THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Knitted architecture and wind

Designing loosely fitted architectural textiles for interaction with wind

ERICA HÖRTEBORN

Department of Architecture and Civil Engineering
Division of Architectural Theory and Methods
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2023

Knitted architecture and wind
Designing loosely fitted architectural textiles for interaction with wind
ERICA HÖRTEBORN

ISBN: 978-91-7905-890-6

Doctoral Thesis at Chalmers University of Technology
Doktorsavhandlingar vid Chalmers tekniska högskola.
Series number: 5356 in the series Doktorsavhandlingar vid Chalmers tekniska högskola
Ny serie ISSN 0346-718X

Department of Architecture and Civil Engineering
Division of Architectural Theory and Methods
Chalmers University of Technology
412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

Cover:
Textiles knitted with a drop-stitch technique, with airflow applied, designed by the author. See page 16 for more information about knitting techniques.

Printing
Chalmers Reproservice
Gothenburg, Sweden 2023

Knitted architecture and wind
Designing loosely fitted architectural textiles for interaction with wind
ERICA HÖRTEBORN
Department of Architecture and Civil Engineering
Chalmers University of Technology

Abstract

Utilising the textile's ability to adapt to external forces such as the wind could lead to the creation of new design expressions and functional features within architecture. Prompted by architectural potentials of textiles deliberately designed to move and flex, this thesis aims to explore and demonstrate how such knitted textiles could contribute to enriched aesthetic expression and improved performance of architectural elements placed in windy environments. A key part of the research is the interaction of textile and wind, viewing it as a source of energy or force that could be used, diffused, or directed - to enrich and create a more comfortable urban environment. As such, this work is positioned at the intersection of three knowledge areas: architectural design, knitted textile design, and wind engineering.

A research by design approach is used to conduct quantitative and qualitative investigations with design prototypes as main vehicles of inquiry. Specifically, a hybrid method of design-based research is applied, involving artistic making and qualitative evaluations of the design prototypes as well as scientific methods featuring quantitative textile performance measurements. Both physical and digital prototypes are utilised to probe the geometric expressions of knitted textiles and investigate the performative features of different knitted textile designs in relation to their wind reduction capacity.

The main finding from the quantitative part of the study, encompassing wind tunnel experiments, is that loosely fitted knitted structures efficiently reduce wind velocities and high-energy eddies. Along with this, the qualitative investigations, involving a series of diversely designed knitted architectural prototypes, show that knitted textiles can be applied to design three-dimensional architectural structures that are aesthetically diverse and have a dynamic, ever-changing expression. Finally, the developed framework for designing loosely fitted textiles for interaction with wind seeks to provide architects with guidance concerning important aspects of such design, including the workflows, tools, and evaluation methods.

Key words: Architectural design, Textile architecture, Knitted textiles, Kinetic architecture, Geometric expression, Wind, Wind simulation, Wind performance, Research by design

Preface

This seven yearlong PhD journey did not take me where I first imagined my destination would be. My researched has evolved and changed through inspirational conversations with the people that I've had the pleasure to have around me and meet along the way. Several times I have found myself to be in unfamiliar territory without a map. As a result, I have found many intriguing areas to explore further along with numerous wrong turns and blocked paths. Looking back, I feel that I have made so many mistakes from which I (and my research) have had the opportunity to learn and grow. While I am incredibly proud of this book that you have in front of you, perhaps these mistakes might be the most valuable outcome of all, on this journey.

None of this work would have been possible if it were not for all the incredible people that I have had the pleasure to have around me. I would like to thank The Chalmers University of Technology Foundation for funding this thesis research. My deepest gratitude to Karl-Gunnar Olsson. First of all, for opening my eyes to all that can be achieved by the merge of architecture and structural engineering and the joy of studying it. But also, for believing in me, encouraging me to take on this Ph.D. journey, and the support throughout the process. This thesis would never have been possible without you. Many thanks also to Mats Ander, you too played an important role in helping me to become a Ph.D. student and have offered invaluable support and positive energy throughout both undergraduate and post-graduate studies. I am extremely grateful to my supervisor, Malgorzata Zboinska, for all the guidance, support, and outstanding feedback. Your support took my research to the next level. Special thanks also to Chris Williams, for all the guidance and encouragement to explore new territory. It has been a privilege to have had you as a supervisor and the conversations we have had have given me many new insights and perspectives. I am also very grateful to Peter Christensson. Our chats about art, the intersection of art and science, and the wonders of the world have given me much joy and inspiration in my research. Thanks for pushing me outside of my comfort zone and guiding me in that unfamiliar territory. Delia Dumitrescu, thank you for guiding me in the fascinating world of knitted structures.

I also want to give warm thanks to Maja Kovacs for your invaluable support, especially in the later stages of my PhD journey. Thank you, David Andréen, for the valuable feedback you gave on this thesis. Big thanks to all my friends, co-authors, and colleagues at Chalmers and around the world who made this research experience extra fun, intriguing, and stimulating. A special thanks to fellow members of the *Architecture and Engineering Research Group*, Alexander Sehlström, Jens Olsson, Emil Adiels and Morten Lund, it is truly a privilege to have you as both friends and as colleagues. Also, Elke Miedema, thank you for so generously sharing your wisdom and positive energy. Thank you, Tabita Nilsson, Peter Lindblom, Peter Lundin and Jesper Martell for your support with all my prototypes.

Last, but certainly not least, none of this would have been possible without the support and unconditional love from all members of my family and my friends. Especially my wonderful husband Axel Hörteborn, you are my rock and my superman. Also, Algot and Ester, my wonderful kids, thanks for helping me completely forget about work.

List of publications and research exhibitions

This thesis consists of an extended summary of the research field as well as the work contained in the following appended papers and exhibition material:

Paper A

Hörteborn, E., Zboinska, M., Dumitrescu, D., Williams, C., & Benjamin Felbrich. (2019).
Architecture from textiles in motion.
Form and Force, 2316–2323.

Paper B

Hörteborn, E., & Zboinska, M. A. (2021).
Exploring expressive and functional capacities of knitted textiles exposed to wind influence.
Frontiers of Architectural Research, *10*(3), 669–691.
https://doi.org/10.1016/j.foar.2021.02.003

- Awarded the FoAR Best Paper in 2021

Paper C

Hörteborn, E., Zboinska, M. A., Chernoray, V., & Ander, M. (2023).
Architectural Knitted Windbreaks for Improved Wind Comfort in the City: A Wind Tunnel Study of Custom-Designed Porous Textile Screens.
Buildings, 13(1), Article 1.
https://doi.org/10.3390/buildings13010034

Exhibition 1

Hörteborn, E. (2022).
(In) Formed by Wind
[Knitted kinetic sculpture, exhibited in Group exhibition, *inMotion,* arranged by SEART].

Exhibition 2

Hörteborn, E. (2022).
(In)Formed by wind
[Exhibition]. SPARK Malmö.

Contents

1 Introduction

As a building material, textile stands out in the sense that it is highly flexible. Usually, this feature is seen as disadvantageous, in such an application, and removed by tensioning the textile until it is virtually stiff. Thereby, the material strength of the textile is utilised. However, instead of forcing the textile into a static shape, embracing its flexibility and ability to adapt to external influences opens new opportunities and generates a new design palette. In combination with wind, an ever-changing appearance is created. Additionally, textiles can also increase comfort by filtering out wind, light and sound.

The research presented in this thesis focuses on knitted textile architectural elements, such as facades and windbreaks. Specifically, it investigates how these could be designed to interact with the natural wind environments in the urban space, to aesthetically enrich the usual static architectural expression while improving wind comfort in urban areas.

1.1 Background

Textiles and architecture

Textile as an architectural material has been widely used and recognized, throughout the history of architecture up to the present times. Architectural textiles have been valued for both their aesthetic as well as performative potentials, serving as both decorative claddings and curtains, as well as shelters from atmospheric conditions, while being highly expressive, tangible, lightweight, durable, and flexible. Applications of textiles include permanent and temporary architecture where, in the latter case, textile's portability and ability to easily fold are significant advantages. As textile structures can be designed to be disassembled, the material is useful for events occurring during a limited time. This feature was integrated into the design of the London Olympic Stadium. The top part of the arena, built with steel and textiles, was designed to be dissembled, to better suit audience sizes after the Olympic games (Nimmo et al., 2011). Further examples are tents and pneumatic structures offering shelter for refugees and homeless during war or after natural disasters, easily transported to where they are needed. Designing for use and adaptive reuse based on ongoing needs is a way to economize with resources, an essential part of the development of a sustainable building industry.

Fridh et al. (2019) suggest using textiles to dress or patch facades and to mend or cover up local cracks to give a facelift, increasing the lifespan of the building while using little material. Here, textile properties like lightness and flexibility as well as variation in appearance and structure are utilised, adding value and unique qualities to the buildings, as well as the settings around them. Furthermore, textiles screens can be a way to furnish urban areas, generating interest as well as a sense of space. Possibly, this could also be beneficial from an acoustic perspective (Fridh et al., 2019).

The research presented in this thesis is focused on architectural applications of knitted textiles that are geared to act as alternative architectural solutions. Namely, as structures that offer both aesthetic qualities and practical performative benefits while being lightweight, foldable, easily transportable, and transformable.

Knitted textiles potential design opportunities

In general, there are two ways of manufacturing architectural textiles from yarns: weaving and knitting. Weaving is the oldest technique of making textiles by combining yarns in rows of warp and weft, that cross over one another. Knitting manufacturing techniques are instead based on a process of arranging the yarn in interconnecting loops. Thus, a knitted textile could be produced from one single thread, whereas the woven structure always consists of arrays of multiple yarns. The microstructure of the knitted textile, with its interlinking loops, makes it uniquely suited for three-dimensional shaping and achieving a surface variation. As the loops can be modified in size and combined in a seemingly endless manner, the knit can be shaped without the need for cutting or sewing. Further adding to the richness of knitted textile expression and functions is the possibility to add multiple yarns, thereby achieving variations in colour, texture, and stiffness. In this study, textiles produced through knitting were the subject of study, due to the broader repertoire of complex aesthetic expressions and the performative functionalities that can be achieved.

In combination with the increasing capacity of the digital simulation, design, and fabrication custom designed CNC[1]-knitted membranes are possible, with every stitch designed to fit a specific design brief. Tamke et al. (2021) talk about "a new material paradigm" that allows for a uniquely designed building material. The specification of the properties of the knitted textile can range from purely decorative functions to structural or other performance aspects, such as shading, tactility, movement pattern, acoustics, insulation, etc.

The architectural design of the knit, in this research, focuses mainly on three-dimensional shaping and grading porosity/transparency. Specifically, on how stitch modifications alter the global geometry of the structure and through that generate geometrically diverse volume in combination with the wind. Grading the knitted structure's porosity allows for the design of a combination of wind reduction and wind-shaped geometry, weighed against resulting reaction forces (which also depend on the porosity of the knit).

Wind and architectural design

The phenomenon of wind is the natural movement of air caused by, for example, differences in temperature and pressure. In urban areas, the layout and geometry of buildings often lead to unfavourable wind conditions that cause reduced pedestrian comfort (Blocken et al., 2016; Stathopoulos, 2009). Even relatively low wind velocities, making hair and clothes flap (≥ 5 m/s), cause discomfort (Penwarden, 1973). To improve pedestrian comfort, and thereby the usability of urban spaces, the wind should be considered early on in architectural design. In addition to thoughtful shaping of the geometry of the buildings, porous windbreaks, such as textile screens or greenery, can reduce wind (Heisler &

[1] Computer Numerical Control

Dewalle, 1988; Hörteborn et al., 2023). Such screens may be added to improve the local climate of an already-built urban area, or they could be integrated parts of designs for new build areas.

The interaction between the wind and loose textile structures is at the core of this thesis. In other words, the focus is both on how the wind can be utilised as a design feature, to shape a textile structure and on how these structures affect the wind environment in their proximity. A central part of this is the relationship between textile porosity and wind reduction.

1.2 Problem definition

Prior research on textile architecture has often focused on tensile textile structures, tensioned to a level where the textile is virtually stiff. This research, on the other hand, aims to investigate the design possibilities with more loosely fitted knitted textiles in architecture, in combination with the action of wind. One application area that is particularly relevant to investigate is windbreak structures. Such an application introduces a new territory for exploring alternative kinetic and geometric architectural textile expressions that simultaneously increase wind comfort.

Designing knitted architectural textiles that improve wind comfort and aesthetically enrich the urban setting is complex. It requires a synergy of knowledge from different fields, namely architecture, textile design, and wind engineering. The design should combine architectural knowledge of the design of liveable spaces and environments with the opportunities for customized design of knitted textiles as well as systematic investigations and fine-tuning of their performance using data from physical and digital wind simulations.

While knitted textiles can be custom designed to fit unique shapes and be graded to exhibit a variation of properties, they are not commonly used as building material. The topic of designing architectural structures from knitted textiles is relatively new in both architectural research and practice, and textile design is generally aimed at clothing. While some research on knitted architecture exists, it is predominantly focused on either tensile textile architecture (Ahlquist, 2016; Ramsgaard Thomsen et al., 2016, 2019; Sinke et al., 2022) or as a stay-in-place formwork (Y. Liu et al., 2020; Popescu et al., 2020). Digital design, simulation, production, and analysis of graded knitted textiles also need to be further researched (Tamke et al., 2021).

Additionally, the issue of predicting, analysing, and simulating how textiles will move in the wind is complex and computationally heavy. Given the textiles' high pliancy and the randomness of turbulent wind, it is a so-called fluid-structure interaction (FSI) analysis with both large and rapid deformations. While there is currently no established method for such FSI simulations, promising methods are developed within the field of computer animations for the gaming and movie industries (see section 2.3.3). These algorithms result in realistic-looking motions. At the same time, their accuracy is yet to be established. Additionally, simulations of how a moving textile affects its surrounding wind environment at an urban scale seem to be non-existent. Following the shortage of research on this type of simulations, for architectural design, is also a need for a discussion and research into the required level of accuracy for the models. Also, using physical models for wind analysis of textile architecture is complex. Scaling a model for wind analysis is not always easy and representing a flexible textile in a scale model is, in many cases, impossible (see section 2.3.4). Full-scale physical models, at a building scale, can be unpractical. Thus, there is currently no way of, in a single model, analysing all aspects of wind interacting with a loosely fitted textile screen, intended to be used as a windbreak.

To conclude, this research is, in multiple ways, entering unchartered territories where knowledge is scarce or missing, to unlock novel research opportunities and practical application potentials. The existing knowledge gaps are explored by investigating loosely fitted knitted textile architectural structures intended to function as windbreaks.

1.3 Aim and research questions

This research aims to provide knowledge enabling a wider application of loose knitted textiles in architecture, shaped by and shaping the wind. Specifically, the focus is to explore the following research questions:

1) How can the knitted structure be designed and employed to create a geometrically alternating, three-dimensional, kinetic architectural element meant to interact with the wind?

2) How are the wind velocity and wind direction affected in the proximity of a loosely fitted knitted screen?

3) How can the design process of knitted architectural elements that interact with the wind in urban space be supported?

The study objectives that follow from these research questions were to:

- Develop textile prototypes that demonstrate the aesthetic and functional potentials of loosely fitted textile structures for application in architecture. Specifically, the focus is on the capability of volumetric and kinetic expressions as well as the improvement of wind comfort.

- Identify and explore different techniques for designing, manufacturing, prototyping, and evaluating knitted structures intended to influence and be influenced by the wind.

- Provide an outline for a design framework supporting the early stages of designing knitted architectural structures interacting with wind, together with a suggestion of enabling methods and tools.

This study addresses the current knowledge shortage in the field that lies in the overlap of three research areas: architectural design, knitted textile design, and wind engineering. Some of the practical benefits that could come out of the further explorations of this crossing are exemplified through a practical application – an architectural windbreak. Such an application has the potential to improve an urban space by aesthetically enriching it while also positively affecting wind comfort. The research presented in this thesis forms a base for further studies. It also provides an outline for a design framework for loosely fitted knitted windbreaks that interact with and reduce the negative effect of wind on user comfort.

1.4 Scope of the research

This study provides an overview and some characteristics of the relatively unexplored area at the crossing of the three fields of research: architectural design, textile design, and wind engineering. As little literature was found that reported results from the knowledge crossing in this particular field of interest, the contextualisation of this study is based on available literature on wider related topics, as well as examples of state-of-the-art from related fields that serve as inspiration. The study also investigates how prototypes can be used in a research by design approach to explore the concept of loosely fitted architectural textiles influenced by wind. As such, the research presented herein does not cover the aspects of large-scale textile production methods, yarn materials, or specific knitting equipment. Neither are specific software for design and evaluation recommended or investigated. Instead, the study provides a high-level discussion on tools and addresses simulation strategies applicable to specific situations. Thus, the research forms a foundation for further continued research and the design of experimental prototypes of loose, knitted textile structures for architecture, shaped by and shaping the wind.

1.5 Overview of the structure of the thesis

The cover text for this compilation thesis is divided into five sections. It starts with this introduction (section 1) that presents the topic through background, aim, research questions and research objectives, and argues for the value of the research. Section 2 deepens the research contextualisation by highlighting relevant literature and the state-of-the-art, positioning the research topic in a wider setting, namely at the intersection of architectural design, knitted textile design, and wind engineering. Section 3 presents the research methods applied to develop the knowledge relating to the research objectives. Section 4 relates the conducted studies to the research aim and objectives. Finally, section 5 concludes the work by discussing the answers to the research questions and how this research is contributing to current knowledge, closing with suggestions for future research.

2 Research context and state of the art

Knitted architecture interacting with wind is an expression introduced in this study to coin an area of research and practical application. This interdisciplinary area can be seen as the intersection between three research fields: architectural design, and knitted textile design, and wind engineering (Figure 2-1). Where the research fields can be defined as follows:

> *'[A]rchitectural design research can be described as the processes and outcomes of enquiries and investigations in which architects use the creation of projects, or broader contributions towards design thinking, as the central constituent in a process which also involves the more generalised research activities of thinking, writing, testing, verifying, debating, disseminating, performing, validating and so on'* (Fraser, 2013, pp. 1–2)

Textile design research (and by extension knitted textile design research) seems underrepresented in the field of design research and in the wider academic environment (Akiwowo et al., 2019). While it can range from technical and traditional scientific to creative and artistic research (Kane et al., 2015), Morgan (2018) claims that there is an increasing movement of textile research for material innovation where design research brings together creative and scientific approaches. Akiwowo et al. (2019) describes textile design research as interdisciplinary and "underpinned by creative practice and is characterised by making, hands-on exploration and applied methods. This facilitates and encourages imagination, tacit skills and inventiveness" (p. 157). Finally, "Wind engineering is best described as the rational treatment of interactions between wind in the atmospheric boundary layer and man and his works on the surface of Earth." (Cermak, 1975, p. 9). This definition includes both qualitative and quantitative descriptions of wind effects, to be used for both design and analysis.

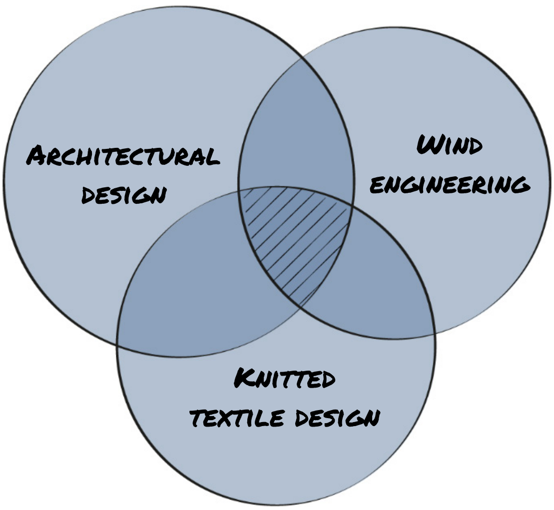


Figure 2-1 The area of investigation, combining knowledge from three research fields.

An important aspect of this research has been to depart in a phenomenon or material and to let that guide the investigations. This aspect fits in all three research fields. The following subsections of this chapter discuss these three fields in relation to textiles and important aspects of the overlaps of the research fields.

2.1 Architectural design and textiles

Garcia (2006) uses the term 'architextiles' to describe a wide field of architecture that relates to textiles, and divides them into four frequently occurring forms:

> *'when a textile or textile-based process is used as a metaphor, when a textile-like spatial structure (such as a weave) is produced in architecture, when textiles (or textile composites) are used as a real material in a real building, and where textiles appear in architectural theory and texts' (Garcia, 2006, p. 13).*

This shows that textile architecture can mean different things to different people. Krüger (2009) limits textile architecture to Garcia's third form and divides it into three main groups, based on the textile's function for space: vertical, horizontal, and three-dimensional space definer. Like Krüger's narrative, the term textile architecture is, throughout this thesis, employed to describe the more specialized use of textiles, as architectural materials defining spaces. The specific focus is on knitted, flexible textiles.

In this section of the thesis, examples of textiles for architectural applications for a wide range of purposes will be brought up, ranging from pure decoration to vital construction. In all cases, the textiles are used directly or indirectly to define space. The examples are divided into three categories, starting with examples from early history, and followed by more current examples, divided into static and kinetic textiles, based on whether the structures utilise the textile flexibility in their final shape.

2.1.1 Early history of textile architecture

Historically, textiles have been used as weather and visual protection in a wide range of ways. The influential architect and professor Gottfried Semper even claimed that the original and true walls are made from textiles, or rather woven materials (Semper, 2010).

The weaving technique is the oldest method of producing textiles. While the earliest representation of a loom is dated 5000 BCE (Broudy, 1993), legends attribute the art of weaving textiles as an invention by the Gods, suggesting that it might predate this representation. The basic tent is even older, 150 000 years old remains found at Grotte du Lazaret, Nice, France, show evidence of primitive shelters consisting of upright poles against a rock wall covered with animal skins (Kronenburg, 2014). As an example, showing the importance of textiles in early architecture, Exodus 26.1-37 (the Bible, Swedish translation, 1999) gives a detailed description of how the tent of the Lord's presence was to be constructed. The description covers the structure and room composition as well as colours and embroidery. Textiles were likely employed partly to enable the temple to be portable, but it also suggests that textiles were significant, and sometimes luxurious, building materials, for shade and insulation, as well as decorative purposes. Regardless of the level of truth in it, the fact that this detailed description has survived and is included in the Bible indicates the importance of the structure and points at its evident application as a building material.

