the movement and tension of the fibres, produces the chromatic variability of the light projected on the surface of the sculpture.

The fabric is made with high-molecular-weight polyethylene and high-tenacity woven polyester fibres with coloured LED lighting.

It was the work of a multi-disciplinary team in which Arup worked closely with Studio Echelman, Autodesk and Shawmut Design and Construction to realise the artist's vision of reconnecting the city on Greenway. Arup's main role was to design the geometric and structural design for the prestressed cable network that supports and forms an integral part of the sculpture.

Arup engineers have developed dedicated software that implements an "adaptive form-finding" algorithm to optimise the geometry and structure of the sculpture. Module research was part of an overall digital workflow, from concept to fabrication [26].

3.5.2. ADA

This project is by Jenny Sabin studio, in collaboration with Microsoft Research, 2018–2019.

This project was born by collaboration with Microsoft Research, after 13 year, and it embodies performance, material innovation, human-centred adaptive architecture and emerging technologies, including artificial intelligence. Ada is a cyber-physical work of architecture that is adaptive, personal, data-driven and informed by individual and collective participation. It is an open responsive system featuring digitally knitted lightweight, high performing, form fitting and adaptive materials.

The constructive system has been made with a lightweight knitted pavilion structure of responsive and data-driven tubular and cellular components employing textiles and photo-luminescent fibres that absorb, collect and emit light. An external rigid experimental shell structure assembled from a compressive network of 895 unique 3D printed nodes and fibreglass rods holds Ada's form in continuous tension. A network of sensors and cameras located throughout the building offers multiple opportunities for visitors and participants to engage, interact with and drive the project. Three scales of responsive and graduated lighting, including a network of addressable LEDs, a custom fibre optic central tensegrity cone and five external PAR lights, respond in real time to continuous streams of data. Specific data are correlated with colours, spatial zones within the project and responsive materials [27].

3.5.3. HygroSkin-Meteorosensitive Pavilion

Permanent Collection, FRAC Centre Orléans, France.

Achim Menges in collaboration with Oliver David Krieg and Steffen Reichert, 2011–2013.

"The project HygroSkin-Meteorosensitive Pavilion (Figure 2) explores a novel mode of climate-responsive architecture. While most attempts towards environmental responsiveness heavily rely on elaborate technical equipment superimposed on otherwise inert material constructs, this project uses the responsive capacity of the material itself. The dimensional instability of wood in relation to moisture content is employed to construct a meteorosensitive architectural skin that autonomously opens and closes in response to weather changes but neither it requires the supply of operational energy nor any kind of mechanical or electronic control. Here, the material structure itself is the machine". The pavilion's envelope, which is at the same time a load-bearing structure and meteorosensitive skin, is computationally derived from the elastic bending behaviour of thin plywood sheets. The material's inherent capacity to form conical surfaces is employed in combination with seven-axis robotic manufacturing processes to construct 28 geometrically unique components housing 1100 humidity responsive apertures. The project taps into several years of design research on robotic prefabrication, component-based construction and elastically self-forming structures. For this pavilion, a computational design process was developed based on the elastic behaviour of thin planar plywood sheets and the material's related capacity to form conical surfaces. The computational process integrates the material's capacity to physically compute form in the elastic bending process, the cumulative structure of the resulting building components, the computational detailing of all joints and the generation of the required machine code for the fabrication with a seven-axis industrial robot [28].

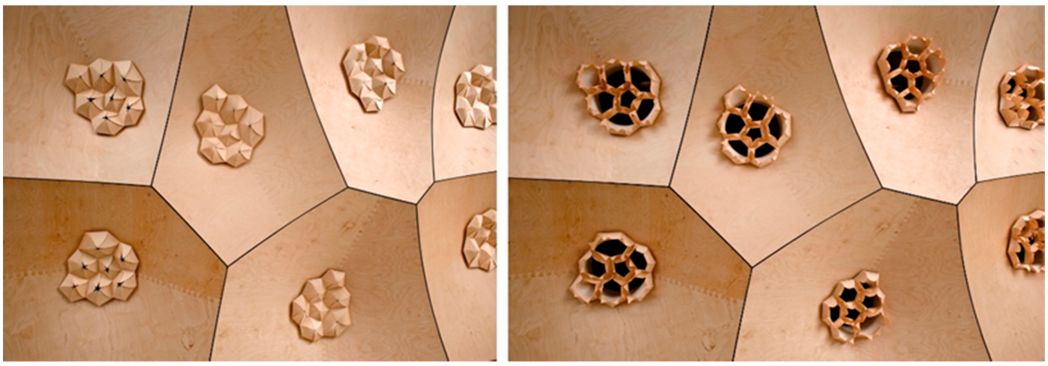

Figure 2. HygroSkin-Meteorosensitive Pavilion, details (© ICD University of Stuttgart, © Achim Menges).

