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Membrane architecture: the seventh established building material. Designing reliable and sustainable structures for the urban environment

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7-9 June 2023

Nantes Université, Nantes, France

Editors

Evi Corne, Marijke Mollaert, Carol Monticelli, Bernd Stimpfle,
Jean-Christophe Thomas

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The 7th International TensiNet Symposium "Membrane architecture: the seventh established building material. Designing reliable and sustainable structures for the urban environment" took place at Nantes Université (France) from Wednesday 7th till Friday 9th June 2023.

TENSINANTES 2023 focuses on the significance and potential of fabrics and foils as established building materials and promotes the use of tensile structures in a world of constant change and adaptation. The optimal use of materials, the realisation of a Eurocode, sustainability and reuse are some of the topics which are covered, ranging from research over practical experiences to realisations.

This three-day event allows prominent experts from the world of architecture and engineering to present inspiring projects, to demonstrate the multitude of possibilities offered by lightweight structures, as well as to show recent research results in the domain of fabrics and foils.

The symposium is organised around 3 main topics including 5 keynote lectures & 47 lectures held in plenary and parallel sessions

• **Structural membrane**: contemporary, innovative, adaptive daring and impactful solutions

• **Tensioned membrane structures**: the seventh building material

• **Structural membrane**: an answer to issues of the 21st century

The papers have been brought together by topic and in the order in which they were presented.

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T-shade: experimental case study conducted to reuse t-shirts as a tensile-shading system

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Abstract

The T-Shade system is a sustainable and cost-effective solution for urban shading constructed from fashion waste that reduces the adverse effects of solar radiation and brings comfort to urban environments. This paper presents the development, evaluation, and potential of the T-Shade system, which is designed and structurally analysed using computational algorithms and form-finding methods. Experimental studies have shown that T-Shade can effectively reduce the amount of solar radiation entering the building while preserving daylighting conditions, and its modularity enables it to be easily installed and adapted to various urban contexts and dimensions. The system was constructed in 2021 at the campus of Politecnico di Milano, demonstrating its real-world application. T-Shade aims to address the increasing demand for sustainable shading systems by promoting comfort and sustainability in urban areas by combining functionality, sustainability, and affordability. The proposed solution is an example of how upcycling practices can lead to innovative and sustainable solutions for urban challenges. The paper concludes by highlighting the importance of sustainable shading systems and the role of upcycling practices in promoting sustainable practices in urban areas.

Keywords: Reuse, Urban shading, sustainability, upcycling, T-Shade, cost-effective, Ultra-lightweight, computational form-finding.

1. Introduction

Clothing is responsible for 2-10% of environmental impact across various sectors, making it a significant contributor. Clothing consumption is projected to increase by 63% by 2030, from 62 million tons in 2015 to 102 million tons (Global Fashion Agenda & The Boston Consulting Group, 2017). The textiles industry, deeply ingrained in society and culture, is among the most polluting industries globally. Moreover, the production of raw materials for the textile and clothing industries has the biggest total environmental impact (Da Silva et al., 2021). Majority of the raw materials used originate from either agriculture or petro-chemical industry of which both are responsible of vast amounts of emissions. The textiles industry faces considerable pressure to meet increasing demand due to a growing population, increasing wealth, and consumerism in emerging markets, and the rise of fast fashion in developed countries. Claudio (2007) defines fast fashion as "a possibility to produce clothing at increasingly lower prices, making consumers consider clothing as disposable." The fast-fashion business model is based on copying styles from high-end fashion and delivering them in a short time, at low prices, and typically with low-quality materials in large volumes and due this to be thrown away after wearing them maximum seven-eight times (European Parliament, 2019). As a result, there is a significant strain on natural resources, which has caused severe environmental impacts and social problems. Furthermore, the overproduction of textiles and changes in consumer patterns have resulted in vast quantities of used and unsold textiles ending up in developing countries, while most post-consumer waste is disposed of as waste. (Wang, 2006; Beton et al., 2006; Zamani et al., 2014).