By looking at how tents are constructed and used in nomadic cultures, we get an understanding of the construction and shape as well as the importance of textiles for providing shelter in prehistoric times. As people started to erect more solid dwellings, textiles were mainly used for festive and courtly occasions and, perhaps especially, military camps. During first the Roman and later the Ottoman Empire, with huge demands for military tents, the art of tent construction for military purposes developed and has continued to advance until today. Techniques that also have developed the tents for recreational camping (Krüger, 2009). Throughout the Ottoman rule tents and fabric structures were an important part of architecture. In the beginning, the main palace structures where mobile tents and in the late Ottoman period, textile structures served transitional spaces between indoors and outdoors, as staging for imperial ceremonies, etc. The resemblance between permanent Ottoman palatine buildings and the imperial tents suggests that the structure of the permanent architecture might be derived from the textile mobile palaces (Dimmig, 2014). Also in interior design in Europe, the imagery of tents has remained, with multiple examples of stately rooms with drapes inspired by tents (e.g., Roman Empire tents or Napoleon's campaign tent), to set a scene of romantic adventures and travels (Eggler, 2009; Norén Isaksen, 2013).

As skills and craftsmanship advanced in maritime technology, knowledge gained from the development of sails crosses over to building architecture. Already in classical Roman architecture such examples can be seen, as textile retractable shading structures applied to theatres and arenas, including the Colosseum in Rome (70-82 CE) (Kronenburg, 2015). Also in 1520, maritime techniques were used to create the royal banqueting and entertainment halls for the political meeting between the English King Henry VIII and Francis I of France. The largest structure was circular with a central mast of 14 m, supporting a double layered fabric roof, and 12 m high wooden sides. The same circular tent form characterizes the archetypal shape of the mobile circus tents of the 1900s.

Fabric drapes, acting as retractable partitioning walls, played an important role in the modern architectural designs of Mies van der Rohe and Lilly Reich (Eggler, 2009). These were clean in shape, compared to the billowing drapes of more romantic architecture, but still provided texture and tactility to the interior. They enabled the function of flexibility and seclusion to the open plan architecture, which can be seen for example in the Tugendhat House (1928-30) and the design for "Cafe Samt und Seide" (Velvet and Silk Cafe) (Berlin, 1927). In line with how Semper argued that the true walls originated from textiles (Semper, 2010), "Mies and Reich's approach [can] be interpreted as incorporating a system of "soft" walls in a Semperesque integration of the "classical" tectonic building frame with the interior system of fabric partitions" (Eggler, 2009, p. 67).

2.1.2 Tensioned and static architectural textiles

In the mid-20th century, Frei Otto, through his work with tensile cable nets and membranes, showed that textiles could also act as much more permanent, durable, load-bearing structures (Krüger, 2009). With their design of the German pavilion at the 1967 World Expo in Montreal, Frei Otto and Rolf Gutebrod started a new chapter in the history of textile structures. The pavilion had 'a tent-like roof made of a net of cables' and was chosen as Germany's flagship design because of the lightweight construction which would be economical to transport overseas (Klaus-Michael Koch, Karl J Habermann, 2004). A more recent example of where the lightness and transportability of textiles played an important role is the *KnitCandela* shell construction, in which the textile acts as a permanent formwork for a concrete shell (Popescu et al., 2020). There are also several other recent examples of projects that utilise the shape adaptability of textiles in combination with concrete, like the structures by West (2016) and Scherer (2021), as well as the *RotoColumn* by Mehdizadeh et al. (2023). In fact, the technique of using flexible textile formwork for concrete could be said to date back to the Roman architect and engineer Vitruvius who recommended the use of reeds as a basis for formwork (Veenendaal et al., 2011). In terms of utilising textiles as formwork to enrich architectural expressions, Miguel Fisac (1913–2006) is a pioneer with projects like the *Casa Pascual de Juan*, 1975 and *Hermanas Hospitalarias Social Center*, Ciempozuelos 1985–1986 (Scherer, 2021; Veenendaal et al., 2011). At the same time, it is important to point out that the characteristic feature of these textile applications is the immobilization of the material to achieve structural goals. Hence, both in the case of tensioned textiles and the concrete formwork, the textile is not allowed to significantly deform or alter its geometric expression in the final form.

Textile as a building material has unique capabilities. Its strength and lightness allow for the coverage of large areas without intermediate supports. As a result, membrane structures have become a popular option for arena structures. Here, the *O2 Arena* (also known as the *Millennium Dome*) in London is a good example. Having 320 m in diameter, it is the largest dome in the world (McLaughlin, 2000). The flexibility of the textile material also provides an opportunity for folding down the structure if needed. The umbrellas at the *Medina Haram Piazza*, where 250 umbrellas give shade to millions of pilgrims every year, exemplify how the flexibility as well as the strength and lightness of textiles can be utilized. Namely, the textile is folded so that the umbrellas turn into narrow columns when not needed. These two are examples of specialized textile structures known as tensile structures, i.e. surface structures designed to only carry loads in tension.

Notably, in published literature, "textile architecture" or "fabric architecture" seem to equivale tensile architecture (Koch et al., 2004; Llorens, 2015), especially within the field of structural engineering. Armijos (2008) states that "Architectural fabric structures – also referred to as tensile membrane structures, textile buildings, or fabric roofs, to mention just a few terms- come in a variety of shapes and sizes"(p. 11). The quote suggests that all three of the terms above are synonymous, thus not acknowledging other types of textile architecture, such as loosely fitted textiles. Tensile structures are limited in their geometry to anticlastic (doubly curved) shapes (the exception being pneumatic structures), to ensure that all loads could be carried through tension. To find the optimal shape for these types of structures, soap-film models (Figure 2-2) have traditionally been used as these always take on the shape of a mathematical minimal surface. The final shape of the tensile structure can then be modified through pre-tensioning. It follows that these types of textile architecture, while structurally light and elegant, are virtually stiff structures and a dynamic behaviour of the textile in these types of constructions is generally seen as undesirable.

Figure 2-2 A soapfilm model as a conceptual model for a tensile structure.

While textile architecture primarily consists of woven textiles structures, current research is also targeted towards using knitted textiles, often together with actively bent struts like the *Isoropia* and *The Tower* developed at the CITA - Centre for Information Technology and Architecture in Copenhagen (Deleuran et al., 2015; La Magna et al., 2018; Ramsgaard Thomsen et al., 2019) and Sean Ahlquist's (2015, 2016) sensory architecture. The *Knit Tensegrity Shell* project by Gupta et al. (2019) combines the concept of tensegrity with knits. Other examples of knitted textile architecture that are more loosely fitted are the installations by Jenny Sabin, *myTread* and *Lumen* (Sabin, 2013; Sabin et al., 2018). An aspect sometimes discussed with textile structures like the ones mentioned here is the sensory experience. In the previously mentioned structure by Ahlquist (2015, 2016) the knitted hybrid structure *StretchPLAY*, the sensory experience of the touch and response from the textile is a key feature. The *Lumen* installation by Jenny Sabin et al. (2018), has integrated yarns that change colour in sunlight, coupled with built-in interactive devices to engage users. Touching as a sensory experience is largely dependent on the textile material. Thus, perhaps not that applicable to the glass fibre and coated woven textiles used in many tensile structures.

The patterning possibilities with knits, allowing three-dimensional shaping, in addition to the transportability of the knitted formwork, were key for the previously mentioned shell, the *KnitCandela* by (Popescu et al., 2020). Similarly, Liu et al. (2020) explored the knitted structures' shaping opportunities as a formwork in the *Knitted Composites Tower* study, in which they applied a resin to achieve a hard shell structure. Sinke et al. (2022) introduced knits as a special type of functionally graded material, i.e. a type of material that can optimise material deployment. For the knitted structure, this is achieved through the combination of stitches and yarns. In this case, the pattern of the knit allows for additional control over the deformation of tensile structures. Sinke et al. (2022) utilised this feature to control the stretch of the textile in tensioned structures, while in this thesis the same is used to govern the wind-induced deformation and motion of loosely fitted knitted structures.

2.1.3 Kinetic and interactive textile structures

A key feature of textiles is their pliancy, expressed in the ability to change shape and form based on external factors. This, in combination with possible lightness and translucency, makes textiles, including smart textiles, relevant for architectural research areas known as kinetic and interactive architecture (Kirstein, 2013; Monticelli, 2015). While the reasons and objectives when choosing a kinetic design may vary, a common factor is that through the utilisation of building elements that can move a new palette of design possibilities is added, with extended abilities to adapt to the surroundings. This palette can be explored intuitively or through the more methodical categorisation of possible types of motions, as described and exemplified by Schumacher et al. (2010). Barozzi (2016) emphasizes the need to design more intelligent systems to reduce buildings' energy demand and gives examples of how kinetic facades have been used for solar shading. Santina Di Salvo (2018) gives a wide description of kinetic facades that also includes the aesthetic and communicative appearance of the building, in addition to energy efficiency, which otherwise seems to be a main driver for kinetic facades. *Eco-29,* by FoxLin, is an example where textiles were employed to achieve rapid layout changes for an event hall, to answer to the spatial needs during different occasions (Fox, 2016). The previously mentioned umbrellas at Medina Haram Piazza are also an example of kinetic textile architecture. *Breathing Room* and *Slow Furl*, by Thomsen and Bech (2011) encourage users to manipulate the position of the textile through touch and movement and therefore have their personal influence on the nearest surroundings. In these installations, conductive fibres are integrated into the textiles, enabling the robotic system to read the position of the textile. Through the interaction with the user, "the installations propose new ways of understanding the relationship between user and environment, occupant and space" (Thomsen & Bech, 2011, p. 36).

While a common method to achieve kinetic structures is through mechanics driven by electric motors and hydraulic pistons, passively driven kinetic structures are also explored in research and at the intersection of art and architecture. Passive here means that motion is enabled by forces in nature, without the help of electrics and other devices. An example is the facade for the *Technorama Building* at the *Swiss Center* by artist Ned Kahn, where a large number of small, hinged aluminium plates is free to move in the wind, generating an effect that mimics a textile flowing in the wind. A similar approach is taken with the fabric facade on a Studio House in Almere, The Netherlands, by architects CC-Studio, Studio TX, and Rob Veening, which has overlapping textile shingles that move with the wind. On a smaller scale, Jane Scott (2012, 2016) is achieving shape change of knitted textiles through the patterning of the knit in combination with the swelling of natural fibres through the absorption of moisture.

Kinetic architecture can be divided into reactive and interactive architecture, where the latter category has an added dimension to the architecture through interactions between the user and the structure. In this concept, Fox (2016) includes examples like the kinetic facades of Ned Kahn and the *Windswept* project by Charles Sowers. He emphasizes that these structures do not only react to the motion of the wind but also visualise this unseen force, thus also enlightening us about an otherwise unperceived natural phenomenon "that moves us emotionally" (Fox, 2016, p. 17). With this definition, loosely fitted textile structures should also be included in the family of interactive architecture. This because a light textile material can pick up the random movement in the wind, creating structures in motion with soft, billowing shapes that adjust to and visualise the force of the wind. This is evident in how Janet Echelman describes her own sculptures (Figure 2-3):

> *…When you encounter one of my sculptures this monumental softness moving in the wind, it reminds us that the wind is already there. It is as if the wind is the choreographer. And I love that I have no control of it! (Highum, 2016)*

Echelman's knotted net sculptures at the border between architecture and art occupy the space in-between buildings, like *1.78 Borås*. Also, at the border between architecture and art, the artists Christo and Jeanne-Claude made use of the wind in many of their textile art works. Examples of this includes *Valley Curtain* and *Running Fence* (Figure 2-4), from the 1970's and *The Gates* from 2005. In the field of architecture, examples of exterior textiles allowed to move in the wind are rare, but they exist. One example that also employs knitted textiles is the installation *Lumen* by Jenny Sabin Studio (Sabin et al., 2018). The *Book House Pavilion* by Olga Sanina + Marcelo Dantas architects, as well as *COS Space* by Snarkitecture are examples of architectural structures employing textiles free to move. Common for all these examples is that even though the structures are free to move, the motion is not designed but rather a welcome side effect.

Figure 2-3 Janet Echelman's sculpture 1.78 Borås.

Figure 2-4. Christo and Jeanne-Claude, Running Fence, Sonoma and Marin Counties, California, 1972-76. Photo: Jeanne-Claude © 1976 Christo and Jeanne-Claude Foundation.

Examples of successful parings of textiles and wind that could be used as an inspiration for architecture can be found in other fields. Sails and kites are two of them. In a dance performance, the dancers could be seen as the structure that textiles are attached to. One artist that took the performance of textiles to a new level was dancer Loïe Fuller, active at the end of the 19th and beginning of the 20th century. 'She became the moving vortex of billowing luminous silk. Movement of the body served only to set the silk in motion, and all movement activated the draperies' (Sommer, 1975, p. 3). Taking this one step further, artist Daniel Wurtzel created similar effects, without the dancer, with his art installations, such as *Magic Carpet, Pas de Deux* and *Air Fountain*. In these art pieces, it is the moving air that becomes the "body" that directs the light textiles. For this thesis, the relationship between textile, wind and the dancer have been further researched. In Figure 2-5 and Figure 2-6, it is evident that the flexible textile adapts to both the force exerted by the wind and by the bodies of the dancers. The images show how the dancers' bodies become the structures that together with the wind direct the motion of the textile. The light and the translucency of the weave further enhance the effects of the motion. On both occasions, the same textile was used, namely a light parachute textile that efficiently catches the wind. However, as can be seen by comparing the two photos (Figure 2-5 and Figure 2-6), the impression of the textile is different. This is indicating the importance of considering both the expected wind force and the situation (or site conditions) when choosing the textile material. In Figure 2-6, the textile appears softer and more pliable because of the stronger natural wind. In their essence, these examples are all variations of textiles held up by some structure or body. Similarly, the building could also be regarded as a body that holds and directs the textile movement in combination with the wind.

With the development of new smart materials such as energy-harvesting textiles (Chen et al., 2016), in the future it might also possible to design loosely fitted textile structures, moving in the wind, with aesthetical qualities as well as an added value of producing electricity.

Figure 2-5 Dancer Arika Yamada, exploring textile motion through dance.

Figure 2-6. A dance between the two dancers Emelia Koberg and Yrsa Heijkenskjeld and the textile and the wind.

2.2 Knitted textile design

When working with designs for architectural textiles, it is essential to have a basic understanding of the behaviour and characteristics of the chosen type of textile, and how it differs from other materials and other textiles. Thus, this section will cover the features of the knitted structure that are most relevant in this aspect. The yarn structure of the knit is discussed in connection with how it is fabricated, in addition to the material properties of the textile. The discussion also addresses how the knitted structure could be utilised to enable three-dimensional shaping of the textile. This is followed by a presentation of how digital models can be used for the design and representation of knitted architectural textiles, as well as a discussion of some of the limitations of such digital representations.

2.2.1 Textile fabrication techniques – knitting

There are three principal methods of forming yarns into a textile: interweaving (i.e. woven structures), intertwining (e.g. braiding and knotting) and interloping (e.g. knitting) (Spencer, 2001). In addition to this, there are also non-woven textiles, like felted materials, that comprise intermeshing fibres. The basic weave consists of the warp, into which the weft (sometimes referred to as fill) is inserted. It is woven over and under the treads of the warp. Depending on how many and which treads the warp passes over and under, different patterns are created. In this thesis, the main focus is on (weft-)knitted[2] textile structures. However, most examples of textiles in architecture use a woven textile, and applications of knitted structures are scarce. One reason for woven structures being more common is the dimensional stability of the textile. Stability and stiffness of a woven textile are more directly linked to the threads' strength and stiffness compared to a knitted textile, since the threads in the weave are close to straight (Figure 2-7, left). In a knit, the thread is forming linking loops, arranged in courses ("rows") and wales ("columns") that are held in place by friction between the yarns (Figure 2-7, right). As yarns can still move in relation to surrounding loops, larger local deformations of the textile occur when forces are applied. Knitted textiles are also, generally, more elastic. Additionally, as the yarns move in relation to each other, they will typically not be stretched until the point of breakage in a knitted structure (Francis & Sparkes, 2011).

[2] In this thesis it is implied that knitted structures are equal to weft knitted structures. For more information about knitting techniques and the difference between weft- and warp-knitting, the reader is referred to (Hörteborn & Zboinska, 2021).

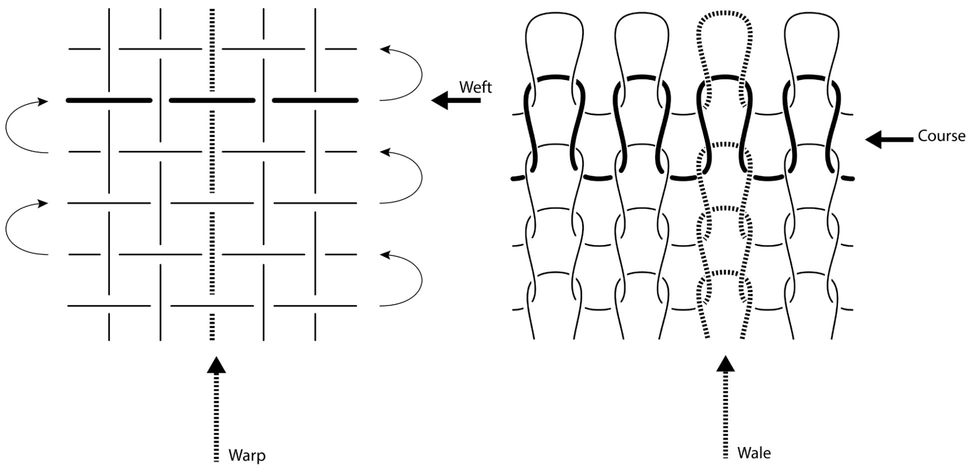


Figure 2-7. Structural logic of textiles. Left: weave consisting of warp and weft. Right: Single Jersey knit, showing course and wale dictions.

The loop structure of the knit enables dimensional alterations of the textile through changes in how the loops/stitches connect to each other. This means that a knitted textile can be varied to a great extent, to create desired aesthetic and structural properties, an aspect that is explored in the appended paper B (Hörteborn & Zboinska, 2021). By knitting two adjacent loops together or adding stitches between wales, it is possible to decrease or increase the width of the knit, i.e. the number of stitches in a row (Figure 2-8). Thus, three-dimensional shaping of large textile surfaces is enabled on a micro- and macro-scale, without cutting and sewing. The structure of the knit can also be modified through e.g. knitting loops/stitches from different courses or wales together, or through locally altering the size of the loops. Sinke et al. (2022) create a graded knitted textile, where a combination of two stitch types allows for control over the expansion of the textile in a tensile installation.

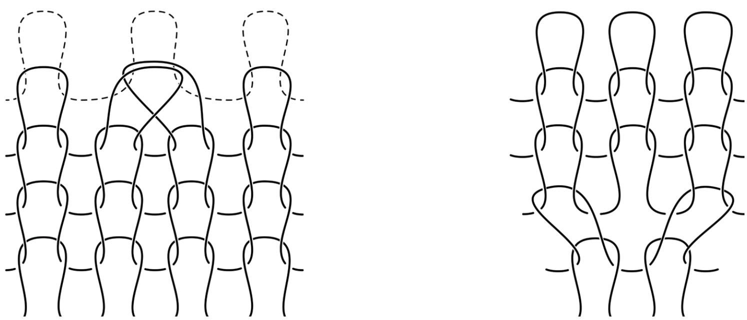


Figure 2-8. Decrease (left) and increase (right) of a knit structure

The knits studied in this thesis were produced on knitting machines. Most of them were produced on a flat-bed manual knitting machine (Silver reed SK-840), but some samples were also knitted on a CNC flat knitting machine (STOLL CMS 330 TC). Patterns for these were generally based on bit-map images, where each cell and colour represent a stitch in the textile. To explain the knitting patterns, an illustration of the yarn on the needle-bed is commonly used. Figure 2-9 shows three different knits. The first is a plain knit (i.e. single jersey), which is the same structure as in Figure 2-7. The knit in the middle is a full rib that is it is knitted on all needles on both beds. And the bottom knit, in Figure 2-9, is a portion of a pattern for a drop-stitch knit, where the stitches on the bottom bed (the ribber) are dropped after the course (dashed lines and arrows are showing how the pattern should be repeated). These illustrations are drawings of the yarn on the needles of a knitting machine. The bottom illustration in Figure 2-9 can be compared with Figure 2-10 showing the yarn on the needles for a drop-stitch knit. Note that in the photo it is the loops on the main bed (top) that are dropped.

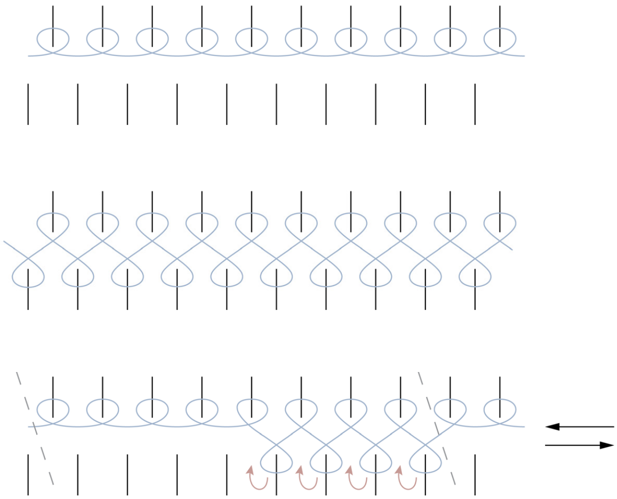


Figure 2-9. Top: representing a plain knit (single jersey), middle: full rib knit, bottom a portion of pattern for a drop-stitch knit.

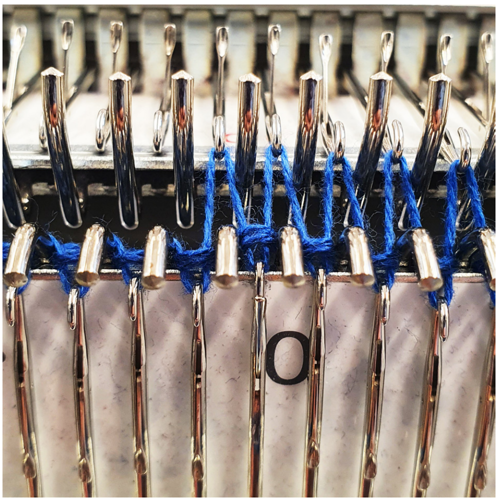


Figure 2-10. Close up of the needle bed of a knitting machine, knitting a drop-stitch pattern. The vertical needles (hooks) are in the ribber bed and the horizontal needles make up the main bed.

This study explored five different knitting techniques: single jersey (plain knit) in combination with smart materials, tuck, hanging stitches, false lace and drop-stitch. The first technique employed yarns exhibiting thermoplastic properties (they both shrunk and stiffened), to achieve geometric alterations of the textile (Hörteborn et al., 2019). Specifically, the yarns were Trevira CS PEMOTE® and COMFIL® PET (Dumitrescu et al., 2014). Through shrinking parts of the textile, a three-dimensional effect was achieved. This effect was then enhanced by applying wind as a shaping factor.

Figure 2-11. Single jersey heat changing textiles. Left and middle: Trevira CS PEMOTE®, modified with hairdryer. Right: COMFIL® PET modified through ironing.