4. Outlook and Conclusions

At the beginning of the research, the goal was exploring the intersection of culture and technology and, later, defining a method of the analysis and categorisation of adaptive textile systems for the urban environment, evaluating their design potential and future developments. It is a multidisciplinary field of research because it requires the collaboration of digital disciplines, chemical and technological research, artistic design and social interaction. During the work, it became clear that a classification of adaptive envelopes does not, at this time; lead to a viable scientific conclusion but only to experimental projects. At the moment, there is no specific line of research, but there are a series of technological experiments that develop on several levels—from interactive systems, to intelligent materials, to the physics of perception and communication in the urban environment. In general terms, it is still necessary to define what these systems can be and the relations they undertake with the urban environment in which they can be placed. As we have seen from the analysed examples, the recent design trends lead to increasingly complex geometries that involve a revolution in the conception of the hierarchy of the building system, cancelling it. Basically, there is no longer a difference between structure and coating but rather a skin interconnected with a "nervous" system of a molecular type, interconnected and interactive.

Another observation is linked to the fact that adaptive textile systems are linked either to the social context (human interaction) or climate context in which they are applied, a factor that greatly influences their effectiveness. Since these are different types of experiments, the comparison between environmental and construction efficiency appears complex.

This study has highlighted the potential of research in two directions: that of high-performance synthetic fabrics and the possibility of using them in integration with an adaptive exoskeleton or cable system—therefore, "intelligent systems"; the second derives from the analysis of the Hygroskin Pavilion, which highlights the adaptive potential of natural materials but in the form of panels.

The next step, which will be the result of analysis and experimentation, will be the integration of these different technologies, evaluating the possibility of making fabrics from materials that are naturally adaptive in shape and environmental performance. They could be yarns derived from woody essences/trees already on the market for the realisation of screening systems or urban installations that are absolutely biocompatible, with zero energy consumption.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Gasparini, K. The Colour of Emerging Textile for Urban Regeneration. In Proceedings of the AIC2020 International Conference, Avignone, ISSN: 2617-2410-ISSN: 2617-2429.

Acknowledgments: The author would like to thank ICD University of Stuttgart for the technical information, photos and drawings for the project Hygroskin Pavilion and WASP for the Sikka project photos.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Van der Rohe, M. Architettura e Volontà Dell'epoca. In De Andreis, L. Scritti e Opere di Mies van der Rohe; *HORTUS*, 1924. Available online: https://vg-hortus.it/ (accessed on 20 March 2022).
2. Salim, F.D.; Burry, J.R.; Peers, J.; Underwood, J. Augmented Spatiality. *Int. J. Archit. Comput.* **2012**, *10*, 275–300. [CrossRef]
3. Horrocks, A.R.; Anand, S.C. (Eds.) *Handbook of Technical Textiles*; The Textile Institute and Woodhead: Cambridge, UK, 2000.
4. Jayaraman, S.; Kiekens, P.; Grancaric, A.M. (Eds.) *Intelligent Textiles for Personal Protection and Safety*; IOS: Amsterdam, The Netherlands, 2006.
5. Stouffs, R.; Janssen, P.; Roudavski, S.; Tunçer, B. (Eds.) Open Systems. In Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013), Singapore, 15–18 May 2013.
6. *The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA): Hong Kong, China*; Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS: Singapore, 2013; pp. 965–974.
7. Underwood, J.L.; Adams, L.E.; Beale, C. Transformative textiles. In *Cumulus 38 Degrees South 2009, Proceedings of the Cumulus Conference, Melbourne, Australia, 12–14 November 2009*; Fennessy, L., Kerr, R., Melles, G., Thong, C., Wright, E., Eds.; Swinburne University of Technology: Melbourne, Australia, 2009; pp. 1–10.
8. Gasparini, K. The colour of emerging textile for urban regeneration: The role of technology between experimentations and craftsmanship. *Color Res. Appl.* **2021**, *46*, 538–545. [CrossRef]
9. d'Estrée Sterk, T. Building Upon Negroponte: A Hybridized Model of Control Suitable for Responsive Architecture. In *eCAADe 21 Digital Design*; Graz University of Technology: Graz, Austria, 2003; pp. 407–414. [CrossRef]
10. Aelenei, L.; Brzezicki, M.; Knaack, U.; Luible, A.; Perino, M.; Wellershoff, F. COST Action TU1403-Adaptive Facades Network. In *Adaptive Facade Network-Europe*; TU Delft Open: Delft, The Netherland, 2015.
11. Gasparini, K. The Colour of Emerging Textile for Urban Regeneration. In Proceedings of the AIC2020 International Conference, Avignone, France, 26–27 November; Available online: https://doi.org/10.1002/col.22644 (accessed on 20 February 2022). [CrossRef]
12. Gasparini, K.; Premier, A. Responsive Skins: Complexity vs. Simplicity. In Proceedings of the Powerskin Conference, TUM Munich, Munich, Germany, 17 January 2019; ISBN 978-9463664066. Available online: https://issuu.com/katiagaspariniarchitetto/docs/powerskin-2021-premier-gasparini (accessed on 6 February 2022).
13. Gasparini, K.; Premier, A. The future of responsive surface in the liquid modernity. In Proceedings of the Future Talks 019, Munich, Germany, 11–13 November 2019; ISBN 978-3-9818165-9-4.