One of the major issues is the enormous amount of waste generated, with 92 million tonnes of garments ending up in landfills each year, which is equivalent to a rubbish truck full of clothes every second. This trend is expected to continue, with fast fashion waste predicted to increase to 134 million tonnes per year by the end of the decade. Dyeing and finishing, along with yarn preparation and fibre production, are some of the most resource-intensive processes in the industry, contributing to 3% of global CO_2 emissions and over 20% of global water pollution. These processes rely heavily on energy-intensive methods using fossil fuels (source:Earth.Org).

Figure 1: The wasted clothes were collected by the HUMANA company

The table below shows the data on global fiber production in 2021 (source: textileexchange.org). In the face of a total production of 111 million tons, it emerges that the two dominant classes are Polyester and Cotton.

Table 1: Global fiber production in 2021 based on: textileexchange.org

Type of fiber	Polyester	Other Syntactic fiber	Cotton	Other Vegetable fiber	Animal Fibers	Artificial (cellulosic matrix)
Percentages	54	10	22	5.9	1.6	6.4

This paper proposes the learning-by-doing development of an ultra-lightweight shading system constructed of wasted t-shirts as a way to utilize discarded t-shirts in the construction industry. Its goal is to raise awareness about the significant amount of textile clothing that is thrown away every year, which has a substantial environmental impact due to the water, energy, and chemicals consumed in its production and service life (EURATEX, 2019).

2. Problem statements

2.1. The application context: the urban shading-system

Cities are rapidly growing, resulting in increased urbanization and its associated challenges. Urban shading systems, including natural and artificial means of providing shade, are essential for creating comfortable and sustainable urban environments (Jiang et al., 2017) due to the need to create comfortable public spaces for gathering people as well as to improve human well-being for urban inhabitants (Source: www.yale-nus.edu). Existing gaps in urban shading systems require further investigation and attention. These gaps include the need for comprehensive design and integration guidelines considering local climate, building orientation, and urban morphology (Jiang et al., 2017). Further research is necessary to evaluate the performance of different shading techniques in various urban contexts, considering their impact on microclimatic conditions, energy consumption, and human comfort (Jiang et al., 2017). Equity and accessibility should be addressed to ensure fair access to shaded spaces, address social justice concerns, and avoid disparities (Webb et al., 2020). Increasing public awareness and fostering community engagement through education and outreach initiatives are essential for successful implementation (Webb et al., 2020). Collaboration among stakeholders, including policymakers, urban planners, architects, and researchers, is crucial to developing comprehensive guidelines, conducting evaluations, promoting equity, and raising awareness for the sustainable and inclusive integration of urban shading systems.

2.2. The material: wasted clothes

Currently, individuals purchase an average of 13 kg of new clothing per year, of which less than 1% is recycled for new clothing, while 13% is reused in other industries such as insulation and mattress fillings (Zanelli et al., 2020). Recycling and reusing of wasted clothes have become an increasingly important topic in recent years due to the negative impact of textile waste on the environment. According to Beton et al. (2006), the overproduction and shifting consumer patterns in the fashion industry have led to significant amounts of used and unsold textiles ending up in developing countries, while most post-consumer waste ends up in landfills. To address this issue, various recycling and reuse strategies have been developed. For instance, mechanical recycling involves shredding and spinning old textiles into new yarns, while chemical recycling breaks down the fibers into their basic components to produce new materials (Hu et al., 2021). Reuse strategies include donation to charities, resale markets, and upcycling, which involves transforming old clothes into new products with higher value (Zamani et al., 2014).

Despite the potential benefits of recycling and reuse, there are also challenges associated with these strategies, such as the cost and complexity of the recycling process and the lack of demand for recycled materials (Hu et al., 2021). Additionally, there is a need for more education and awareness among consumers to encourage a shift towards more sustainable consumption patterns (Goworek et al., 2019). Nonetheless, recycling and reusing of wasted clothes have the potential to reduce the environmental impact of the fashion industry and create a more circular economy.

The raw materials used in the products are not only valuable but also have potential to be utilized for construction industry, as they are or by shredding into their raw materials. Emerging technologies on sorting discarded textiles exist; simultaneously, utilization in construction sector may prove lower processing requirement and faster applicability in comparison to recycling textiles waste back into consumer garments.