The four other explored techniques allowed to achieve geometric variation of the textile pieces through the alteration of the stitches (Hörteborn & Zboinska, 2021). The tuck stitch (Figure 2-12) and the hanging stitches technique (Figure 2-13) are both methods to group stitches from different courses (rows) to achieve local bulging of the textile. The false lace (Figure 2-14) alters the porosity and microstructure of the textile through a pattern that dictates if one or both yarns are knitted at each needle. In the presented example, this is further enhanced by choosing yarns that exhibit different properties: a thicker wool yarn (dark green) and a lighter linen yarn (yellow). The plain knit's tendency to curl, in combination with the denser knit with the heavier wool (knitted together with the linen yarn), causes these patches to deform inwards. As a result of this, the looser linen knit is pushed outward, generating a pronounced textured, tactile, surface. Finally, the drop-stitch technique (Figure 2-15) enables changes in the geometry of the surface and porosity through changes of the loop sizes. By knitting sections of the knit on both beds, to then dropping stitches either from the ribber or main bed, a significant change in loop size is achieved. This results in both the changes in the geometry of the surface and in its porosity. With larger sections of dropped stitches, the actual dropping of stitches becomes even more apparent, as this usually requires manual pulling out of the stitches after the manufacturing in the machine is finished (Figure 2-16). Note that the pattern is produced so that only the assigned stitches can be pulled out.

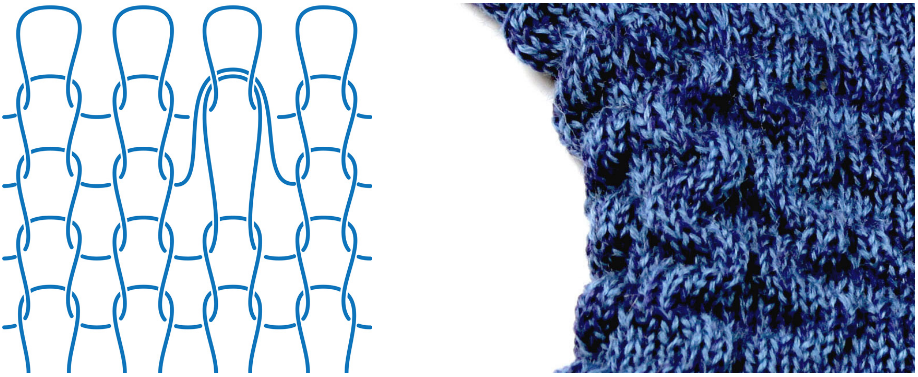


Figure 2-12. Tuck stitch knit. On the left is an illustration of the principle of a tuck stitch and on the right is a prototype knitted with wool yarns.

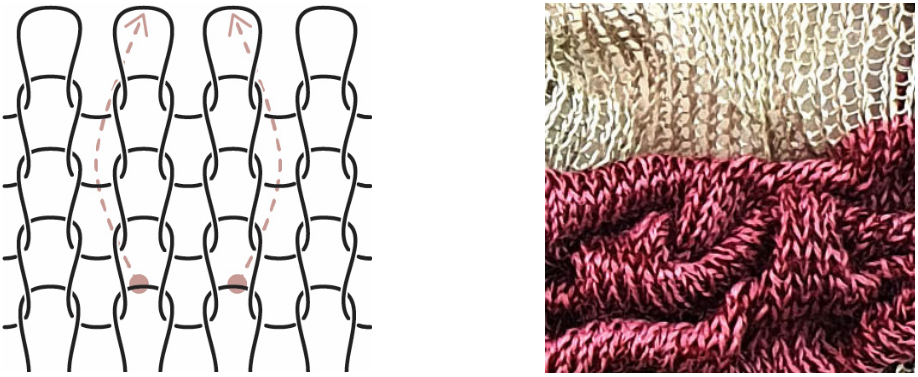


Figure 2-13. Hanging stitches technique. Left: an illustration of the principle of the knit. Right: a section of a prototype knitted with the technique, using wool (pink) and linen (beige) yarns

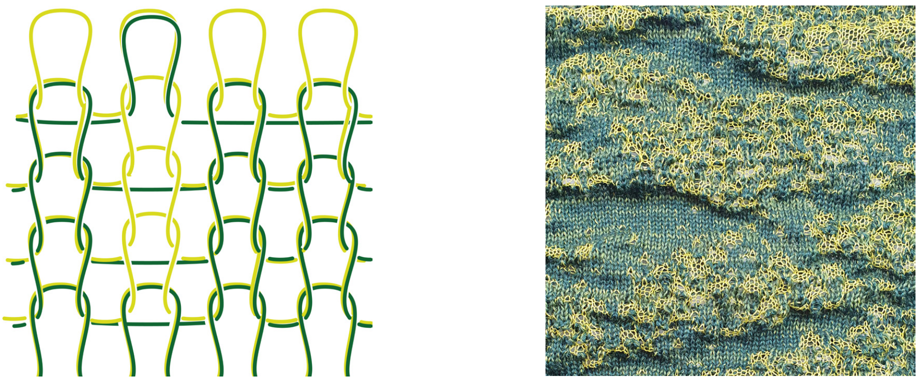


Figure 2-14 False lace pattern. Left: an illustration of the principle of the knit. Right: a section of a prototype knitted with the technique, using wool (dark green) and linen (yellow) yarns

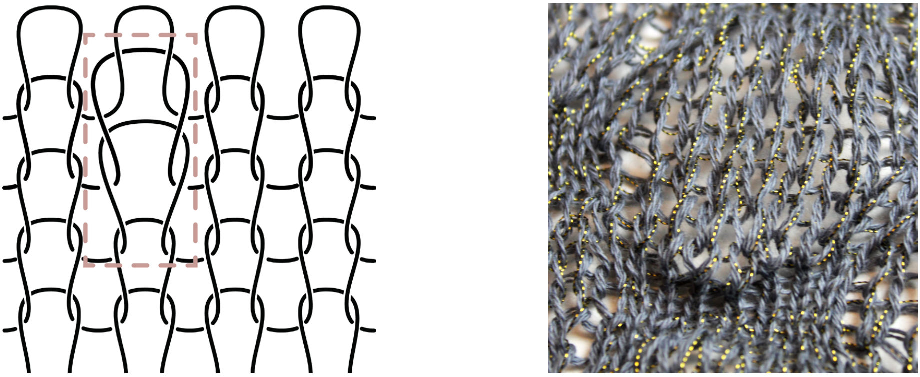


Figure 2-15 drop-stitch technique. Left: an illustration of a drop-stitch knit. Right: a section of a prototype knitted with the technique, using cotton yarns in combination with a golden "effect yarn".

Figure 2-16. Left: dropping stitches on the purl side. Middle: Close up of the purl side stitches dropped. Right: Close up of the right side stitches partially dropped.

2.2.2 Digital representation of knitted textiles for design and simulation

In theory, it is possible to directly translate a computer model via a production pattern to finished built architectural element. This allows to combine the shaping possibilities of the knit with digital models and simulations and production methods of CNC knitting machines, similar to the digital fabrication methods such as 3D printing. However, architects, engineers, and textile designers are struggling to find the right set of tools to smoothly enable this transition (Ramsgaard Thomsen et al., 2016). Although successful prototypes have been achieved, such as the knitted formwork for *KnitCandela* (Popescu et al., 2020) and the tensile installation *Zoirotia* (Sinke et al., 2022), the differences between the design and fabrication logics remain a challenge.

Typically, structural simulations of textiles in a digital environment require a representation model of the textile geometry and topology that can handle the local orthotropy of the material as well as the mechanisms connected to the specific textile structure. This is linked to the composition of textiles, in which a weave is built up through warp and weft, and a knit is created with loops organized in courses and wales (Figure 2-7). Depending on what level and scale are of interest, different methods will be appropriate. Generally, for textiles within architecture, the deformation of interest is on a larger scale compared to the stitch level. Thus, the textile is usually simplified into a continuous surface or a coarser mesh that carries information about the material properties, such as stiffness in different directions. This is the most common approach for the special case of simulations and analysis of tensile, woven, textile structures, as described in previous publications by the author (Henrysson, 2012; Henrysson et al., 2016)[3]. On a weave/stitch level, the textile could also be simulated as a set of nodes, positioned at the intersection of the threads in the textile (Figure 2-17). This might be more appropriate for knitted structures, as each individual knitted stitch and the friction between the loops have a bigger impact on the textile's shape and deformation. That is compared to the woven structure, which is built up by several threads acting in parallel. Cirio et al. (2017) use this representation approach in their simulations of different knits and deformations of them for computer graphics. With their method, they can also simulate the unravelling of the knit by pulling out treads. The same type of grid structure could also be used for a structural FEA model of plain knits (Araújo et al., 2004). At an architectural scale, Schmeck and Gengnagel (2016) are applying a similar approach, but using a courser hexagonal grid (i.e. not representing each stitch). This allows to have a sufficient resolution to generate good analysis data while keeping the computations light enough to be useful in a conceptual design stage.

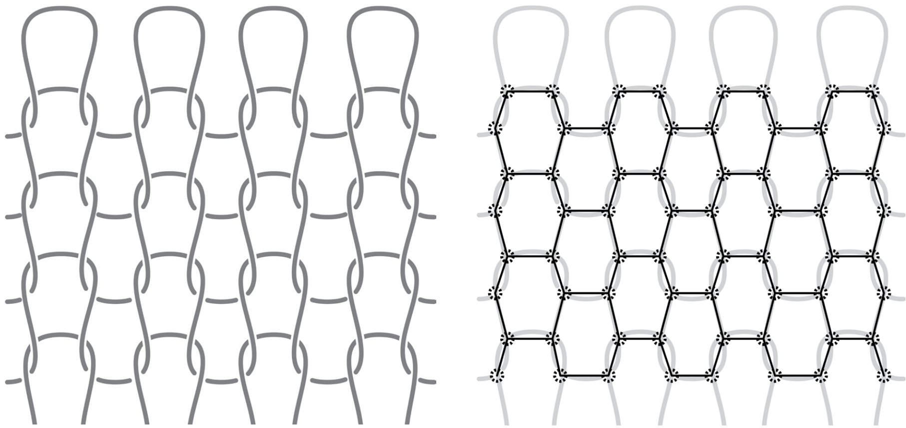


Figure 2-17 A plain knit structure (single jersey) and the translation into a hexagonal grid of nodes.

For computational simulations, like the ones in this research, a simplified quadrangular mesh representation of the knit is deemed to be the most suitable option (Hörteborn & Zboinska, 2021). This is concluded after weighing in computational cost, visual communication of shape, and level of accuracy and detailed information (and the need thereof). With a quadrangular mesh, the knitting patterns could also be directly related to the mesh, as the patterns are also grid/pixel based. Since the focus is on volumetric expression and movement, the simulation speed is valued higher than information, as well as accuracy, on a stitch level. Therefore, a particle-based method is a good option for such simulations. In short, this means that both the textile and the wind were represented by particles connected through

[3] The author changed her name from Henrysson to Hörteborn in 2017.

stronger or weaker links. The movement of these particles in relation to each other results in forces in the links between them. This is further discussed in section 2.3.3 that addresses wind simulations.

In this research, the approaches for simulations explored different knitting techniques affecting the geometry and porosity of the textile (Hörteborn & Zboinska, 2021). These knits fell into two main categories. The first category concerns stitch manipulation through knitting together one or several stitches/loops from different courses. The most successful representations of this were achieved by introducing additional stiffness by adding springs in the mesh. This principle resembles smocking, i.e. using a stitching technique to gather fabric (generally woven fabrics). For the second category, modifications concerned larger sections with altered loop size and/or porosity. Here, the mesh representing the knit was sectioned following the manufacturing pattern (a bit-map image with colours assigned to different stitch types). In this way, the fields in the pattern could be assigned sets of different parameters, numerically describing the main textile properties. In Figure 2-18, the difference between the two approaches can be observed through the explorations of representing a tuck knitting pattern. The left image is produced through the method of adding springs to the prototype (first category). In the right image, the link length between the nodes is altered (second category). Both methods are achieving the sought stronger links between the stitches knitted with the tuck stitch. However, it is a stronger gathering achieved with the first method that better mimics the resulting bulging in the textile that can be seen in Figure 2-12.

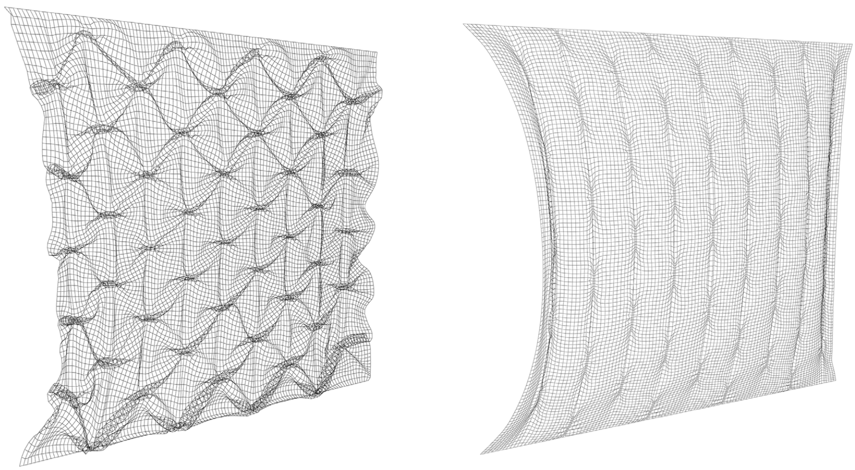


Figure 2-18 Prototypes exploring methods to represent a tuck knitting-pattern, the left prototype is produced using added springs and the right with alterations to lengths of links between the nodes in the mesh.

When adding wind forces to the digital mesh prototypes, a deformation of the model is achieved. Note that with just altered porosity (mimicked by adjusting the applied wind load), the stitch modification was generally not visually perceivable, as the changes only affected how much wind load was applied to the different sections. Instead, the deformation was more homogenous over the whole surface (Figure 2-19). On the other hand, when alterations were made to the lengths of the links in the mesh (i.e. meshface edges) the overall geometry change was apparent. This can be seen in Figure 2-20, showing a digital prototype of a drop-stitch knit, with wind applied, where sections have been assigned longer links and a higher porosity (representing larger loops in the knit). The changed parameters for the mesh, representing stitch modifications, affect how the wind loads are applied, thus also further altering the appearance of the prototype. In Figure 2-20, the colouring of the mesh is based on how much each link is stretched, indicating where there is a high risk of strain in the textile. However, as the knit is represented through a quadrangular mesh without friction nodes, these values should only be regarded as a coarse risk assessment and not proof.

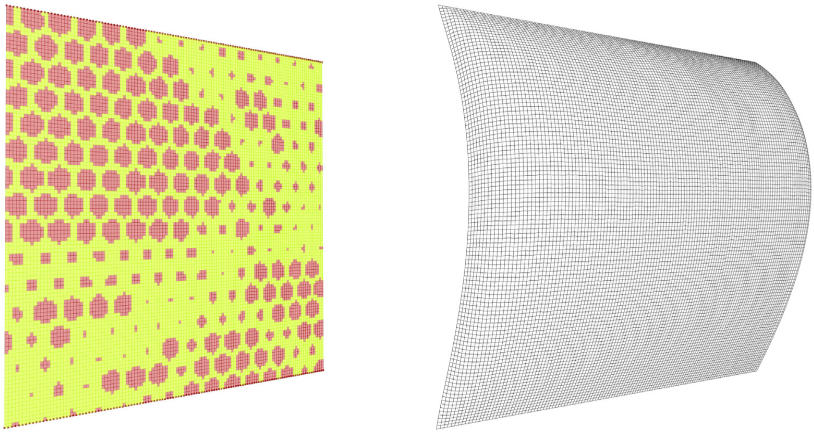


Figure 2-19 Left: mesh patches representing the varying properties of the pattern. Right: wind simulation for the same mesh/knit.

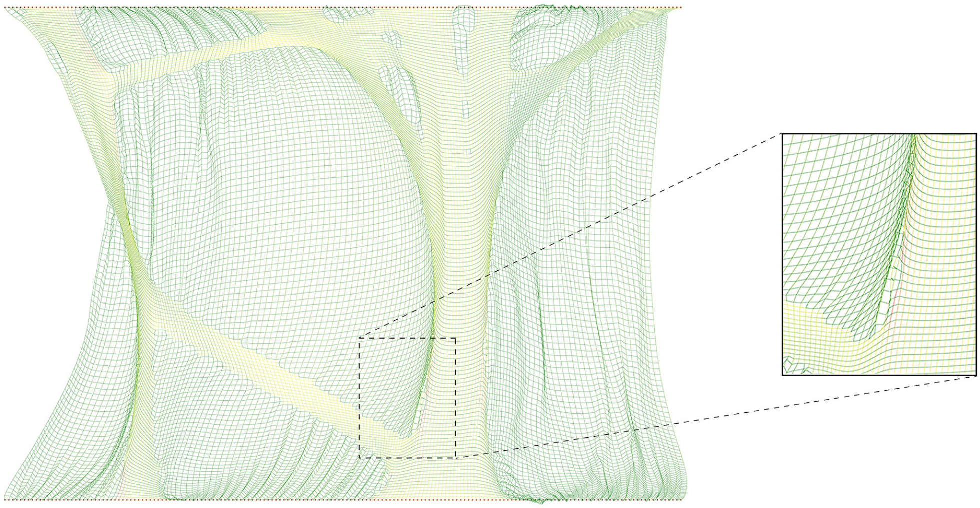


Figure 2-20 Visualisation of strain in the knit, where red represents the most strained links in the mesh and green the least strained ones.

2.3 Wind engineering and textiles

As discussed earlier, flexible textiles adapt to and are shaped by the wind. However, they are also, in turn, influencing the wind. Both the effect that the wind has on the textile and the effect the textile has on the wind, as well as the interaction between the two, are interesting to further examine from an engineering perspective. This section will lay a foundation for such a discussion. Starting with characteristics of how architecture generally relates to wind, followed by wind characteristics concerning textiles, ending with sections on the topics of simulating textiles moving in wind digitally as well as physically.

2.3.1 Shaping the wind and shaped by the wind

The built environment has a big impact on the wind, and the reverse – the wind effects the built environment. As wind has a large impact on the shape of textile architecture, it is relevant to explore how architecture, in general, can deal with wind. In other words, wind is an important parameter that needs to be considered in the design process, especially with the climate changes that result in a harsher climate. Different design approaches or architectural goals concerning wind can be taken. Based on architectural design focus and function, four categories are identified here and shown in Figure 2-21:

a) Indoor climate and wind: utilizing wind as an active part of the ventilation.

b) Shape and wind: shaping the building to reduce wind loads on the structure itself.

c) Space and wind: achieving a comfortable microclimate around the building/buildings.

d) Design expressions through wind: achieving a desired expression by using the wind as a dynamic design material.

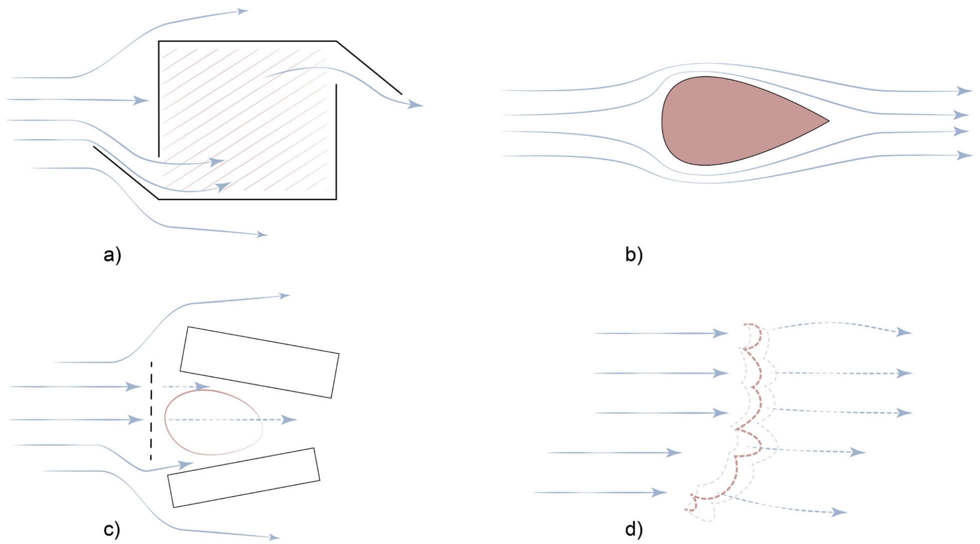


Figure 2-21 Categories for wind-inclusion in design. a) using wind as natural ventilation to increase indoor comfort, b) designing the shape of the building to reduce wind loads on the building itself, c) designing the wind climate/ room, and d) using wind as a design element to actively scape the structure.

The above categorisation is based on the desired outcome and the space or structure itself. Different principles can then be applied to reach these goals. Kormaníková et al. (2018) identified five ways that architectural design can deal with the wind: minimum resistance, concentration, diffusion, deflection, and materialization. These concepts can all be applied and combined to achieve the goals in the above foci (a-d).

An example of a building designed to shield from the wind (category b, in Figure 2-21) is *Jean-Marie Tjibaou Cultural Center*, by Renzo Piano. It is designed both for the exterior and interior environment, as it is situated in an area with harsh monsoon winds from the oceans. In addition, it is also intended to use wind to achieve natural ventilation even though Wu et al. (2011) claim that their wind simulations show that the building was not perfectly designed from a wind perspective. An early example of natural ventilation relying on wind force is the old technique to utilise windcatcher towers which transport the wind and fresh air down into a building (Bahadori, 1978). Saadatain et al. (2012) describe that this passive tool of towers with one or multiple openings has been the main cooling system for thousands of years in the Persian Gulf region and the north of Africa. A modern example is the *University of Qatar* in Doha, where wind towers are used to absorb the wind power for electricity production.

The *30 St Mary Axe,* a.k.a. *the Gherkin* building in London, by Foster + Partners has spiralling airshafts designed to naturally ventilate the building (category c, in Figure 2-21), thus reducing the energy demand (Freiberger, 2007). The circular floorplan was chosen to minimize turbulence that otherwise is common around tall buildings. Thus, it is also a good example of architecture that is shaped with a minimal resistance approach (category b, above). Like cars and airplanes that are aerodynamically shaped, buildings can also be designed to minimize wind loads. Of course, for buildings winds may come from any direction. In the design for *Glasgow Tower* (formerly known as the *Millennium Tower*), this was resolved by shaping the tower as an airplane wing that can rotate according to the wind direction, thus achieving both low wind loads and a steady wake (Liddell & Heppel, 2001). It should, however, be noted there have been issues with the structure, including the rotating base (Brocklehurst, 2013). In a recent research study, Kabošová et al. (2019) explored how a tensile membrane structure that passively adapted its shape to the wind affected the wind pattern around the structure. They found that the dimples in the structure, caused by the wind, improved the microclimate around the building. Furthermore, they highlighted wind deformation of the textiles as an aesthetic value in the articulation of the wind phenomena.