14. Salim, F.; Burry, J.; Underwood, J. Augmenting public spaces with live forms and fabrics. In *Open Systems, Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013), Singapore, 15–18 May 2013*; Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS: Singapore. Available online: http://papers.cumincad.org/data/works/att/caadria2013_263.content.pdf (accessed on 6 February 2022).
15. Vural, Y. Tensile Membrane Structures: Form, Material and Design. Master's Thesis, Anhalt University of Applied Sciences, Köthen, Germany, 2019.
16. Premier, A. 2022, Parametric Design in the Creation of Screening Fabrics. Available online: http://www.architetturatessile.eu (accessed on 2 April 2022).
17. Lampadiari-Matsa, A. Adaptive Fabric Facade for a High-Rise in Paris, p5 Report | July 2017, TU Delft MSc Architecture, Urbanism and Building Sciences | Building Technology Track. Available online: https://repository.tudelft.nl/islandora/object/uuid:a1ef4211-504c-4908-8a12-e1342719335b?collection=education (accessed on 15 April 2022).
18. Panya, D.S.; Kim, T.; Choo, S. A Methodology of Interactive Motion Facades Design through Parametric Strategies. *Appl. Sci.* **2020**, *10*, 1218. [CrossRef]
19. Woodbury, R. Elements of Parametric Design. In *Elements of Parametric Design*, 1st ed.; Routledge: London, UK, 2010.
20. Eltaweel, A.; Su, Y. Parametric design and daylighting: A literature review. *Renew. Sustain. Energy Rev.* **2017**, *73*, 1086–1103. [CrossRef]
21. Dereje Berihun, S.; Ahrendt, D.; Kyosev, Y.; Kabish, A.K. Additive Manufacturing and Textiles-State-of-The-Art. *Appl. Sci.* **2020**, *10*, 5033. [CrossRef]
22. Wyller, M.; Yablonina, M.; Alvarez, M.; Menges, A. Adaptive kinematic textile architecture. *Constr. Robot.* **2020**, *4*, 227–237. [CrossRef]
23. Sabin, J. Lumen. 2018. Available online: https://papers.cumincad.org/data/works/att/acadia18_444.pdf (accessed on 1 June 2022).
24. Available online: https://www.shapemode.it/sikka-textiles-3d-printing?v=78533df0a516; https://www.3dwasp.com/wasp-sponsor-tecnico-del-vincitore-della-expo-dubai-2020-design-competition/ (accessed on 15 April 2022).
25. Le Architetture di Toyo Ito. Available online: http://org.noemalab.eu/sections/specials/tetcm/2002-03/toyo_ito/architettura_citta.html (accessed on 3 February 2022).
26. Studio Echelman, 2019. Available online: https://www.echelman.com (accessed on 6 February 2022).
27. Available online: https://www.jennysabin.com/ada (accessed on 10 April 2022).
28. Hygroskin Pavillion, Katja Rinderspacher, ©ICD University of Stuttgart. Available online: https://www.icd.uni-stuttgart.de/projects/hygroskin-meteorosensitive-pavilion/ (accessed on 6 February 2022).