2.3. Form-finding and Computational design process

Despite the advancements in computational design and form-finding methods, there are still gaps in the field when it comes to utilizing wasted materials as structural elements. While techniques like mesh relaxation can create optimized shapes for tensioned structures, there is a lack of strategies for incorporating discarded materials into the design process. This gap presents an opportunity to explore how wasted clothes, for example, can be integrated into the form-finding process to create sustainable and cost-effective designs. By addressing this gap, we can move towards a more circular economy where discarded materials are repurposed and reused in innovative ways.

3. Research questions and objectives: Can wasted T-shirts be used as a membrane for urban shading systems?

The research question of whether wasted t-shirts with acrylic sources can be used as a membrane for urban shading systems is an interesting and relevant topic for sustainable design. With the growing concern about the environmental impact of textile waste and the need for sustainable urban solutions, repurposing discarded t-shirts as shading membranes could be an innovative and eco-friendly approach. However, this research question presents several challenges that need to be addressed, such as the durability and strength of the material, the production process, and the feasibility of using this material for large-scale urban shading systems. Investigating these challenges could provide valuable insights into the potential use of textile waste in sustainable urban design. This paper presents a learning-by-doing project that mostly involved the form-finding and fabrication of a temporary waste-based shading system.

4. The project approach and methodology

The project approach involves collecting discarded t-shirts from HUMANA, a multinational social enterprise, and processing them in the TextilesHUB laboratory to create a repurposed fabric. The digital form-finding technique will be employed using Kangaroo, a grasshopper plugin, to optimize the shape of the shading membrane based on the physical properties of the repurposed fabric while Finite Element Analysis (FEA) with Karamba evaluates its structural performance. The selected t-shirts will be interconnected to create a cohesive membrane and installed on-site as an urban shading system. The methodology will include a series of physical testing and evaluation to assess the durability and strength of the material and the feasibility of using it for large-scale urban shading systems. This research aims to contribute to the development of sustainable design solutions and demonstrate the potential for transforming waste into valuable resources.

The T-Shade, a temporary shading system, was installed on the Politecnico di Milano campus during the summer 2021, taking advantage of low wind loads on non-windy days. As the project is still under development, the structure is not yet a permanent solution. Further enhancements are being explored to ensure its strength and stability under varying wind conditions. The temporary installation serves as a prototype to gather valuable insights and feedback, informing the ongoing development of the T-Shade as a robust and reliable urban shading system.

4.1. Collecting the wasted T-shirts

In order to explore the potential of using wasted t-shirts as a material for urban shading systems, a source of such t-shirts was identified in HUMANA, a multinational social enterprise operating in 45 countries. HUMANA collects discarded clothing via 5,000 bins located across 1,200 municipalities in Italy, with an annual intake of approximately 20,000 tons of clothing (4,000 tons sorted) (Source: Interview with Karin Bolin in mid-2022 published on Youtube by progettolabelab). Around 150 wasted t-shirts were brought from HUMANA (The clothes selection center of Pregnana Milanese) to the TextilesHUB laboratory and those that were not significantly damaged were selected to be used as a membrane in the next step. However, there exists a non-textile fraction of discarded clothing that is contaminated with non-recyclable materials such as metals or plastics. The challenge of recycling t-shirts lies in the diversity of their composition, the presence of potential chemical contaminants, and the difficulty in separating out non-recyclable materials. To address these challenges, a clustering approach was employed to group t-shirts with similar characteristics and enable efficient processing for reuse or recycling. Acrylic is a synthetic polymer that is commonly used in textile production. The wasted t-shirts used in the t-shade project are made of acrylic fiber. According to the Textile Exchange's Preferred Fiber and Materials Market Report (2021), an estimated 1.7 million tonnes of acrylic fibers were produced in 2020, giving acrylics a 1.57 percent share of the world's fiber market.

4.2. Mesh Relaxation Form-finding and FEA

Kangaroo, a plugin for Grasshopper, offers a form-finding method called mesh relaxation, which utilizes a balance between forces and geometry to create optimized shapes for tensioned structures such as textile membranes. These structures require complex form-finding methods due to their non-linear behaviour under load. The mesh relaxation method can simulate the forces acting on the structure and create an efficient shape that minimizes material usage and maximizes structural performance. Understanding a structure's behaviour under load is crucial in designing lightweight, tensile structures, and the mesh relaxation method aids in creating efficient and cost-effective designs. The mesh relaxation method shares similarities with other structural form-finding techniques for fabric-formed concrete structures design, such as dynamic relaxation. Mesh relaxation and its application in Kangaroo are detailed by Piker (2013).