The third category (Figure 2-21) is about achieving a comfortable microclimate. For this, wind can be redirected or dampened by different types of barriers and structures to create a shielded, calm space, or to achieve a cooling effect. A solid windbreak can efficiently deflect the wind, but in terms of enhancing wind comfort it is not that effective (Raine & Stevenson, 1977). Additionally, the deflected wind can potentially create a worse wind situation in the proximity of the structure. This is illustrated in Figure 2-22, through the spacing between the streamlines. The solid structure, blocking the way, results in a larger concentration of streamlines above the structure. Similarly, in the plan view, a solid object will generally force the wind to concentrate near the edges of the object. Thereby, a stronger wind is generated. A more effective way to enhance wind comfort is to employ a porous windbreak, resulting in a larger shielded area without high energy, large vortices (Figure 2-22), and with less drag force acting on the structure. Raine & Stevenson (1977) found windbreaks with low to medium porosity to be most efficient, ideally around 20%-permeable. They also state that a taller and more permeable windbreak might give better overall protection. For knitted textiles, Hörteborn et al. (2023) found that an optimal porosity, in terms of wind reduction, is around 10%. In the category of windbreak structures, trees and bushes are good examples of efficient porous structures that redirect some of the wind and filter and dampen parts of it (Bitog et al., 2011; Zhou et al., 2005). While it is a frequently used approach, with several benefits, it is not always practical or possible to use greenery. Moya et al. (2013, 2014) are exploring another approach to windbreaks. They simultaneously increase wind comfort and use the wind as a driver for a kinetic structure. The combination of kinetic aesthetics with windbreak functionality is also explored through loosely fitted knitted textiles by Hörteborn & Zboinska (2021) and Hörteborn et al. (2023). In the latter cases, several of Kormaníková et al.'s (2018) ways to deal with wind are combined: diffusion, deflection, and materialization. Diffusion through the porosity of the knit results in part of the wind passing through the textile while a large part of the wind is also deflected. Finally, materialization as the wind is shaping the structure and causing it to move.

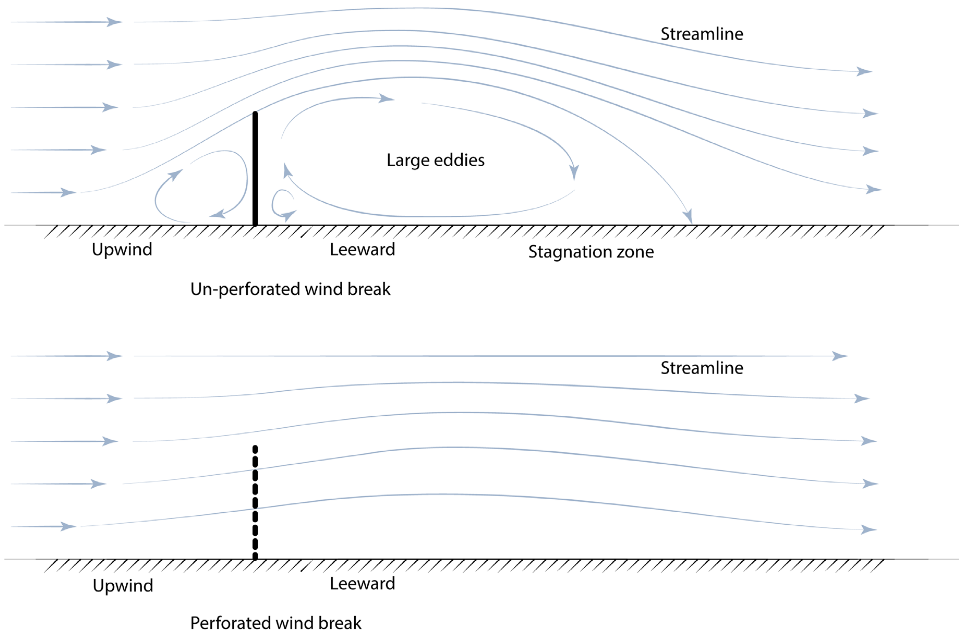


Figure 2-22 2D flow around windbreak. Redrawn after illustration by (Raine & Stevenson, 1977)

Artists like Janet Echelman, Ned Kahn, Theo Jansen, and Antony Howe all use the wind in their creations as a driver for motion and as something that adds another dimension to an art piece. The soft billowing motion in Echelman's structures, Kahn's ever-changing facades, the perfectly balanced, mesmerizing sculptures by Howe, and the curious *Strandbeests* by Jansen all use the wind to enrich our environment and invoke curiosity. As discussed in section 2.1.3, the textiles' ability to pick up the movement in the wind makes them interesting for a wind-driven type of interactive architecture. This falls under the abovementioned category d, where wind is an active part of the design expression. This thesis aims to combine this design approach with the one labelled as category c, and thereby achieve a valuable combination.

2.3.2 Wind characteristics relevant for architectural textile windbreak design

Determining the wind flow around buildings quickly gets complicated, as it is affected by all details in the surroundings. In addition to this, turbulence occurs in wind flows at the scale of buildings. R.M. Ansley (1999) even claims that, for wind flow around architecture, "intuitive guesses as to what an airflow pattern will be are usually wrong" (Aynsley, 1999, p. 73). Architects should, therefore, test their designs with reliable techniques. However, with an understanding of how wind behaves, initial estimations can be closer to reality, and time and costs can be saved in the design process. Therefore, some basic principles of fluid flow and wind will be given in this section.

Wind is a motion of air resulting from pressure differences arising from unequal solar heating of the earth's surface, and the strive to equalise these (Cermak, 1975). Because of friction, the velocity of the air close to an object is the same as the velocity of the object itself. In the case of wind close to the ground, that velocity is zero. The roughness of the surface determines how far this effect is noticeable, i.e. the thickness of the boundary layer where viscous forces are significant. Above this, there is no velocity increase with the increase in altitude. This variation in velocity with height is called wind profile (Figure 2-23). To put this into context, in terms of wind profiles, a city with tall buildings is classified as a "rough surface" compared to a coastal landscape where the wind speed will increase quicker with height.

Wind behaviour can be described through Navier-Stokes equations, which are essentially based on Newton's 2nd law of motion, $F = ma$ (force is equal to mass times acceleration), and the conservation of mass, i.e. the mass of a fluid[4] body, is constant. These equations can be found in the appended Equations for fluid dynamics, on page 94, together with a brief mathematical description of some of the terms in the equations. For an irrotational and steady flow, where viscous forces are negligible (i.e. outside the boundary layer), the Navier-Stokes equations can be simplified into Bernoulli's equation (2-1), declaring that the sum of the pressure, p, the kinetic energy, $\rho v^2/2$, and the potential energy, ρgz, along a streamline, are constant (i.e. conservation of energy). Where ρ is the density of the fluid/gas, g the gravitational constant, both of which are, normally, considered to be constant in the case of wind, and z is the vertical distance. Bernoulli's equation shows that the pressure is at a maximum in the *stagnation zone*, Figure 2-23, where the velocity is equal to zero (the simplification makes it not applicable in the wake region).

$$p + \frac{1}{2}\rho v^2 + \rho g z = C \qquad (2\text{-}1)$$

[4] In the field of fluid mechanics air and gases are seen as fluids, which means that wind is a form of fluid motion

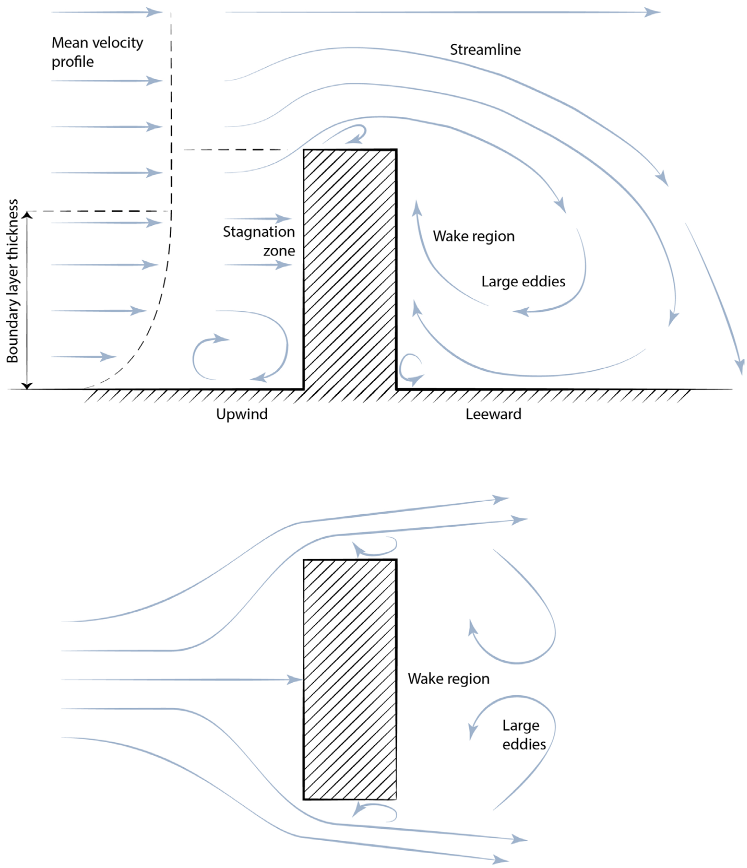


Figure 2-23 2D simplification of wind flow around a building, in a cross-section and a plan view.

Wind flowing around an object will result in forces acting on the object. These forces are commonly known as *drag* and *lift* forces and their values are linked to the geometry of the object. Simplified *drag* forces are forces acting parallel to the motion of the fluid (in relation to the object), and forces acting perpendicular are called *lift* forces. In the same way as water follows the surface of a cylinder before dripping to the ground, wind strives to maintain contact with the surface that it flows around. This fact can be used to generate a lift force by shaping an object to direct wind to push against the ground. More importantly, the geometry of an object or a building will affect the windspeed around it, thus causing pressure differences (see Bernoulli's equation (2-1)) resulting in a lift force (or negative lift). *Drag* is a force that could be described as resistance to flow. It is a combination of pressure and friction forces (viscosity), hence a rough surface on an object would create a larger drag.

Most fluid flow that appears in nature is turbulent. While it is difficult to give a clear definition to turbulence (Davidson, 2018; Tennekes & Lumley, 1972), some characteristics of turbulent flow (wind) are the randomness of the flow, that it is 3-dimensional, diffusive, dissipative (i.e. kinetic energy from larger eddies is transferred to smaller and smaller eddies until dissipates in the form of heat), and it occurs at large Reynolds numbers (Table 2-1). At an architectural scale, Reynolds number tends to be high because of the low viscosity of air and the large linear dimension[5]. Typically, wind flows around buildings are turbulent and have a Reynolds number of the order of 10^5-10^8.

Table 2-1 Reynolds number

Reynolds number (Re) is the ratio between inertia forces to viscous forces at a point in a fluid flow.	
$Re = \frac{\rho v D}{\mu}$	(2-2)
Where ρ s the density of the fluid (1.2 kg/m^3 for air), v is the velocity of the fluid, D "characteristic linear dimension" (for a rectangular body it is the with (m) normal to the flow) and μ is the dynamic viscosity of the fluid (18 × 10^6 Pa×s is typical for air). Thus, it is a dimensionless number. *Laminar flow* steady, parallel, non-turbulent flow occurs for flows with low Reynold's number. *Turbulent flow* have Reynolds numbers greater than ~3000 (Aynsley, 1999)	

Looking at the motion of a textile affected by wind, it is not so much an oscillation as it is waves travelling across the fabric (Williams, 1990). For a loose textile moving in the wind, the mass of air moving with a fabric will usually greatly exceed that of the fabric itself[6], which means that it is possible that in a soft fabric the wavelength is controlled more by the wind vortex scales. Whereas larger waves are more dependent on the mass of moving air, the speed of the smaller waves, the ripples, traveling along fabric moving in the wind is dependent on both the wavelength and the tension in the fabric. The speed of the ripples is proportional to the square root of the tension per unit width divided by the wavelength. Thus, shorter wavelength waves travel at a higher speed and overtake longer wavelength waves. In the case of a flag, the tension is at a maximum at the mast and drops to zero at the trailing edge. This means that the wave speed drops as waves leave the mast resulting in increased wavelength (further reducing the wave speed). The tension in a flag is due to viscous shear stress in the air, and the inertia of the flag itself as it flaps. A detailed discussion of these aspects is presented by Shelley and Zhang (2011).

---

[5] The linear dimension is usually the size of the building or, in the case of flow in a channel, the width of the channel.

[6] Density of air is 1.2 kg/m^3, and a coated fabric can weigh 0.3 kg/m^2 (Koch et al., 2004).

2.3.3 Digitally simulating textiles in combination with wind

For computational fluid dynamics (CFD) simulations, there are two approaches to describe the fluid flow (in this case airflow/wind). Firstly, the Eulerian approach, where the flow is studied from fixed coordinates, and the fluid flowing past these. Mesh-based simulation methods and traditional CFD simulations fall under this category. The second category is the Lagrangian approach, which instead tracks the fluid particles and their properties (like velocity and pressure). With this category, a mesh is not necessary. An example of this is the smoothed-particle hydrodynamics (SPH) method. In addition, there exist hybrid simulation methods that use a combination of mesh and particle simulation. Hosain and Fdhila (2015) give a brief overview of different simulation methods, focusing on non-conventional 'accelerated methods'. They argue that while being highly accurate, conventional CFD methods based on the Eulerian approach tend to be slow in terms of computation time. This is especially true for simulations of flow around a highly flexible body, where the deformations of the body can be larger than the mesh cell size. This requires re-meshing the model to avoid overlaps in the mesh. Thus, for complicated geometries generating a good mesh can be time-consuming and requires substantial computing power.

For textile architecture, the wind is usually the governing load case, yet it is difficult to calculate the wind around these geometrically complex shapes. The analysis is further complicated by the fact that the wind will cause the textile to deflect and move, which, in turn, will change the wind pattern. For strong winds, this is true also for heavily prestressed structures. Thereby, the analysis is a so-called fluid-structure-interaction (FSI) problem, meaning that it is necessary to track both the movement in the fluid around the structure and the movement in the structure itself, as well as the forces that they exert on each other. This is a challenging area within CFD, especially with large deformations like textile movement. The partitioned or the monolithic approach can be used for FSI simulations. The former seems to be the prevailing approach for most engineering problems. Here, the Eulerian-Lagrangian method is used in classic mesh-based simulations, i.e. the fluid flow is calculated through an Eulerian approach and the "solid" structure is calculated separately with a Lagrangian approach. A drawback of this approach is the necessity of information exchange between the two systems and the difficulties associated with that. The large deformation of the two meshes generally calls for re-meshing of the model, which requires substantial CPU power. With the second approach, the monolithic approach, the forces and movements of the fluid and the solid are calculated simultaneously. This could be done with, for example, an SPH[7]-SPH approach or an SPH-FEM[8] approach (i.e. SPH for the fluid and either SPH or FEM for the solid). SPH is one of the more common meshless CFD methods (Shadloo et al., 2016) and is well illustrated through the example of wind interacting with a flag in Figure 2-24. In this simulation, only the particles that have collided with the flag are visible as red or blue dots, depending on their rotation. With SPH, the state of a system is represented by a set of particles that interact with each other. These particles all possess material properties. In the example with the flag, these materials are either textile/flag or air.

[7] Smoothed Particle Hydrodynamics

[8] Finite Element Method

Which particles that influence each other are controlled by a smoothing function. This means that particles close to each other will have a higher influence on each other’s motion compared to particles further away. All particles in the system are iteratively looped through and reaction forces from surrounding particles within a diameter, *h*, from the original particle are calculated (Figure 2-25). This results in a velocity and distance moved. After all positions are updated, this is repeated.

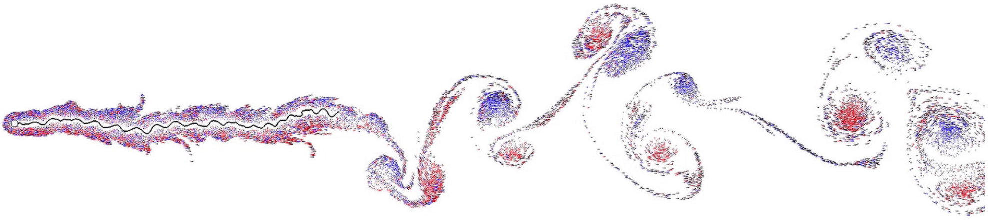


Figure 2-24. Particle simulation of fluid flow interacting with a flag, in 2D (a cross-section, seen from above).

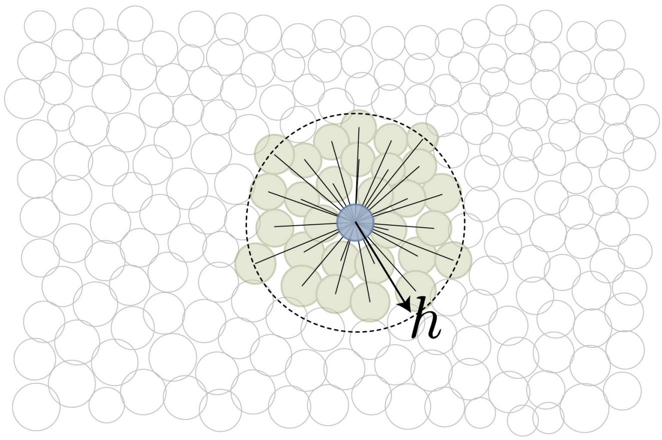


Figure 2-25. Visualising the principle of which particles (green) that will influence a particle in an SPH-system (blue).

There are several advantages with an SPH method for FSI simulations. Firstly, it is a particle method of Lagrangian nature and can obtain the time history of the material. Secondly, free surfaces, material interactions and moving boundaries can be traced naturally within the process. Thirdly, the method is relatively easy to numerically implement and use for 3D models. Finally, and most importantly, as the material is modelled by "free" particles, it allows for straightforward handling of large deformations and rips/fractures, since the relationships between the particles are updated throughout the process. Thus, a particle can be attached to one particle in the beginning, and during the simulation de-attach and reattach to another particle. However, for fluid and solid mechanics, there are challenges involving the accuracy and stability of the SPH simulations (Shadloo et al., 2016). Over the past years, different modifications have been tried to improve this. One of these is the finite particle method (FPM), which uses a set of basis functions to approximate field variables at a set of arbitrarily distributed particles (M. B. Liu & Liu, 2010).

Given the high speed of meshless methods and the ability to handle large deformation, it is the prevailing simulation approach in the field of computer animation. However, it does not seem to be widely used for fluid engineering. However, Hosain et al. (2019) claim that for fluid dynamics SPH has great potential to become an alternative to the more commonly used finite volume method (FVM). Furthermore, within the field of solid mechanics, Olsson et al. (2021, 2022) have shown that meshless methods also work well for simulations of crack-propagation. Still, given the large number of particles needed to simulate complex phenomena, also the meshless methods require a substantial amount of computational power (Olsson, 2022). A freely moving textile is one example of such a complex phenomenon.

Fluids interacting with flexible materials is a common topic in computational fluid dynamics research. However, usually, the movement in the FSI studies is relatively controlled. Examples consist of tensile structures interacting with wind or fluids interacting with materials that have low bending stiffness. This can be compared to a piece of cloth, free to move, flap and intertwine in the wind which has virtually no bending stiffness. The more common studies of relatively controlled deformation might be one reason why mesh-based analyses seem to be more favoured within the field of CFD, also for FSI problems. One of the few studies of the dynamic behaviour of textile structures in wind was done by Michalski et al. (2011). They did wind simulations as well as validation with a full-scale 29 m umbrella structure using a partitioned Eulerian-Lagrangian approach (Michalski et al., 2009). Others have also described computer fluid simulations and analysis of tensile flexible structures (Elnokaly, 2014; Glück et al., 2001) and the usefulness of these simulations. In the previously mentioned study of wind-adaptive textile structures, Kabošová et al. (2019) chose to conduct wind analyses for different static stages of the design adaptations to save on computational cost and thereby bypass the challenges with FSI simulations. In this case, they chose to focus only on the wind environment and not the simultaneous deformation of the textile.

Given the large deflection of loose textile structures, particle-based/mesh-less methods seem to be the only option for the simulations of this wind-induced movement. In this category, three software tools were explored as means to represent textiles moving in the wind: a custom program, Flexhopper, and Kangaroo 2. The custom program was written specifically for this research in a Java-based textual programming platform Processing, using an approach based on SPH. FlexHopper (open-source) and Kangaroo 2 are both plugins for McNeel's Rhinoceros® and Grasshopper®, which are commonly used by architects. Both of the plugins use particle-based simulation methods (Cuvilliers, 2020; Felbrich, 2017/2020; Piker, 2017; H. Wang, 2015). Specifically, they are based on a method called position-based dynamics (PBD) (Bender et al., 2013; Müller et al., 2007), and FlexHopper combines this with fluid particle simulations through SPH. All three tools handle the large wind-induced deformations and movements well but larger digital prototypes require substantial computational power to run at real-time speed. Common for these tools is also that the textile is represented by a continuous mesh surface and no method to represent the knit-specific friction nodes was found.

2.3.4 Physical simulations and analysis of textile combined with wind

In a computer model, it is currently close to impossible to correctly simulate the behaviour of a loose textile that is both porous and deforming considerably, like the knits explored in this research. The author's studies have shown that a combination of digital and physical prototypes is beneficial for a design process as it gives a more complete picture of the phenomena (Hörteborn et al., 2019; Hörteborn & Zboinska, 2021). Prototype explorations with a physical wind machine allow for a more hands-on experience of the motion and deformation of the knits. They also show the behaviour in turbulent wind, something that has been challenging to achieve in the digital simulations for this study. Also, specific material properties are possible to explore in physical explorations, in a different way than in a computer simulation. In relation to wind, this includes aspects like motion-induced sound, material and perforation appearance under wind force and motion, the speed of the wind-induced movement, etc.

Liu et al. (2017) explain that there is a knowledge gap in the linking of the material structure of the knit to the overall mechanical behaviour of a knitted structure. This makes it particularly complex to represent wind simulations of knits digitally. Thus, the more traditional, physical wind tunnel tests are a good option to get quantitative wind data as well as measurements on geometrical deformation. Specifically, windbreak porosity, which is of interest in this research, is an area where wind tunnel research can be applied and has been used successfully in the past (Guan et al., 2003). Even so, the wind tunnel experiments also have their limitations, mainly due to the dimensional restrictions often necessitating the use of scale models, or only testing a fraction of a structure instead of full-size prototypes. Liu et al. (2014) showed that the flow pattern behind a windbreak looks different in a scale model compared to a full-scale prototype. Furthermore, textiles like the ones studied in this research cannot be accurately scaled down, mainly due to their thickness and flexibility. This further increases the complexity when it comes to conducting wind tests of loosely fitted knitted structures.

3 Research methodology and research design

Research methodology

The objectives of this research (outlined in section 1.3) revolved around developing prototypes, exploring techniques for manufacturing and evaluation, and to outline a design framework. This governed the choice of the research methods. Generally, a mixed methods approach (Creswell, 2014) was employed, i.e. a mix of quantitative and qualitative research. More precisely, a mix of three different methodological types of design-based research has been applied, namely artistically driven, architecture-centred and science-inspired, following the concept of architectural research in hybrid mode (Zboinska, 2021). This is relating to the fact that the research presented in this thesis relies on two cultures of knowledge building: the engineer's and the architect's. The former is a more traditional, scientific culture with the development of mathematical models for physical phenomena and the application of mathematical algorithms used for verification of hypotheses and design. Whereas the latter does not rely on any single research approach, relating to how architects operate in practice, navigating between creative and practical goals. Predominantly, a research by design approach (i.e. design-based architecture-centred research) has governed the work. The early explorations have been driven by artistic research methods whereas the later studies also involved science-inspired methods of quantitative research experimentation.

Regarding the research by design part of the methodology applied in this research, is worth noting that while it is well-established within architecture, there is no universal definition or even a universal term. Instead, several terms are used interchangeably, such as research through design, practice-based or practice-led research, all of which relate to the same or very similar methodologies, where design is used as a method to generate knowledge. Installations, structures, and prototypes play a vital role in the knowledge-making, serving as means to intervene with, explore and research a place, material or phenomenon, and, generally, the work is carried out iteratively. Furthermore, Wensveen and Matthews (2014) claim that research through design, as a method that uses prototypes as a vehicle for knowledge production, is not one single method but rather many different ways in which the practice of producing prototypes is central in generating knowledge. Verbeke (2013) defines research by design as:

> *[…] that kind of research in which the process of designing, as well as experience gained from practice, plays a crucial role in research – not only as inputs to be observed, but, more importantly, as the actual methods and outcomes of the research itself.* (p. 139)

Further descriptions are given by Foqué (2010) who outlines research by design as a heuristic activity, deriving its methodology from both methods in science and art. According to Foqué, research by design is about exploring how things could be in contrast to scientific research which focuses on how things are. Compared to scientific methods, a major difference is that multiple hypotheses are usually explored, and they are adapted and adjusted during the research. The experiments and tests are contextual and not necessarily objective or repeatable. Overall, the studies conducted as part of this doctoral research align with all of these mentioned definitions and modes of knowledge production.

In relation to the research methods applied for this thesis, it is also relevant to discuss it in the context of the established scientific reasoning patterns. Traditional science-based research usually uses deduction or induction. Deduction is about finding the results from a known "what" and a known "how". Induction is about finding out how something leads to a known result. In design research, it is instead a value that is strived for, and the "how" is unknown, or both the "what" and "how" are unknown, which is termed as abductive reasoning (D. Wang & Groat, 2013). For this thesis, a combination of abductive and deductive reasoning was applied, with more emphasis on deduction in the later phases of the research.

Research design

The research design embraced three phases of investigation for the design of architectural textiles interacting with wind, including the use of various types of prototypes, evaluation methods, and explorations. These phases were based on the purpose of the studies: research problematisation and positioning within the field, volumetric design investigations, and quantitative evaluation (Figure 3-1 and Figure 3-2). The subsections of this section departs from these three phases. The first was about contextualising the research and identifying the knowledge gaps, as well as conducting open-ended, artistically driven explorations. Here, both research literature along with design precedents in architecture as well as in relevant neighbouring fields were analysed. The purpose of this was to form a base for the second and third phases and act as an inspiration for the design and evaluation of loosely fitted knitted architectural textiles in combination with the wind. The second phase of the research focused on using design prototypes for qualitative explorations of the identified knowledge gaps. Studying architectural qualities such as geometrical expressions in relation to knitting techniques and behaviour under the influence of the action of wind was the main focus. And finally, in the third phase, these prototypes were further developed and evaluated through quantitative studies that explored geometric deformations as well as the performance of a selection of knitted textiles, and their capacity to act as windbreaks.

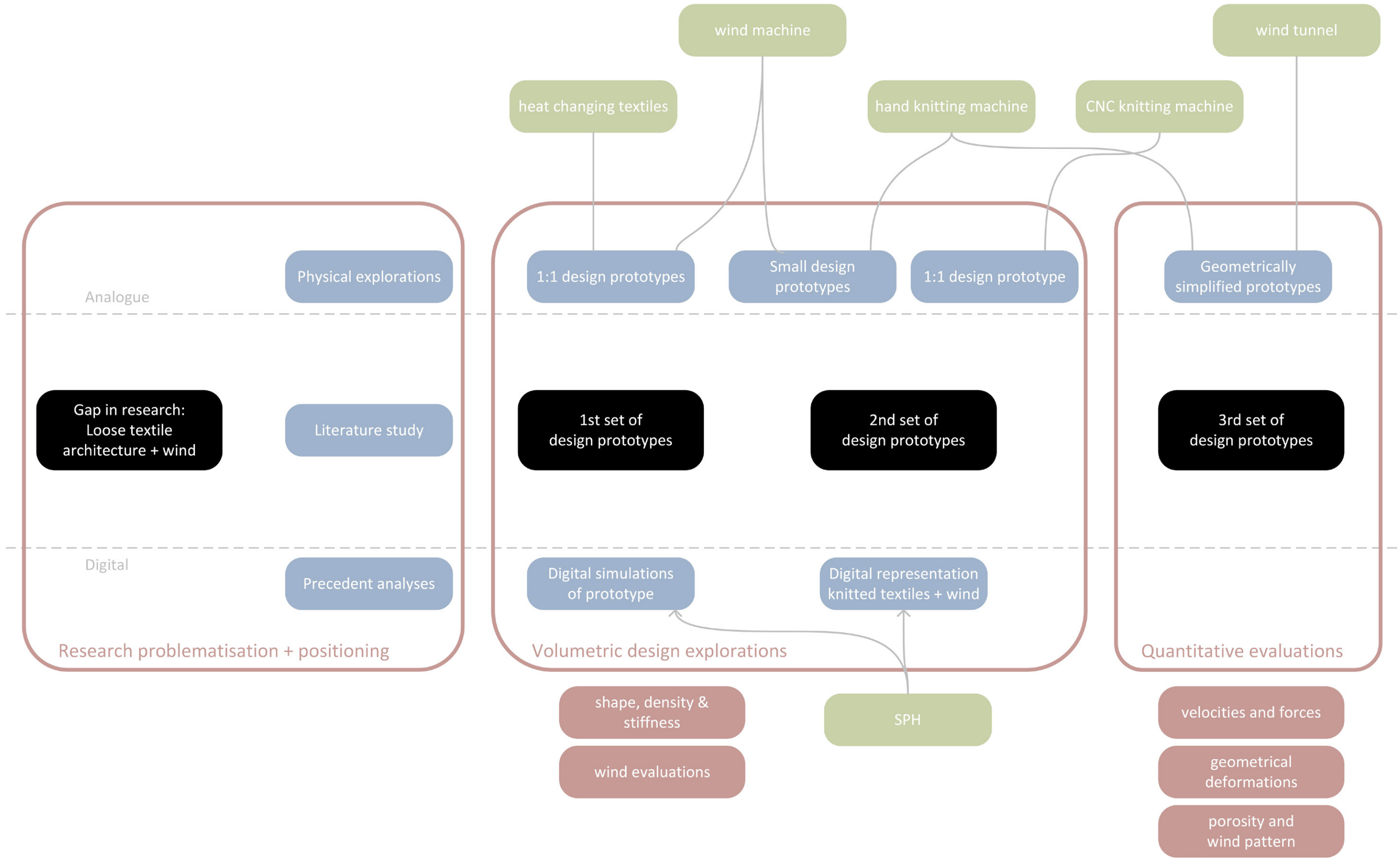


Figure 3-1. Visualising the relationship between different tools and concepts and the phases and studies of this research.

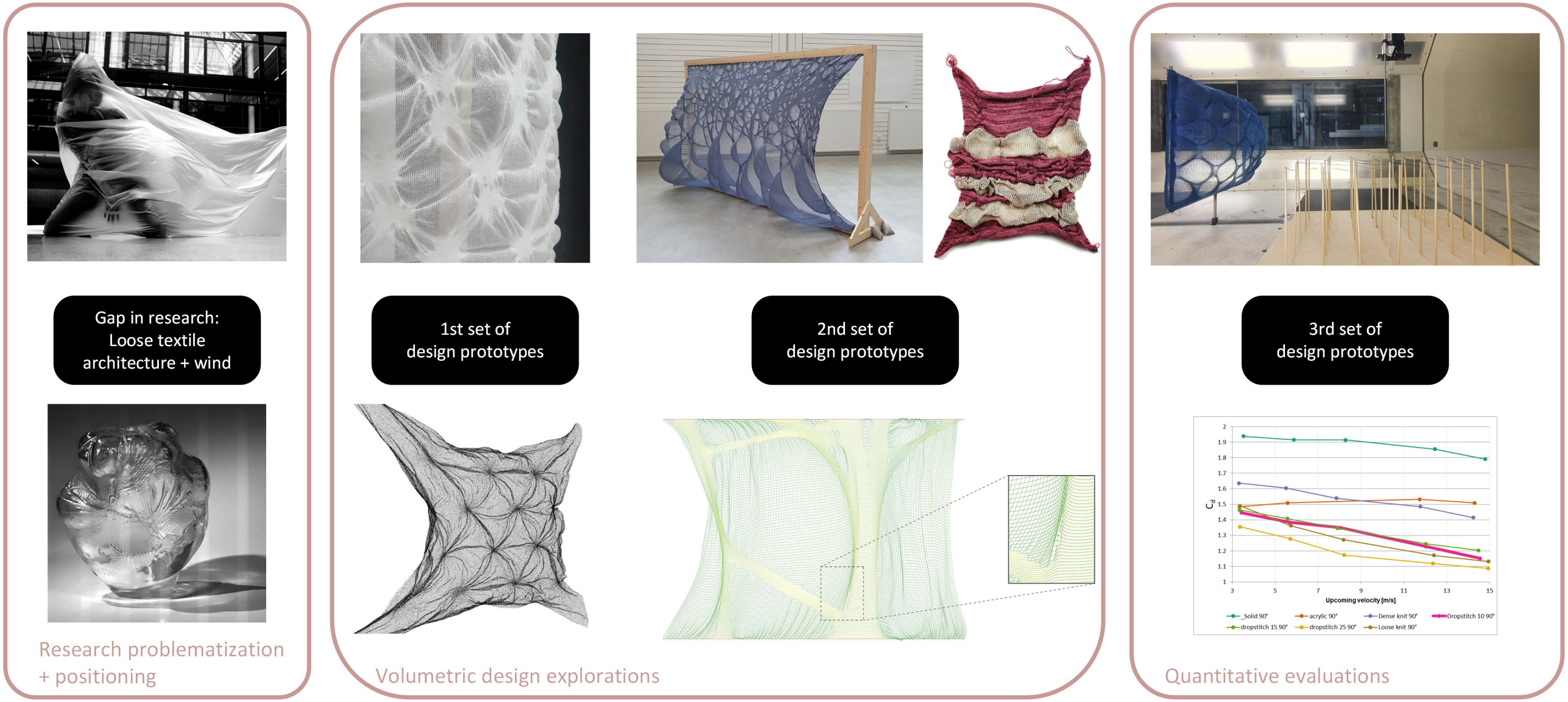


Figure 3-2. Connecting some of the explorations and prototypes to the different phases and sets of prototypes, of the research

3.1 Scoping and positioning

To frame the research and put the explorations of the textile material and wind into context, a literature study was carried out. This study consisted of two parts. Firstly, key aspects of the research field and relating topics combined with associated examples of state-of-the-art were studied and summarized. The common denominators for the examples were the load-structure-interaction, a strive to create beauty or curiosity, and the architectural scale. Special areas of interest were movement driven by passive forces such as wind, loose/flexible textiles, textiles as the main element and lightweight structures. The second part was a mapping of the research field identified through the first part of the literature study. For this, a structured literature search in a selection of databases was made. Keywords in the searches were: textile, architecture and wind. The relevance of the sources was evaluated through a flowchart (Figure 3-3), developed to enable a more objective as well as quicker grading of the relevance of the findings and to rely less on intuition. After analysing 782 publications, 24 were identified to carry some relevance and only two of these touched upon all the key aspects of the interdisciplinary crossing between textile architecture, motion and wind. The first study, by Mossé (2018), focused on smart textiles in the setting of the Western home, with little connection to the wind. The second study, by Santina Di Salvo (2018), mentioned textiles and motion in relation to kinetic architecture, and kinetic architecture using wind. However, the paper did not connect the three: kinetic architecture, textile and wind. Neither were any examples given of textile architecture that embraces wind motion. For a detailed description of the literature study, the reader is referred to the licentiate thesis (Hörteborn, 2020). While there might be publications not included in the main databases, this scan of the field illustrates that textile architecture moving in the wind is a rarely explored research area.

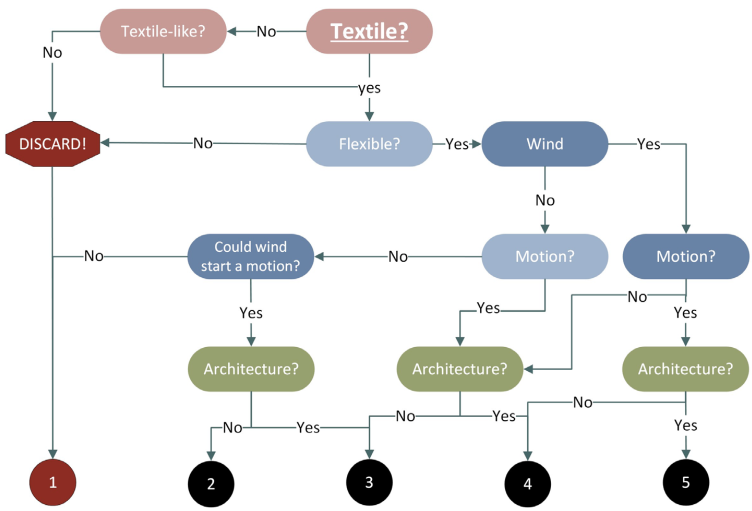


Figure 3-3 Flowchart to establish relevance of paper or book, with textile focus.

An important part of this first phase of the research was also the artistically driven explorations. Artistically driven research is a common method of inquiry within the field of architecture that generates knowledge through artistic practice (Zboinska, 2021). Linking to Ulf Jansson's (1998) argument that sketching is used by architects as a tool for explorations of the situation and specific factors for the project in question, the prototypes and explorations in the first phase of this research, could be seen as some of the early conceptual sketches for the research project. Jansson relates this to Donald Schön's expression *reflection in action* (Schön, 1983, as cited in Jansson, 1998). In contrast to reflection after action, reflections deliberately induced during the making process lead to unplanned input and unexpected turns in the explorations (Schön, 2003). Similarly Hauberg (2011) talk about sketching as a way to generate insight and knowledge, he argues that "the drawing is active: it 'talks back' […]"(p. 50). Hence, a dialogue with the making/piece that is in keeping with the methodologies of artistic research (Foqué, 2010) as well as research by design (Hauberg, 2011). The goal of the initial explorations in the thesis has been to explore a phenomenon without knowing exactly what will be found and strive to keep an open mind to unexpected outcomes. Similar to Ramsgaard Thomsen's and Tamke's (2009) concept with the design probe that enables speculative inquiries and defining the direction for the project.

In line with this type of research, the different aspects of the research inquiry have also been investigated through artistic explorations extending beyond the field of architecture. One example is using dance to explore textile movement in wind (section 2.1.3 touches upon this). For the purpose of the thesis, a collaboration with professional dancers was initiated. The dancers were asked to freely interpret the coupling of wind and textiles, and interpret the situation and movement, through spontaneous dance. The first investigation made in collaboration with Arika Yamada, explored the relationship between her body, the textile, and the moving air (manufactured with a wind-machine), Figure 2-5. In the second investigation, Emelia Koberg and Yrsa Heijkenskjeld explored the contrast between the light textile with its soft ripples and the strong force in the natural wind, as a dance between them, the textile, and the wind, Figure 2-6. In both investigations, the dancers expressed how the textile in combination with the wind became a dance partner, something to interact with, to follow as well as to guide. Through the dance explorations, inspiration regarding how to think of supporting structures for the textile was gained, as well as a deeper understanding of wind motion.

The third artistic investigation, outside the main field of architecture, was an exploration of a textile interacting with another fluid material - hot melted glass. Examples of this can be seen in Figure 3-4, Figure 3-5 and the bottom left in Figure 3-2. In this case, a glass fibre textile was employed as the main material, from which moulds were sewn. The glass was then blown into these (Figure 3-4). As the glass, in its liquid form, is pushed out by air to shape the textile, these investigations could be seen as frozen moments in time, almost like frozen wind. The tactility of the textile was also explored through this investigation. The glass sculptures feel textile to the touch, but they are static and hard in their finished shapes. Thereby, they differ drastically from traditional textiles that yield to external forces and move with touch. They look and feel like a textile but are not a textile in a traditional sense, as they exhibit shapes that would be impossible in an unloaded state. The geometrical shapes of the sculptures are affected by the choice of textile. A textile woven with glass fibre yarns can manage the high temperatures of the melted glass, but it is also relatively stiff. As a result, the glass that was pushed out against the textile walls appear more structured and bulging in a controlled matter. Whereas the glass leaking out in the seams, both by design and by accident, seems more free-flowing and free in shape. It looks like glass bubbles that are billowing out between stiffer textiles. This relationship between the more controlled geometrical shape and the more soft and free shapes is something that has been explored further throughout the research.

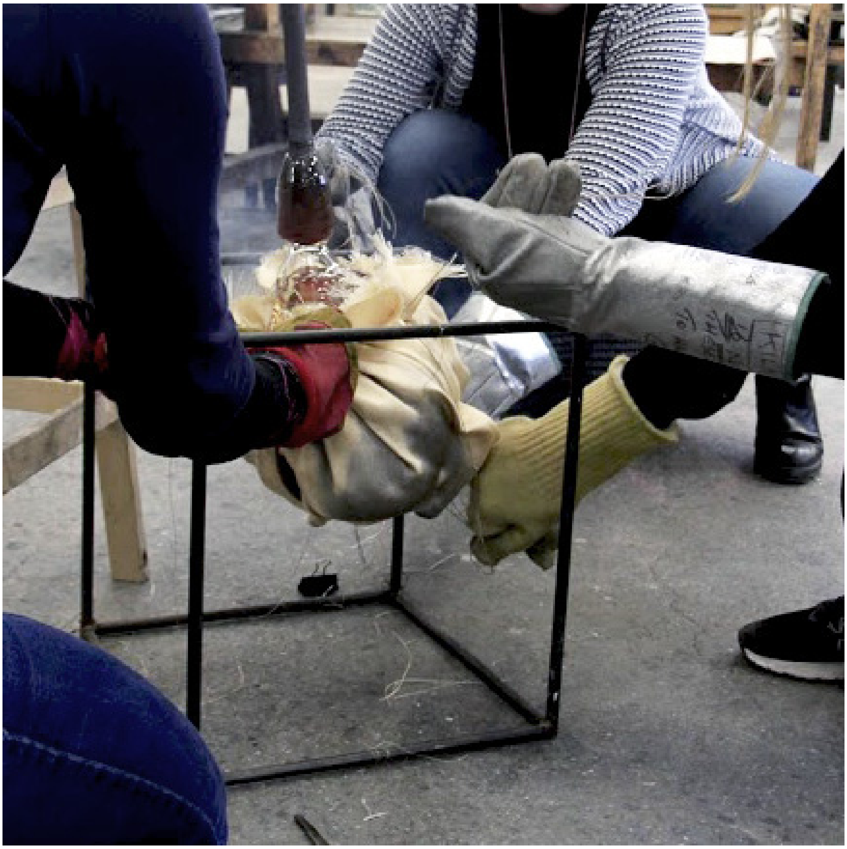


Figure 3-4. Glass blown into a textile mould mounted on a steel frame.

Figure 3-5. Using glass as a medium to explore textile, through fabric molds for glassblowing.

With these early artistic investigations, the intention was to place the wind-induced textile motion into a new context to provoke new ideas that cast light on the research from an alternative, often unexpected, perspective.

3.2 The role of the prototype

Prototypes and the process of prototyping can play various roles in research. Wensveen and Matthews (2014) outline four categories: prototypes as an experimental component, as a means of enquiry, as a research archetype, and the process of prototyping as a vehicle for inquiry. These roles may also overlap. Central roles for the prototypes within this research have been first as a research archetype, where the prototype is an embodiment of the research concept and means of understanding both the research field as well as the design. Secondly, in the later stages, prototypes were employed as experimental components, as a means to answer the research questions formulated during the first and second stages of the research (Figure 3-1 and Figure 3-2). Here, it is worth emphasising that, in this thesis, the prototype is not limited to only physical objects, and digital prototypes are seen as equally important.

Similarly, Ramsgaard Thomsen and Tamke (2009) talk about material evidence, which, to some extent, is equivalent to a prototype, and they identify three sequential modes for it:

- *The design probe: a design-led investigation allowing speculative inquiry, theorisation and the setting out of design criteria.*
- *The material prototype: a materially-led investigation allowing exploratory testing, of craft and material behaviour. The prototype answers and develops the design criteria of the design probe.*
- *The demonstrator: an application-led investigation allowing interfacing with real world problems and constraints.* (p. 3)

These modes could be compared to the steps in the flow chart in Figure 3-1, keeping in mind that the third mode was initiated but not yet fully accomplished in the third phase of this research.

In architecture, reflection, assessment and evaluation take place through making. Furthermore, as Ramsgaard Thomsen and Tamke (2009) highlight, the design process is an iterative process where the design poses new questions which inform the problem formulations and design criteria which in turn initiate a new iteration of the design. Rarely is it a linear process. In this process, the drawings, models and prototypes are a vital part of both the design but also the problem formulation. This is also true for the process of this research. The linear chart in Figure 3-1 is arranged for readability and clarification purposes, whereas in the actual research, the phases were intertwined, overlapping and looped.

3.2.1 Form explorations

When designing structures that are built out of flexible materials like textiles there is a need for a form finding process, which could be seen as a special case of prototyping. In this case, the textile material adapts to external forces such as wind and gravity. Also, the mounting techniques and patterning affect the shape and the applied forces.

For tensile textile architecture, form finding is an established term that, previously, was mainly carried out through physical models, such as the soap film models (Figure 2-2). Architect and engineer Frei Otto has shown several well-known and established examples of applying such explorations in the design of large-scale tent-like tensile roof structures (Otto et al., 2017; Otto & Rasch, 2006). However, with computers becoming more and more advanced, digital models have to a large extent replaced the physical prototypes of tensile structures. Here, the method of dynamic relaxation, originating from the 1960s, played an important role (Barnes, 1999; Day, 1965). In the context of form finding, it is also worth mentioning Heinz Isler, one of the pioneers of free formed concrete shells and famous for his physical form finding methods, such as "the hanging cloth reversed" (Chilton, 2000; Chilton & Chuang, 2017; Kotnik & Schwartz, 2011).