To simulate the behaviour of t-shirts as shading devices in urban areas using Kangaroo, information on the elastic modulus and yield strength of t-shirts is required. Therefore, based on (source: matweb.com), the elastic modulus of t-shirts made of acrylic would fall within the range of 2.76 to 3.3 GPa, and the Ultimate Tensile Strength would fall within the range of 44.9 - 86.0 MPa and elongation at break is from 33 to 64% (Grishanov, 2011).

The form-finding process of T-Shade using Kangaroo was performed to create a temporary shading solution in the summer of 2021. In this process, the T-Shade was designed to be suspended from three anchor points that were located on the facades of existing buildings, and a cable was used to hang the membrane. To preserve the environment, a hole with a radius of 50 cm was included in the design to accommodate a tree.

The form-finding process using Kangaroo to simulate the behaviour of the T-Shade resulted in the identification of the maximum deformation points in the membrane structure. The analysis indicated that the corners of the T-Shade experienced the highest degree of deformation, as evidenced by the red color coding in the corresponding figure (figure 2.2). This finding is consistent with the behaviour of membrane structures under load, where corners and edges are known to experience more significant stresses and deformations due to the concentration of forces in these areas. The identification of these areas of high deformation will be useful in determining the areas of the structure that may require additional reinforcement to maintain stability and longevity over time.

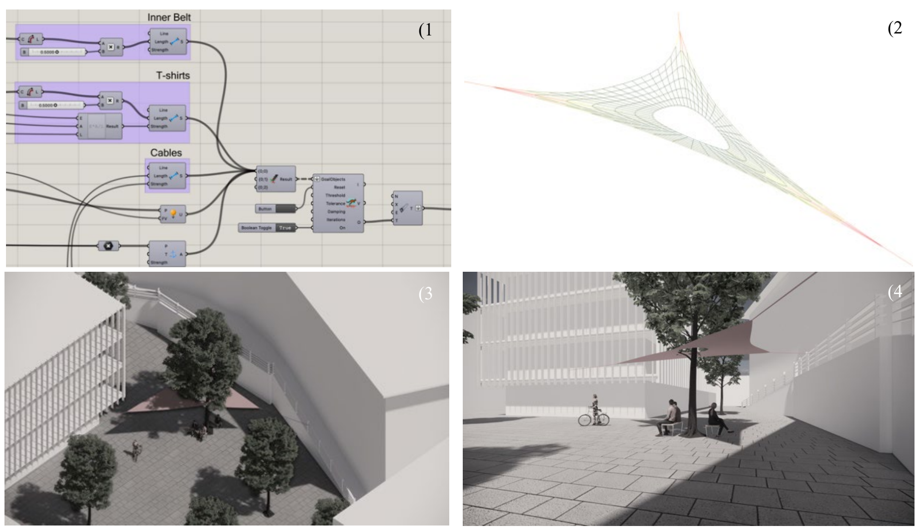

Figure 2: Form-finding process through Kangaroo plugin

To evaluate the structural behaviour of the t-shirt membrane, the form-finding results obtained from Kangaroo were imported into Karamba 3D as a mesh. The analysis in Karamba was performed on the membrane as a shell element, considering a zero bending stiffness to account for its inherent flexibility. Moreover, the membrane was subjected to pre-tensioning to capture its actual behaviour under different loading conditions. The loads considered in the analysis included wind loads and the self-weight of the membrane. However, it should be noted that the installation of the T-Shade took place during the summer and was temporary, and as such, the wind loads were not explicitly considered in the calculation. The FEA results indicated a high utilization percentage, primarily influenced by the effect of wind load. These findings highlight the importance of considering wind loads and ensuring structural stability for the long-term performance of the membrane, especially for permanent installations. Figure 3-1 showcases the percentage utilization of the membrane under wind load, while Figure 3-2 presents the corresponding structural model view, with weak points that are normally located beside the anchor points and the reaction forces of supports.