In the studies presented in this thesis, explorations of shape and geometry have been key in both physical and digital prototypes. Examples of this can be found in all appended papers as well as in the exhibitions.

For the digital prototypes, the form finding approach was similar to the dynamic relaxation method, used for tensile structures.

Diverse pattern designs were explored by evaluating the prototypes' volumetric forms when influenced by wind from different directions. Figure 2-12 to Figure 2-15 show examples of explorations of how the stitches in the knit in combination with yarn material affect the shape of the textile. Figure 3-6 demonstrates how knitting techniques, in combination with airflow, generate new geometries (these examples are found in (Hörteborn & Zboinska, 2021)). Photographs and videos were vital tools to capture and communicate these form explorations, as the wind influence adds an ever-changing design variable.

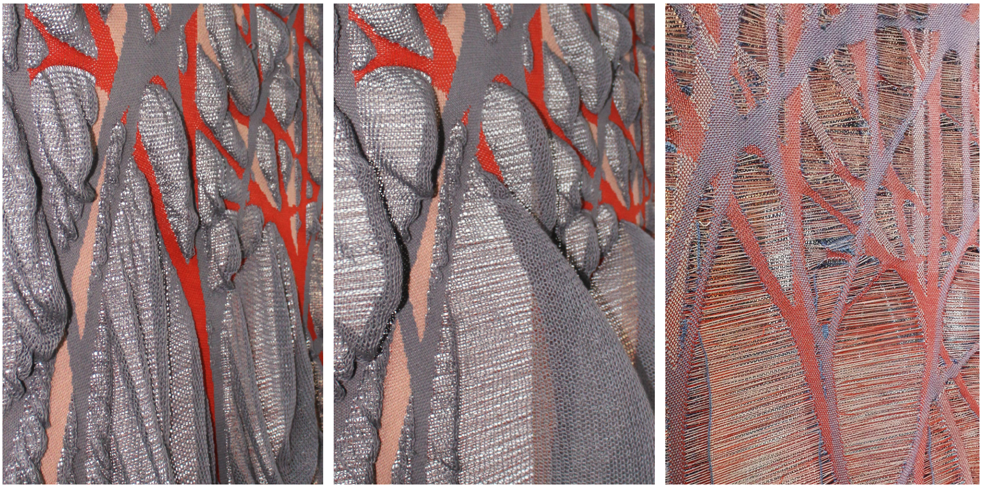


Figure 3-6. The drop-stitch pattern combined with three-colour jacquard. Left and middle: the right side of the piece without and with wind applied. Right: the purl side of the piece.

3.2.2 Materiality

An important aspect of using physical prototypes is the possibility to explore materiality and tactility, a dimension that is usually lost in computer simulations. The moderate success in attempts to digitally replicate the surface structure as well as movement behaviour of a set of knitted physical prototypes, made for the studies in the appended paper B (Hörteborn & Zboinska, 2021), highlights the complexity of such a task. Some explorations may also be easier and quicker to carry out through physical prototypes. In addition to this, as discussed in section 2.3.3, movement in wind is computationally heavy to simulate. It follows that the important real-time feedback might not be possible in a computer simulation, which limits interactions with the prototype.

Thus, certain knowledge about the material can only be gained by directly engaging with it. Therefore, in this study the geometric, expressive and formational phenomena of the textile subjected to the influence of wind required the development of not only computational but also hands-on strategies. Thereby, the researcher could participate in the process of textile transformation from the perspective of a designer and work closely with the material. Consequently, in the second phase of this research, knitted textiles with varying densities and structures have been observed as airflow was applied. Two types of manipulation to achieve three-dimensionality of the knits were applied: firstly, using smart textiles with yarns that deform with applied heat, and secondly, manipulation on a stitch level through different knitting techniques. The samples were mounted on frames and exposed to airflow using a fan (Trotec R TTW 45000 Wind Machine). More detailed descriptions of the methods and set-up of these studies can be found in the appended articles A and B (Hörteborn et al., 2019; Hörteborn & Zboinska, 2021).

3.2.3 Digital prototypes

In parallel to the explorations through physical prototypes, digital prototypes were also produced. These were used to evaluate design iterations and patterns and to assess at what level the physical prototypes could be replicated. Thereby, they helped to determine to what extent and when a digital prototype is useful.

For the studies of textile behaviour in combination with wind, such as those presented in this thesis, it is difficult to find readily available computer software, as it should be able to simulate large, rapid deformations while still allowing swift interactions with the simulation. Therefore, own written scripts and programming were deemed to be a suitable path to explore, as they gave better control over the calculations as well as larger design freedom. In the design investigations, it was important to be able to control some aspects of the wind as well as the structure of the textile and its boundary conditions (i.e. the digital mounting). Secondly, it was also vital to conduct simulations in real-time, or close to real-time, so that both the initial design as well as the effect of different interventions could be seen and reacted upon. Simulations of large deformations, such as the ones exhibited by a textile affected by forces from wind, are difficult to handle for traditional fluid simulation software (see section 2.3.3). Thus, an SPH (smoothed particle hydrodynamics) inspired approach was chosen to enable high-speed simulations of this behaviour. Here, three different methods were tested, the first being the open-source software Flexhopper (Felbrich, 2017/2020), a plug-in for Rhinoceros® and Grasshopper®, the second being a script, developed by Chris Williams and the author, written in Processing, and finally, the third one being software Kangaroo 2, also a plug-in for Rhinoceros® and Grasshopper®. More details about these different methods are found in appended articles A and B (Hörteborn et al., 2019; Hörteborn & Zboinska, 2021).

3.2.4 Exhibitions

In the same way as a designed artifact can be both just an artifact and employed as a vehicle for knowledge production, exhibitions can serve multiple purposes, ranging from being purely an object display to an information display (Dean, 1996). One extreme is similar to arranging decorative pieces on a coffee table, purely for beauty. The other extreme is a presentation with just text and no objects at all. The exhibitions of this research lean towards a more object-oriented display but with information to support the understanding and perception of the showcased prototypes.

As Lackey (2008) points out, exhibitions are about creating a space and experience where others may respond to and learn from the display. They can be a way to present artifacts, or they could be a way to communicate research and gain knowledge through observing the responses to the prototypes and allowing people to interact with them. Dean (1996) talks about exhibition design as a complex task, involving creativity, problem-solving and a desire to communicate ideas. Therefore, the act of planning and curating an exhibition can generate new insights and thoughts. By shifting the focus from the artifact, the research outputs are studied from new angles. This is achieved through questions like how they should be approached and perceived, and how to achieve this within the given spatial settings, as well as what collection of artifacts should be selected. Similar to writing a paper or a thesis, the exhibition requires a theme or thread that holds it together. It is an alternative method to tell a story.

Prototypes from this research were exhibited on two occasions. The venues and locations for these differed considerably as did the exhibition types. On the first occasion, the large, knitted prototype, seen in the middle of Figure 3-2 was a part of a group exhibition at Sergelstorg, Stockholm (Figure 3-7). This exhibition was mainly visibly accessible by watching through the windows of the venue. However, as it was situated close to one of the busiest subway stations in the city and viewable at all hours, it was accessible to a range of people that might not have otherwise taken a detour to see the exhibition. The second exhibition was situated in a smaller gallery, off the beaten track, in Malmö (Figure 3-8). Here, several knitted prototypes were exhibited, and the audience was invited in and welcome to touch and interact with the pieces.

Both exhibitions had multiple purposes. The first one was to promote the research and the research field. Another was to get some initial responses as well as view the research from a new angle. The first exhibition can be seen mainly as marketing or as a teaser, and the second allowed for more exploration and a fuller experience. As the design intent with this type of knitted structure has been interaction, both human-structure and wind-structure (and human-wind), the second exhibition, where a multisensory interaction was possible, provided more input regarding the experiential aspects. As Hauberg (2011) argues, new knowledge from research can be communicated through physical experiences as well as in a written product(s). The exhibition can communicate a sensual and physical experience that is impossible to publish in the form of a written text.

The knitted prototypes and sketches, by themselves, tend to invoke curiosity. The intent with the second exhibition was to foster that curiosity and allow further exploration and a multisensory experience of both the textiles as well as the wind/air movement in the room. The focus was on a larger prototype, which was large enough to influence the wind, in the scale of the exhibition room. The additional prototypes and sketches were selected based on how well they could communicate the iterations of the concept that lead up to the main prototype, as well as pointing in a direction for future iterations. They also needed to be large enough and visually intriguing. Two prototypes were also made specifically for this exhibition. These were iterations of three-dimensional textiles generated through heat-changing yarns. One of these had a pattern that was inspired by the main prototype in the exhibition. Short information about the project as well as about some of the digital explorations was also available. No information was given about future applications or practical purposes for this type of structures. There were mainly two reasons for this. Firstly, to let the structures evoke curiosity and interplay without colouring with issues of practicality or feasibility. Secondly, the hope was that visitors might think of unexpected uses for the structures.

Figure 3-7 Group exhibition *in motion*. Left: poster for the exhibition. Right: showing the 360 degree view venue, Superellipsen, for the exhibition, situated at Sergelstorg at the heart of Stockholm.

Figure 3-8 SPARK Gallery Malmö, venue for the second exhibition. Photo as well as a sketch of it.

3.3 Quantitative evaluation

To investigate the capacity of knitted structures to reduce wind velocities, measurements on custom-developed prototypes were made in a physical wind tunnel (Figure 3-9). Five knitted prototypes, with varying porosity, were tested and compared against two solid reference samples, one of which was perforated. The test measured incoming wind velocities and the velocity at one point downwind from the prototype. In addition to this, the wind pattern was also visualised through an array of small tufts, mounted on wooden rods (Figure 3-9). A detailed methods description is found in appended paper C. A flow chart of the essential steps in this process can be seen in Figure 3-10. In this specific case, the variation in porosity was achieved through a drop-stitch pattern, with an array of ellipses representing the sections with dropped stitches (Table 3-1). By increasing the area of the ellipses, an increase of porosity was achieved. Initially, only one drop-stitch pattern (drop-stitch 10%) was compared against two homogenously knitted (plain knits) prototypes (with porosities, corresponding to the different sections of the drop-stitch pattern), as well as a non-porous reference. From this first set of tests, it was concluded that a larger set of prototypes was needed to determine any trends in the study. In terms of the flowchart in Figure 3-10, after the first set of wind tunnel tests, and an evaluation of the results, it was concluded that the gathered data was not enough to draw clear conclusions. Thus, both an additional reference model was created as well as two new knitted prototypes.

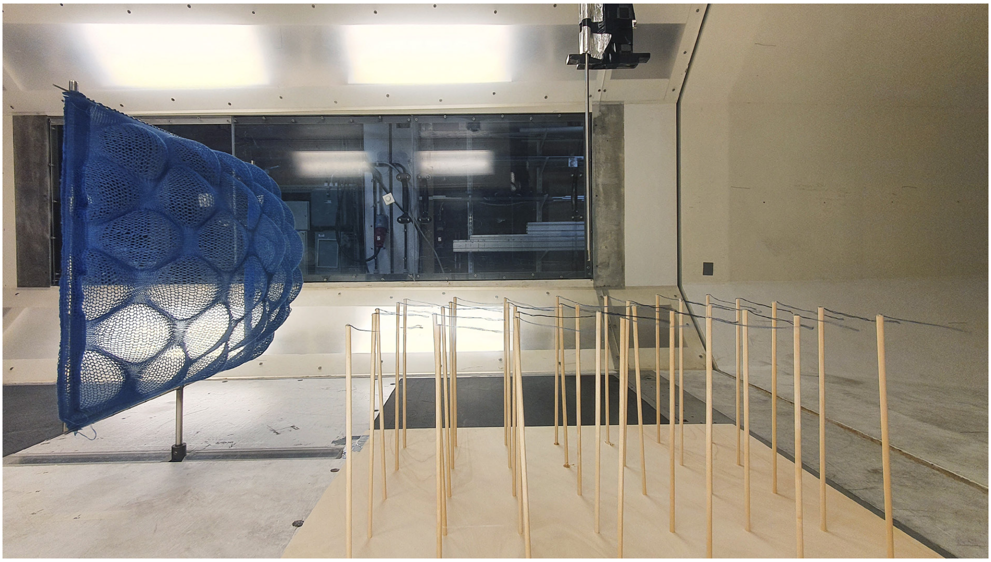


Figure 3-9. Showing the wind tunnel set-up for measuring the effects, in terms of wind reduction, altered wind patterns and deformation, of the knitted drop-stitch prototype (drop-stitch 25%).

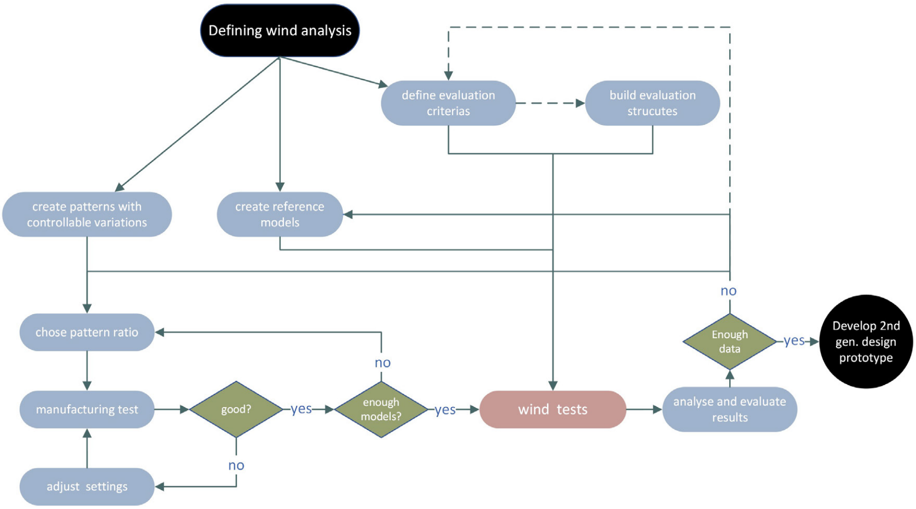
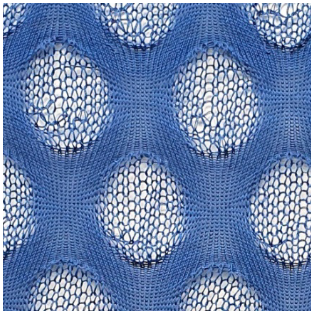
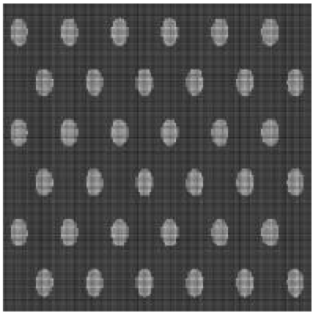
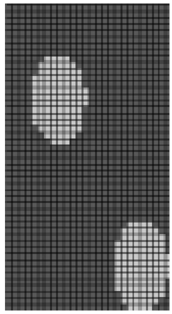
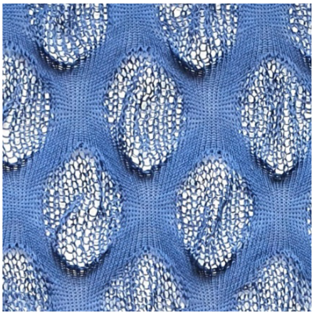
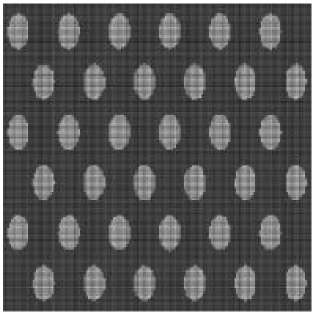
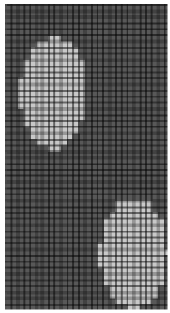
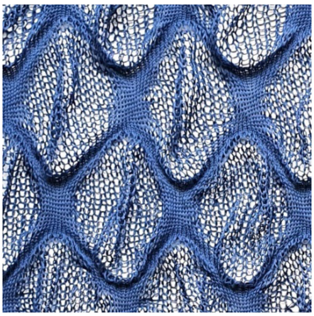
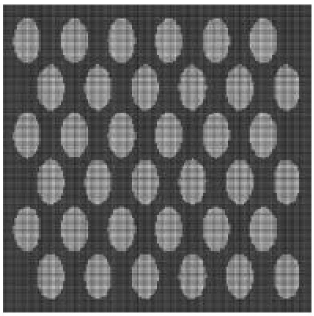
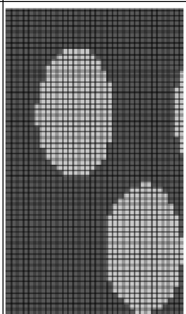
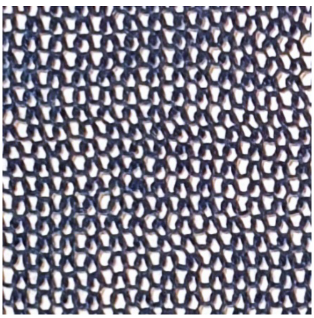
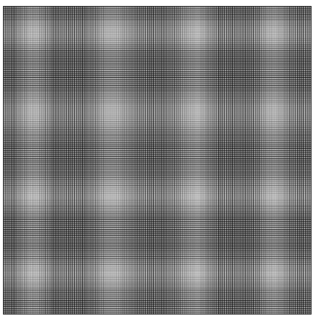
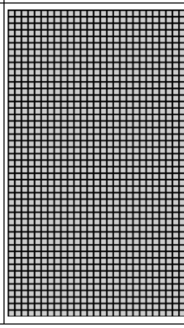
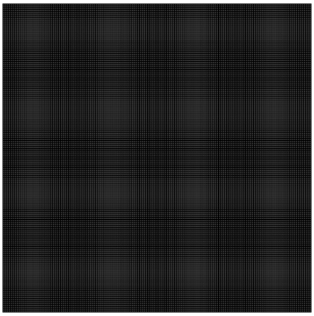
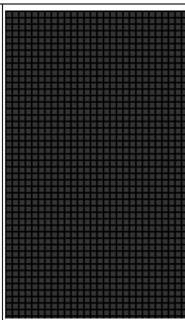
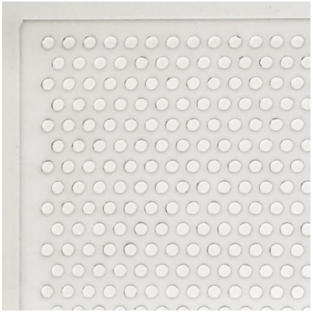
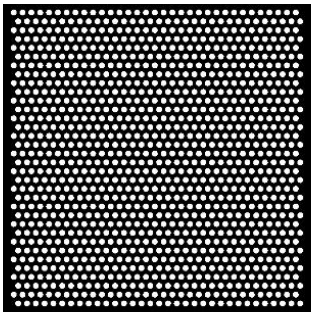
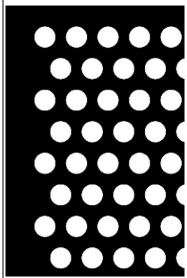


Figure 3-10 research process for the quantitative evaluation phase (Figure 3-1) of this study.

Table 3-1 Knits, patterns and calculated optical porosity for the perforated prototypes tested in the wind tunnel.

	Knit	Pattern	Zoomed in Pattern	Porosity
Drop-Stitch 10%				21% (11% unstretched)
Drop-Stitch 15%				16%
Drop-Stitch 25%				21%
Loose				28%

Dense				9.5%
Perforated Board				32%

4 Research results and communication

The results of this research are reported in the appended research articles and additionally communicated through the exhibitions of the prototypes. Based on the knowledge gained from these, an outline of a framework for designing a full-scale, site-specific, knitted windbreak is also presented. In this section, these results are summarised in relation to the research objectives.

The first objective of this research was to develop prototypes that demonstrated both aesthetic and functional potentials of loosely fitted knitted textile architecture. This is reported in all three papers and the two exhibitions. Paper A has laid the groundwork for explorations of volumetric and kinetic knitted prototypes (physical and digital), which were then further studied as reported in paper B. The results of wind tunnel tests of prototypes were presented in paper C, demonstrating some of their functional capacities. That this type of knitted textiles had the potential to reduce wind was also observed through research through prototypes in the study presented in paper B. The second objective focused on explorations of knitting techniques, which are presented in paper B. Inspiration for these prototypes, which governed the choices of knitting techniques, came partly from the explorations presented in paper A. The drop-stitch knit was then further studied in paper C. The final objective was to provide an outline for a design framework for this type of knitted structures, which is presented in the last part of this section. The foundation for this framework is based on the studies presented in the three papers.

4.1 Paper A: volumetric shaping of textiles through prototypes

This study explored wind as a positive design parameter for textile architecture, with the aim of achieving kinetic volumes when wind is applied. It presents investigations of how modifying the internal structure (micro-scale) of the textile effects the design on a macro level. The implications of such a design approach were formulated based on a two-day workshop held at the conference Advances in Architectural Geometry (AAG) 2018. For the explorations, a combination of digital and physical prototypes was employed, using particle-based animations for the digital simulations and knitted smart textiles that could be modified using heat. One example can be seen in Figure 4-1.

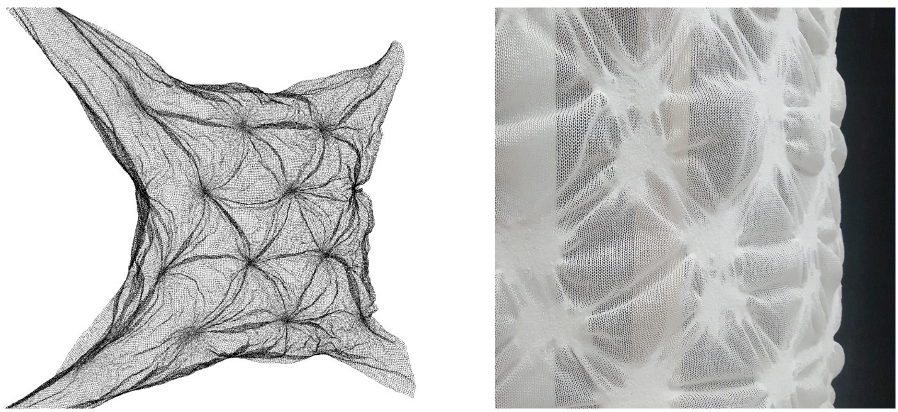


Figure 4-1. Digital and physical prototype with a Chesterfield pattern, placed next to each other.

A conclusion from this study was that for loose textile architecture interacting with wind, digital and physical design prototypes are of equal importance in the conceptual stage. They complement each other and provide a broad overview of the material behaviour and the aesthetic consequences of fine-tuning the design parameters. A digital model offers many advantages in terms of quickly exploring several design options as well as a possibility to go back to a previous version. However, rapid explorations are dependent on the capacity of the software and hardware for real-time feedback. Furthermore, the digital models in the presented study were produced through simplified interpretations of the physical textile, thus they were not able to represent all details of its behaviour. Still, less exact simulations are useful in an architectural design process, but the designer must bear in mind that it is a simplification.

When it comes to understanding the material behaviour physical prototypes are essential. This also includes getting a feeling for, and understanding, how a modification on a micro-scale alters the structure on a macro scale. This, in turn, can inform the digital prototype. In this study, it was also noted that the choice of digital tool(s) seemed to direct the design investigation and the outcome, which is likely also true when it comes to the choice of the physical design tools.

4.2 Paper B: Volume through manipulating the knitted structure

The focus was here to explore the design possibilities with knitted architectural textiles subjected to wind action. Through both physical and digital prototypes, it was investigated how such textiles could be applied to alter the usual static expression of exterior architectural and urban elements, such as facades and windbreaks. The physical prototypes were produced using both a manual knitting machine and a CNC (computer numerically controlled) flat knitting machine. Four knitting techniques - tuck stitch, hanging stitches, false lace, and drop stitch - were explored based on their ability to create a three-dimensional effect on the surface level as well as at an architectural scale. All prototypes were exposed to airflow generated using a wind machine, and the resulting deformation and kinetic behaviour were studied. The digital experiments were aimed to probe the possibilities of digitally simulating and replicating textile behaviours in the wind.

The study shows that especially the drop-stitch pattern exhibits potential in terms of geometric and kinetic expression when influenced by wind. Variations of density and surface geometry demonstrated both aesthetic and volumetric effects (Figure 4-2). In addition, initial measurements indicated that this knit also improves the wind climate by reducing wind, suggesting that structures knitted with a drop-stitch technique have the potential to improve aesthetic as well as comfort experience in windy urban environments.

Figure 4-2. The large-scale drop-stitch prototype with wind applied, shown with two different mountings.

There is a lack of suitable methods for systematically translating the yarn structure of the knitting techniques into a simplified mesh representation in a digital model at an architectural scale. This was evident during the search for ways to translate the variation in stitches into a digital model. Each knitting technique required a customized approach and while some generated a visually satisfactory result, such as the representation of the drop-stitch pattern, others were less successful. In all cases, the mechanical and structural properties of the digital model are a coarse simplification. For the simulation of the wind-induced deformation of loosely fitted textile structures, a mesh-free simulation is preferable. Such large deformations would otherwise require frequent re-meshing of the model, a process that requires substantial computational power.

4.3 Paper C: wind reduction using drop-stitch knitted structures

The hypothesis from the previous study (Paper B), namely that knitted structures could be applied as efficient windbreak structures, was tested. Specifically, the focus was on the drop-stitch technique, which enables a grading of the porosity of the textile as well as the potential to generate a pronounced three-dimensionality in the wind. Quantitative data of the wind reduction performance, as well as resulting reaction forces was generated through physical wind tunnel tests of custom-made protypes.

The results indicate that the optimal porosity for this type of knitted structure lies around 10% (Figure 4-3 and Figure 4-4). The knitted prototypes with this porosity reduced the wind velocities by around 85-90%. This could be compared against previous research on optimal porosity for windbreaks, which recommended a higher porosity (ranging from 20-35%) (Cornelis & Gabriels, 2005; Dong et al., 2007; Raine & Stevenson, 1977). The difference in results is likely related to that this study might have underestimated the porosity of the knits. Alternatively, that optical porosity is not a good way to measure porosity in the knits. The knitted structure also behaves differently than a static structure in the aspect of porosity, as the knit stretches with increased wind load resulting in increased porosity.

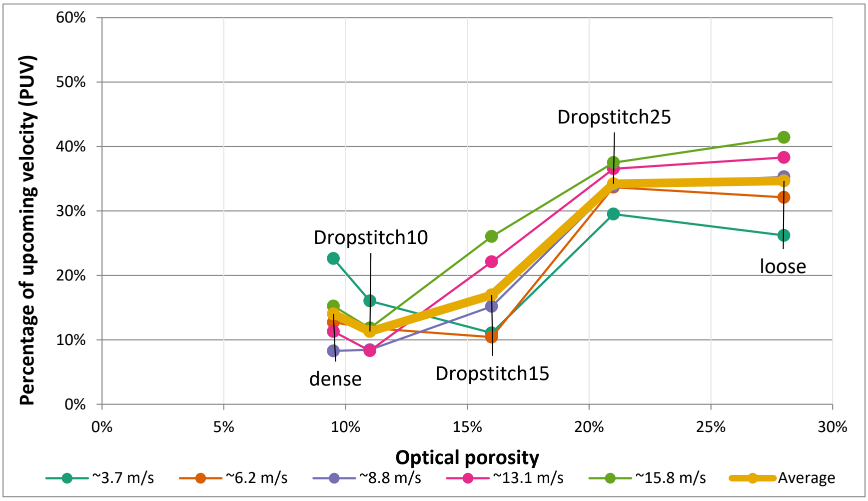


Figure 4-3. Percentage of upcoming velocity (PUV) depending on the calculated optical porosity using the value for un-stretched drop-stitch 10%

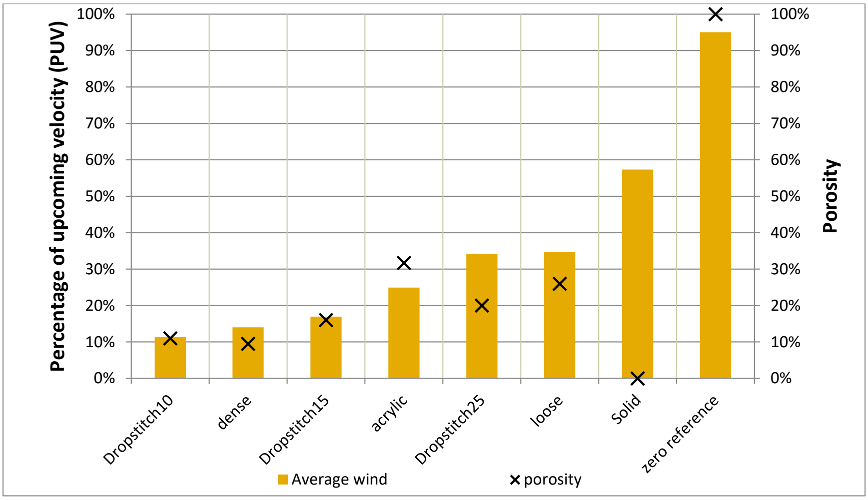


Figure 4-4. Percentage of upcoming velocity (PUV) for the different models, compared against the calculated optical porosity.

Furthermore, comparing the tested knits with the perforated, static, acrylic board, the results indicate that the knits, depending on the pattern, perform better as a windbreak. High performance is here referring to high wind reduction in combination with low reaction forces (Figure 4-5). This suggests that a knitted windbreak could also require less foundation anchorage. Another interesting result from the tests was the decreased drag coefficient (C_d) with increased wind velocities that the knitted prototypes exhibited (Figure 4-6). This reinforces the result that knitted structures generate lower reaction forces compared to solid structures and could be explained by the fact that the textile stretches and, as the wind increases, so does the porosity.

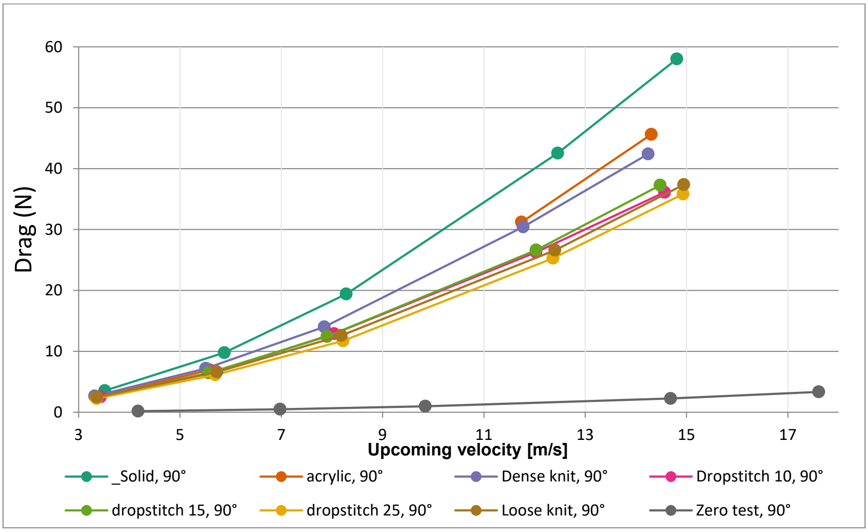


Figure 4-5. Drag force exerted on the models, positioned at 90° toward the wind direction.

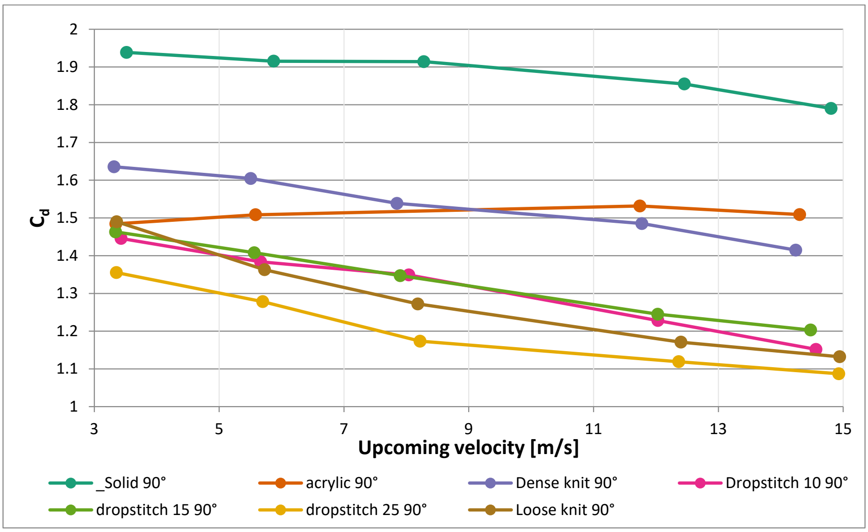


Figure 4-6. Drag coefficient (C_d) for the tested models, at different wind velocities.

Moreover, the formation of high-energy vortices behind the windbreak structure is less likely to occur with this type of knitted structures compared to the tested perforated as well as solid boards. In other words, the study indicates that this type of knitted structure would generate less problematic turbulence. As an illustration of this, the tufts' directions and behaviour during the test of the unperforated board and the drop-stitch 10% at a wind velocity of 8 m/s are shown in Figure 4-7. Common for all the knitted models was that they did not seem to generate much turbulence within the test range, nor did they direct the wind to any large extent.

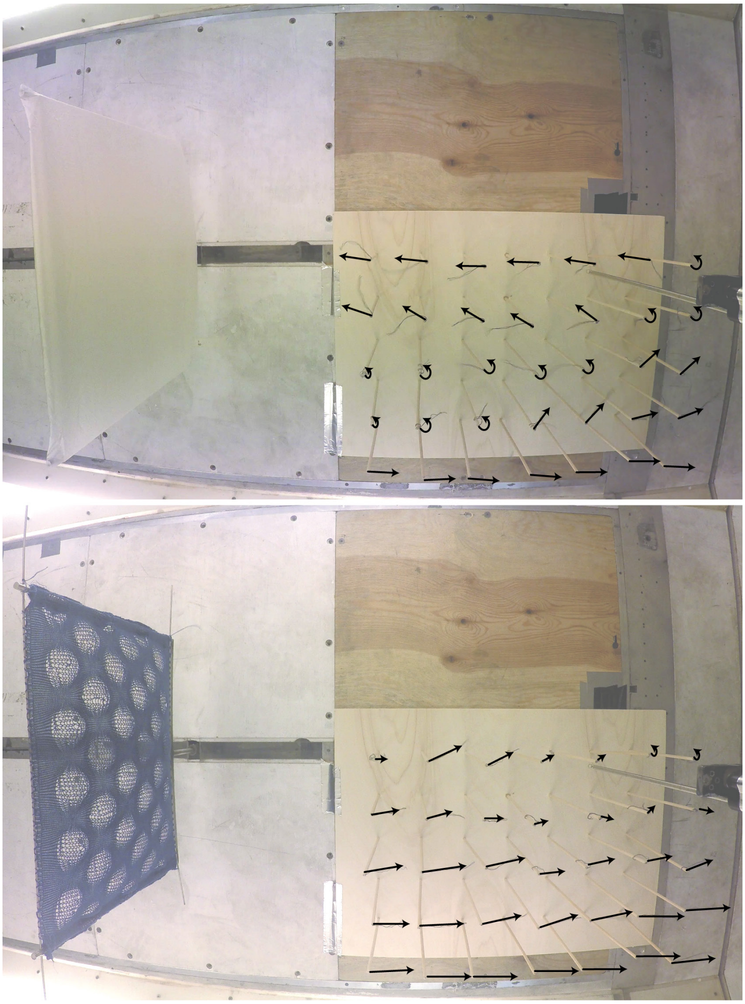


Figure 4-7. The wind tunnel test of the unperforated reference model as well as the drop-stitch 10%, with wind velocities of 8 m/s with arrows interpreting the direction and behaviour at the positions of the tufts (based on both still and video footage). Circular arrows represent tufts that were moving around and rotating mainly in the direction of the arrows.

4.4 Exhibitions

An important aspect in terms of the communication of the artistic research results is the two exhibitions of the work (Brečević et al., 2022; Hörteborn, 2022) (see appended exhibition material for more information). With them, the research reached a broader public audience, outside of the academic context. Another outcome of these was the possibility to observe the work in a new light and to observe people experience the structures. Figure 4-8. and Figure 4-9. show the piece *(in)Formed by wind* (from the second set of design prototypes (Figure 3-2)) at the group exhibition *In Motion* at Superellipsen, Sergelstorg, Stockholm. Here, the knitted structure from this research could be experienced in relation to other artists' work relating to the theme *in Motion*. This was a 24-7 exhibition that could be viewed through windows and via private tours. Being situated in the very centre of Stockholm, where thousands of people pass by, it was easily accessible and visible also to people not seeking art. Figure 4-9. and Figure 4-10. shows the second exhibition *(in)Formed by wind* at SPARK Gallery in Malmö. This was a smaller venue outside of the beaten track, where the audience was invited in and could walk around and interact with the pieces. In this case, the main piece was the same knitted prototype, and in addition, other prototypes as well as images of digital prototypes from the first and second set of design prototypes were also exhibited (see section 3), along with more information about the project. With this exhibition, there was an opportunity to select prototypes from different stages of the research and highlight the artistic and aesthetic aspects of these. The selection in combination with the positioning of the pieces in the venue has brought an opportunity to tell a story and to communicate the research, as well as how it has developed. Thus, both exhibitions positioned the research (or art from the research) in a broader context. In the case of the group exhibition, the research was placed in an external context, and in the SPARK exhibition it was about a zoomed-out view of the research itself.

Figure 4-8. (in)Formed by wind at the group exhibition In Motion, Superellipsen, Sergels torg, Stockholm.

Figure 4-9. Pieces at the exhibition (in)Formed by wind, at SPARK Gallery, Malmö.

The intent with the exhibited prototypes was to provoke thoughts and challenge the perception of what a building material is, what architecture is, and open for a wider application of loosely fitted knitted architectural textiles in combination with the wind. Thereby, also to unlock a broader design palette within architecture. The exhibited prototypes, as they were, did not have an immediate application in architectural practice but still bore distinct architectural features. They challenged the usually static architecture around us by, intentionally, bringing the motion of the wind into a design. Invoking curiosity about what effects a soft material, like a knitted textile, will have if applied as a building material. The features of the soft, moving, knit drastically differ from the more common concrete structures around us and could transform the urban landscape. Thereby, the exhibitions contributed to the broader aim of the research. That is, they provided knowledge and inspiration that have the potential to enable a wider application of loose knitted textiles in architecture, shaped by and shaping the wind.

Figure 4-10. Interactions with the knitted design prototype at the exhibition (in)Formed by wind, at SPARK Gallery, Malmö.

Through the exhibitions, a sensory, bodily and cognitive experience was enabled. Especially so when the audience was able to touch the prototypes (Figure 4-10.) and experience the motion of the knits first-hand. In addition to the visual and sensory experience of the knit itself, other effects could also be experienced, such as how the light affects the moving textile as well as the shadows on the floor, and how the motion of the air (wind) changes around the structure.

Another result of the exhibitions was the feedback and comments from visitors. For instance, the attraction and fascination that the larger prototype has generated. It was described with a variation of metaphors ranging from a peaceful magical forest to being intriguing and spooky. Most people seemed to be drawn to touch and feel the knit. One person suggested that it could maybe be applied as a facade on “ugly” temporary buildings at hospitals and schools. Though all feedback and comments were positive, it should be noted that all comments came from people who had actively chosen to visit the exhibition and were likely to be intrigued from the start. Thus, it was likely not an objective reference group.

4.5 Towards a design framework

Based on the findings that are summarised in this section, an initial sketch for a design framework for a drop-stitch knitted windbreak structure was developed. This framework is shown in the flowchart in Figure 4-11 and is directly related to the third research question of this thesis. Through it, the separate studies and results are placed into the context of architectural design practice, attempting to make the findings accessible and useful for practitioners.

The opening design idea is the starting point in the flowchart (Figure 4-11). The idea should consider ambitions and/or requirements regarding aspects like the aesthetic and volumetric experience, space-defining aspects and wind comfort. It is also assumed that there is a specific site in mind for the windbreak. From this, in the initial stage, physical and digital sketches are developed in parallel. These inform each other and enable explorations of pattern concepts, volumetric goals and suitable yarns/materials for the knit, including aspects like colours and loop sizes. This stage is about the design probe (Ramsgaard Thomsen & Tamke, 2009), focusing on speculative inquiries through the creation of prototypes and finding a desired design concept. For the physical sketches, a manual knitting machine would be an ideal tool, as it provides hands-on experience with the material and production. Other options could be smart textiles like the ones explored in Paper A (Hörteborn et al., 2019). However, with the latter option, the possibilities of exploring the knit properties are limited to more volumetric studies (thus excluding explorations of tactility, porosity/transparency, surface texture, colour, etc.). Through heat-changing textiles, properties such as density, stiffness, and a limited variation of porosity can be explored, as well as the effect these have on the shape and geometry of the structure on a macro scale. Insights from such explorations could inform patterns, choice of stitches/knitting techniques and yarns for knits with more traditional materials.

For the digital sketching, a particle-based simulation in a design-friendly 3D environment should be used. (See appended papers A and B, as well as section 2.3.3 for more details about simulation methods.) The tools explored in appended Papers A and B are good options, i.e. the suggested, readily available options are Flexhopper or Kangaroo 2 (plug-ins for Rhinoceros® Grasshopper®). However, it should be noted that these plug-ins are not developed to simulate the effect of different knitting techniques/stitches, but rather homogenous membranes or woven textiles. Thus, the simulation process of the effects of stitch alterations is currently far from intuitive. These digital explorations, in combination with the simultaneously conducted physical ones, should lead to the design of an initial knitting pattern, which is based on an image file. They should also help to inform a design concept (the second black oval in Figure 4-11).

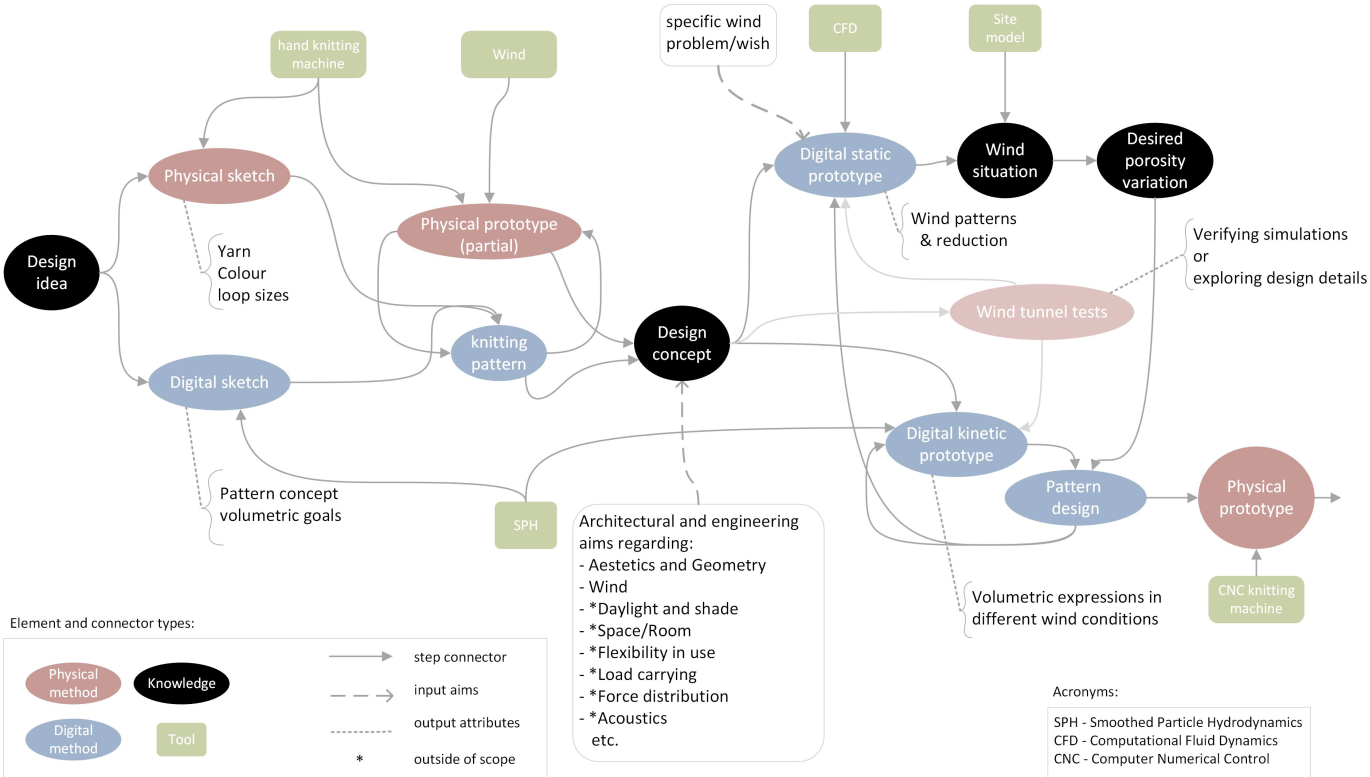


Figure 4-11. Outline for a design framework for a drop-stitch knitted windbreak, departing from a design idea that includes thoughts and ambitions for properties, shape and wind reduction, for the structure.

Based on the developed pattern(s), a physical prototype is produced, with the pattern image as input for the knitting machine. At this stage, the aim is to roughly estimate how the design will behave and look. Thus, it needs to be sufficiently large to judge its movement and deformation in the wind, but small enough to be manageable to produce. Around the size of an A3 (297 × 420 mm) is likely suitable, yet this will depend on the pattern. There might also be a need to produce prototypes of several sections of the full pattern. Informed by the developed prototypes, a design concept can be developed. Note that likely several design iterations of the pattern are needed.