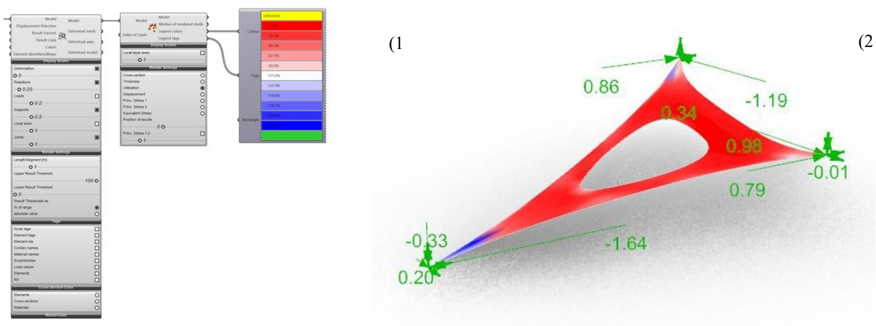

Figure 3: FEA analysis of T-Shade

4.3. Prefabrication procedures

After collecting the wasted t-shirts from HUMANA and completing the digital form-finding process, which allowed us to determine the cutting pattern of the membrane and the number of t-shirts required to cover the target area, the next step was to create a large membrane by connecting the t-shirts together. Each t-shirt provided four connection points, with one located on each short sleeve and two near the corners of the bottom part. The aim was to create a continuous and uniform surface to serve as an urban shading system. In order to connect the t-shirts together, grommets were used at each connection point. Grommets are commonly used in fabric structures for their ease of installation and durability, and were suitable for connecting the t-shirts due to their light weight and flexibility. The use of grommets also allowed for quick and easy assembly of the membrane on site, as well as easy disassembly for storage and reuse in future installations. This connection process was carried out for a total of 54 t-shirts by four non-professional students in the TextilesHUB laboratory, and it was completed within two days. The resulting membrane was a unique and sustainable material that was ready for installation as an urban shading system.

Figure 4: Connection of wasted t-shirts using grommets to create a large membrane for urban shading system.

4.4. On-site Installation

During the final stage of the T-Shade project, the on-site installation of the membrane was carried out on the Leonardo campus of Politecnico di Milano. The installation process involved hanging the T-Shade membrane from three anchor points to create an effective urban shading system. The membrane was carefully positioned and adjusted to ensure proper coverage and maximum shading efficiency. This process was challenging due to the size of the membrane and the need to position it accurately in order to maximize its performance. The installation was carried out with the help of the project team, which included a group of 5 architectural students in 6 hours. Overall, the on-site fabrication and installation of the T-Shade project was a success, and the final product provided a functional and aesthetically pleasing urban shading system for the campus.

Figure 5: T-Shade after installation

Based on the provided information, the T-Shade made from wasted t-shirts had a total weight of 12 kg and could cover an area of 29 square meters. This makes the T-Shade an effective and lightweight solution for urban shading. The use of wasted t-shirts as a material not only provides a sustainable alternative to traditional shading systems but also allows for the reuse of discarded clothing. Overall, the T-Shade project showcases the potential of using innovative materials and design strategies for sustainable and eco-friendly solutions in the built environment.

5. Conclusion

In conclusion, this project demonstrates the potential for the innovative reuse of waste materials in architectural design. By repurposing wasted acrylic t-shirts as a membrane material for an urban shading system, this project challenges the conventional approach of using these materials solely as fillers. The use of digital tools such as Kangaroo, Grasshopper, and Mesh Relaxation enabled the creation of a precise and optimized membrane design. The resulting T-Shade structure not only provides effective shading for gathering spaces but also creates a unique aesthetic and spatial quality. Moreover, the fast and easy fabrication process, carried out by a group of non-professional students, highlights the potential for low-cost and accessible fabrication techniques. Overall, the T-Shade project represents a promising example of sustainable and innovative architectural design, showcasing the possibilities of repurposing waste materials to create functional and aesthetically pleasing structures. As such, it represents a valuable contribution to ongoing efforts towards a more sustainable built environment. The project aims to raise awareness in the scientific community about the vast amounts of wasted t-shirts and the need to implement circular practices for their reuse instead of resorting to landfilling or incineration.

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