At this stage, specific quantitative and qualitative site data, requirements, and goals are merged with the developed design concept, to create more informed, and detailed prototypes. As discussed earlier in this thesis, as well as in the appended research Papers A to C, simulations of wind interacting with a flexible material, like the knitted prototypes, are a highly challenging as well computationally heavy task. Thus, it is not realistic to achieve a model for a full-scale digital prototype, covering all aspects of interest, in a single simulation. At least not in a reasonable timeframe for a conceptual stage, in the near future. Too many factors influence the wind. Aside from the knitted structure itself, which is changing its position due to the wind, the surrounding buildings, objects, and/or vegetation affect the wind pattern. Adding to the complexity is also the fact that the wind is turbulent. Therefore, the work at this stage is better divided into two digital prototypes: one static model that gives information on the wind pattern around the structure, and one kinetic model visualising a realistic appearance of the structure itself. Depending on the available computational power, it might also be necessary to use simplified models for the wind simulation or to only run simulations on a fraction of the model. In that case, an additional static, digital model would be required to communicate and explore the textile design's architectural effect on the site, concerning defining the room, achieving privacy, shade, character to the place, etc.

The static prototype is merged with a site model to get site-specific wind data and information about how the windbreak design is likely to affect the site conditions. This model should have information about the porosity variation of the knitted textile. Here, it might also be good to test one or several static deformations of the windbreak structure, i.e. shapes it will likely take when wind load is applied. A more traditional CFD analysis can be a good option for this type of simulation (see section 2.3.3 for more information about wind simulation methods).

There is a direct relationship between the porosity of a structure and the wind reduction capacity. This was observed in the study presented in Paper C and aligns also with previous studies on windbreak efficiency (Cornelis & Gabriels, 2005; Dong et al., 2007; Raine & Stevenson, 1977). Such a relationship could be applied as a design parameter for the pattern of a knitted windbreak structure. Therefore, the simulation tool should have parameters to control the model's porosity values. Through this prototype, it is possible to get information or indications of whether the overall porosity, as well as the porosity ratio, are suitable. From that, it is possible to make educated guesses about how the knitting pattern should be further iterated to achieve the desired goals.

As an example, for a larger windbreak there might be areas that require a calmer wind situation and areas where more wind would not be a problem or even beneficial. These areas should then have a porosity that suits the specific site requirements. For a knitted structure, the variation in porosity is mainly achieved through varying the loop sizes, i.e. grading the textile's function and shape across the surface. In the case of the drop-stitch knit, the variation in loop size is also what generates the three-dimensional volume. Thus, varying the porosity would also affect the shape of the design.

In parallel to the static wind model, a kinetic digital design prototype should also be developed, with the wind and material simulation particle-based, like an SPH approach. This prototype aims to explore volumetric and kinetic expressions in different winds. As the interest lies in exploring shape and motion, it is an advantage (if not necessary) if the simulations are real-time or close to real-time. Hence, it is recommended to use a coarse enough grid/mesh, to keep down computational time while still achieving enough resolution to communicate and explore the design.

If there are doubts about how realistic the achieved simulation results are, then it would be advisable to do tests in a wind tunnel or measurements in tests with a wind machine or outdoors. Note that scale models are likely not an option in this situation. It might also be the case that there is a wish to further analyse details of the knitted prototype, at a level that is not achievable in the computer model. This would also be a situation when physical explorations or measurements are useful.

Ideally after the explorations of the pattern's impact on the shape and wind through the two types of digital prototypes, the next step would be to manufacture a larger physical prototype. One that is on a scale of 1:1, and that can act as a proof of concept. However, this requires access to a CNC-knitting machine, as well as knowledge of how to operate it, as such a large knit is not realistic to achieve on a manual machine.

Note that the framework for design, as it is laid out in Figure 4-11, could be perceived as a straightforward process. While in practice it will be an iterative process and not likely neatly aligned (as with most design processes). As an illustration of this, Figure 4-12 is a sketch of one way through the flowchart in Figure 4-11. It is also probable that the design process requires several more, larger and smaller, iterations through the map.

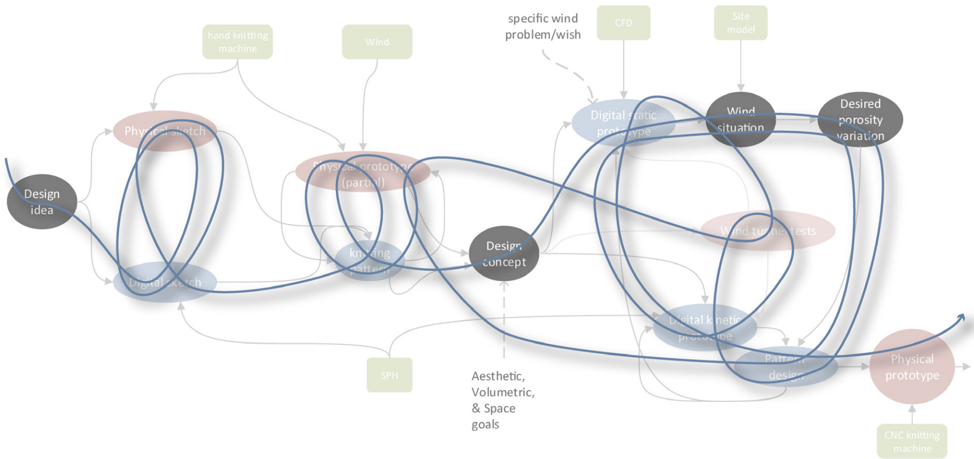


Figure 4-12. Example of a design process using the steps in Figure 4-11.

Applicability of the design framework

When designing a knitted structure like a windbreak, there are several decisions and aspects to consider that will influence the final design. The focus of this thesis has mainly been on the three of them: pattern, stitches, and porosity, and how they affect the shape of the structure and the wind. The sketch for the framework in Figure 4-11 builds on the knowledge gained from explorations of this selection of design parameters. However, the main structure of the design framework could still be followed when including other aspects. Architectural and engineering goals are therefore included as suggested input for the design concept in the framework. Although not included in the scope of the study, these important goals are presented as a list in the middle section of the framework diagram (Figure 4-11). These could incorporate important architectural and urban design parameters such as daylight, shading, visual transparency and connection, space-defining/divisions, privacy, acoustics, etc. Future iterations of the design framework might also reveal a need for additional physical and digital prototypes in the flowchart.

5 Conclusion and discussion

This chapter summarises the key research findings in relation to the research questions and highlights the value and contribution thereof. Following this is a discussion regarding simulations and the choice of knitted textiles. Finally, suggestions for future research are given.

5.1 Addressing the research questions

Question 1:

> *How can the knitted structure be designed and employed to create a geometrically alternating, three-dimensional, kinetic architectural element meant to interact with the wind?*

By exploring the relationship between modifications on a micro and macro scale paper A presents an initial step towards understanding the desired outcomes of stitch manipulations in a knit. The shaping of the physical prototypes, achieved through modifying the yarn, increases the stiffness and shortens the length of the yarn (and thereby the loop size). These modifications are also possible to achieve already in the manufacturing of the knit, through the choice of yarns, number of threads, and controlling the loop sizes, as shown in Paper B.

It was found that the knitted structure and specifically a drop-stitch pattern, through its possibility to vary loop size and density, has high potential in terms of achieving a geometrically diverse structure in wind. The variation in transparency, achieved by this type of pattern and stitch type, further enhances the diversity. A welcome side-effect is also the varying shadow display on the ground. This type of knit effectively catches the wind, and, as wind on an urban scale is turbulent, it will pick up the variations in the wind, thereby generating an altering kinetic structure.

The combination of the variation in three-dimensional shape, the density (and thereby weight of the textile), and the porosity also means that the appearance will vary depending on wind velocities. Three variations of the same drop-stitch pattern were tested in a wind tunnel (paper C). These tests showed how the variation of the knitting pattern affected the overall shape of the prototypes in different (laminar) wind velocities.

Question 2:

> *How are the wind velocity and wind direction affected in the proximity of a loosely fitted knitted screen?*

A knitted screen will reduce the wind velocities. The results presented in paper C indicate that the highest reduction in wind velocities is achieved with knits that have an optical porosity of around 10%, positioned perpendicular to the wind (see Figure 4-3 and Figure 4-4). Compared to both a solid and a perforated board, the tested knits exhibited less tendency to shape (the undesirable) large energy eddies downwind (see examples in Figure 4-7). Furthermore, the knitted prototypes did, generally, not direct the wind (which could lead to increased wind velocities in areas around the structure). For all the tested angles of the knitted prototypes, towards the wind direction, the wind was reduced at the measuring point downwind. In terms of wind reduction, when the screens were more aligned with the wind direction (an angle of 20°), the knitted screens performed significantly better than both the perforated and unperforated boards. In the case of the unperforated screen, it even caused an increased wind at this angle.

In summary, the results suggest that loosely fitted knitted textile windbreaks can perform equally well, or better, than more traditional windbreaks in terms of wind reduction. Furthermore, the knitted windbreaks seem to be effective in a wider range of wind directions. This is valuable since a windbreak will have a fixed position, while the wind may come from any direction.

Question 3:

> *How can the design process of knitted architectural elements that interact with the wind in urban space be supported?*

All the studies presented in the appended papers are exploring different aspects of the design process. The conclusions drawn from these were used to formulate the outline of a design framework, presented in Figure 4-11.

An initial step towards understanding how modifications on a micro (stitch) level, effects the shape on a macro level, was presented in paper A. This study was employing textiles knitted with a heat-modifiable yarn (i.e. smart textiles). Which is a method that can support early stages in the design process of knitted architectural elements, influenced by, and influencing the wind.

The same study also concludes that a mix of digital and physical prototypes is beneficial in such a design process. For early sketches and shape explorations, it is useful to have tools that feel intuitive, that generate real-time feedback. In this sense, smart textiles are ideal. Wind can, at this stage, be generated by just moving the textile through the air, with a small fan, or just conducting explorations outdoors. Also, smaller parametric, digital models are useful for the explorations. Especially in terms of evaluating variations of a design concept. However, as freely moving textiles in wind are complex and heavy to simulate, digital models need to be simplified and course to be useful at this stage. This applies to both the representation of the wind as well as the textile.

In the explorations presented in paper B, it was found that the methods used for the digital representations, of the studied knits, needed to be adjusted and explored for each prototype. Two approaches for methods to represent different stitches and modifications were found to be successful: changing edge lengths in specific mesh cells and adding springs to the mesh. These mesh representations of the textiles were then combined with a wind force achieved through a particle simulation. Thereby, wind deformation, as well as motion, could be studied.

When studying the aspect of the wind interaction that focuses on wind pattern around the structure, the most reliable and practical method is, currently, to do physical tests in a wind tunnel, as was done in the studies presented in paper C. With a physical model, it is possible to simultaneously study the dynamic behaviour of the textile and the effect that it has on the wind. However, it should be noted that for the types of knits that are presented in this thesis, it is not possible to accurately scale down the textile. Thus, the sizes for the tests are limited to the dimensions of the wind tunnel.

5.2 Contribution to knowledge

Loosely fitted, knitted architectural elements, such as windbreaks, influenced by, and influencing the wind in urban space, are a new type of application for textile architecture. This kind of wind-influenced textile architectural design is an unchartered territory with many challenges. Firstly, knitted structures, of any kind, are uncommon within the built environment and architects, in general, do not possess detailed knowledge about the characteristics of knitted textiles. Secondly, knitted-textile designers and engineers possess material knowledge but seldom work on an architectural scale with shaping a place. And finally, the analysis of highly flexible structures, such as loose textiles, moving in the wind, is a challenging area within the field of wind engineering. No publication was found that presented an analysis of fluid flow around structures with such large and rapid deformations. The research presented in this thesis is starting to explore this gap in research and present a practical application for such structures, a windbreak. It is addressing the need for improved wind comfort in urban areas and presents a concept for achieving this, which is combining aesthetics and functionality. To communicate the research and new application of knitted textile architecture, prototypes have also been publicly exhibited.

The research is also providing performance data, from initial tests of this new type of structure, that could be used as a base for future research and design developments. Both quantitative and qualitative analyses are presented. It shows measurements of efficiency in terms of reducing wind velocities, as well as the knitted structures' functionality in terms of reducing high energy eddies (vortices) compared to solid structures. In other words, data relating to the capability to improve wind comfort. Along with this, aesthetical performance data is also presented, relating to aspects like three-dimensionality, diversity, and the ability to pick up motion from the wind.

Since this application seems to be previously unexplored, the research is also providing an outline for a design framework for this new type of textile kinetic windbreak. This is intended to give architects guidance concerning important aspects of such design and how it can be explored as well as communicated through a combination of digital and physical prototypes.

The work presented in this thesis is also contributing to the discussion of the limitations of currently available digital simulation and design tools for flexible, knitted, textile architectural design. This includes tools to design knitted architecture as well as tools that can simulate flexible structures interacting with wind. With knitted architecture, the main challenge is to replicate the effects of varying or manipulating stitches across the surface, on a macro level as well as on a stitch level. In terms of wind simulations, the rapid and large deformations remain a challenge for traditional, mesh-based, CFD simulations (also for fluid engineers), and the mesh-free methods are not fully developed in tools available for architects. As is shown in this thesis, it is possible to do digital models and simulations, but the required computational cost is high, as is the required textile and wind knowledge from the designer. For the design of loosely fitted knitted textiles interacting with wind, the exploration, as well as the visualisation and communication of a design concept, is best achieved through a combination of digital and physical prototypes. The two types of prototypes complement each other and add information about different aspects of the design, to together paint the full picture.

5.3 Discussion

The core elements of this research are wind and knitted textiles, and how these relate to architectural design, specifically, the design of knitted textile structures that could act as windbreaks. Especially the wind has been a complex phenomenon to handle in this combination, with its unpredictability as well as immense complexity. Thus, the accuracy of simulation of the wind, in relation to explorations with textile prototypes is discussed here in more depth. Following this is also a discussion regarding the performative aspects of the knitted structure, particularly relevant for architecture.

Accuracy of simulations of wind and textiles

Key to the research has been to enable an increased understanding of the phenomena of knitted textile structures interacting with wind and to find tools and methods for conceptual designs of these architectural elements. Specifically focusing on how stitch alterations affect the global geometry of the textile structure and its ability to interact with wind. Digital simulations have been used in parallel with physical prototypes to recreate and explore an observed or desired behaviour. A key step to expand creativity and speculate in future possible creations and designs. As simulations of wind interacting with textiles are computationally heavy, it is a good idea to adapt the level of complexity to the level and type of information sought from the simulation. It is also important to consider what we want to use the acquired information for, and what type of data we need to be able to visualise and communicate it. This is particularly relevant for the simulation of wind, which to a large extent is invisible. In the case of this research, detailed information about the stitches of the knit and how that effect the surface texture and tactility was more easily obtained through the physical sketches. Thus, the digital models could focus on the global geometry of the prototype. It is then acceptable if the digital model is not fully accurate in every detail if the overall shape is sufficiently truthful. Digital simulations are particularly useful for getting quick feedback about the consequences of alterations of the pattern, surroundings, and wind.

Smaller digital and physical prototypes could inform the creation of a larger digital prototype, on an urban scale, which would provide information about the effects the prototype will have on the urban space. Aside from wind climate and aesthetic impressions, this could also include shading, people flow, sense of seclusion, etc.

If we exclude extreme wind scenarios, where it is likely that a knitted windbreak would be dismounted or disabled, it is the more common "every-day-wind" that is of interest. This still includes a large variety of wind scenarios. Thus, the behaviour and effect of the knitted structure are going to vary vastly, making the need for precise simulations less important. Instead, it is the general behaviour and effect that is relevant.

It should also be mentioned that, while the physical prototypes could be said to be accurate and precise per definition, as they are physical, real objects, they could be misleading. For the prototypes in this research, it is mainly two aspects that could lead to false impressions of the properties and behaviour during the design process. Firstly, as scaling yarns and knitting gauge, and in extension the model, is not realistic to achieve, and full-scale prototypes are impractical, the only option is to produce prototypes of a fraction of the complete architectural element. This limits the possibilities to explore big patterns and cannot fully display the global behaviour of the architectural element. Secondly, the choice of yarn greatly affects the behaviour of the knitted structure. Depending on if the available and suitable yarns for the design prototypes and final architectural elements align or not, this might lead to changes of yarns during the course of the project, which in turn might have unforeseen design consequences.

The accuracy of the digital simulations in this research was qualitatively evaluated, through visual comparison with physical prototypes. While these evaluations showed limitations in representing the properties and behaviour of the knits, it can still be initially observed that also rough digital prototypes aid the design process. It also remains to quantitively assess the accuracy of these and this type of simulations, despite the observed limitations. The simulations produced for this research allow the designer to get an initial impression of the design and its behaviour and appearance in combination with the wind. Furthermore, even rough digital models can be valuable when it comes to evaluating the effects variations of design parameters have on the shape and appearance of the knitted textile, as well as how these affect the space around it.

Potentials with knitted textiles as a performative material for architecture

There is a large variety in the performative qualities, such as appearance, functions, and behaviour within the group of materials that could be classified as knitted textiles, or even more specifically weft knitted textiles. Depending on the chosen stitch type(s) and composition, yarn material, type of yarn and combinations of yarns, the textile will exhibit varying functional and aesthetic potentials and properties. One of the main advantages that set knitted textiles above woven textiles, for structures such as the ones researched in this thesis, is the possibility to easily incorporate different combinations of yarns and stitches and vary them across the surface of the textile. This also includes increasing and decreasing the number of stitches on each row (course) of the textile.

Four performative potentials of knitted textiles are particularly interesting for this research, and the design of architecture that interact with the wind:

1. Three-dimensional volume variation. The possibility to three-dimensionally shape the knitted textile without cutting or sewing, is an advantage in terms of freedom in design, artistically as well as in ability to adapt to external conditions. As such it allows for the knit to be shaped into geometrically altering volumes when wind is applied (as wind is naturally varying). In combination with digital tools and CNC knitting machines, it is possible to produce a ready-to-

be-applied textile that is both aesthetically interesting and suited for the site-specific geometrical conditions.

2. Porosity, texture, and opacity variation. With knits, it is possible to vary the porosity, texture and transparency across the surface of the textile, through specific arrangements of the knitted yarns. Thereby, to some extent, it is possible to control the amount of wind force that is applied to the different sections of the knit as well as the wind reduction it achieves. Further, the textural and porosity variance creates opportunities to affect the aesthetic and haptic human experience but also modulate daylight and generate acoustic damping effects. Based on the explorations of the knitted prototypes in this research, and the response from the exhibitions, it became evident that this type of knitted structures invites to a multi-sensory experience.

3. Structural performance characteristics, on a micro-level. The knitted structure's ability to adapt to and reshape under applied load allows for a redistribution of strains in the yarns. As the yarn, and in extension the textile, is held in place by friction between the loops in the knit, the textile can substantially deform and locally stretch out, without breaking. This ability can be utilised, or it could be "restrained" through the choice of stitches/pattern (with or without adding more yarns in the pattern). Additionally, when it comes to a kinetic wind application the knit's ability to adapt and reshape itself is ideal.

4. Adaptability and stretch. The knitted structure tends to increase its porosity when stretched. Thus, a knitted windbreak structure can, to some extent, self-regulate and allow a higher percentage of the wind to pass through the textile as the wind load increase. Thereby the strain on the structure itself, as well as the anchoring of it, is reduced. It is reasonable to expect that this type of structure can cope with a wider spectrum of wind velocities, compared to static structures. From an aesthetical point, the adaptation of stretch and resulting variation of porosity, according to wind loads, generates interest through altering the shape and visual transparency of the structure. Thus, the design will have a different appearance both from day to day, as well as with the more instant fluctuations of the wind.

To put this into context, these aspects could be discussed in relation to the exhibited large prototype (Figure 4-2, Figure 4-8 to Figure 4-10), and how its design could be iterated for a windbreak, of a similar size, at a specific site. Such designs should take multiple objectives into account simultaneously. For instance, the fractal tree pattern can be replaced with a pattern based on a desired force distribution to fit specific mounting possibilities. In addition, the designed knitted textile's loop-sizes, and in extension its porosity, should also be considered in terms of a desired wind reduction. Varying the porosity also means varying the transparency of the structure, its three-dimensional shape, and its dimensional stability. These aspects must also be considered in relation to other site-specific desires, such as visual communication or a wish to mask or hide objects or views, the need for shade, effects of shadow patterns, the haptic experience of the structure, and the need to define or divide the space. Aesthetical ideas and ambitions about shape, colours, patterns, haptic sensations etc., should also be included in the design to generate beautiful as well as better-performing architecture. Thus, there are multiple, linked, performative qualities and possibilities that need to be considered and weighed against each other simultaneously. Outside the scope of this research there are also additional properties that are beneficial in terms of architectural performance:

5. Grading stiffness and load-carrying capacity. Through stitch choice, dimensional stability and stiffness can be increased at desired patches of the knitted textile, or channels added to insert additional stiffeners (rods, cables, etc.). Thereby increasing the structure's capacity to carry loads. Additionally, it is also a way to alter or control the three-dimensional shape and moving pattern of the structure. These parameters can also be graded to control the stretch of the textile. Thus, also regulate the change in three-dimensional appearance, ranging from a flat surface to bulbous and voluminous and if the knit should hang loosely or not without wind.

6. Openings in the knitted textile. Openings can be incorporated into the pattern, to act as windows, passages, etc. These can be holes in the middle of the knit or edges arching in, with various shapes and sizes. Allowing for multiple design options in terms of defining, dividing, and connecting spaces, as well as fitting the knitted textile into existing architecture or nature.

7. Grading the textile to optimise for shade and daylight. With the patterning possibilities that the knitted textile brings, it is possible to grade or control how much sun that passes through the textile. This could be done through simple linear grading or intricate patterns, allowing for control of thermal comfort as well as possibilities to generate decorative structures and shadow patterns.

8. Variations in colour and pattern. Increased aesthetical interest can be achieved through varying patterns and colours across the surface. This includes visual expressions with colour variation, but also patterning transparency as well as the surface structure generating a tactile experience. All of which could be combined through patterns, to achieve a fuller experience.

9. Yarns and materials. Through the selection of yarn material and types, in combination with stitch composition, the behaviour, appearance and properties of the textile could be drastically altered. Effects include texture and tactility of the knitted surface, as well as stiffness and elasticity, shrinkage, etc. As an example, with a yarn that easily absorbs moisture the density of the textile will change during humid or rainy days, which will affect its appearance and moving pattern. This in combination with wind could become a disturbing element for pedestrians, or potentially generate an intriguing display, like a water feature, depending on the design, position and materials.

10. Ability to adapt to existing architecture. Virtually endless shaping possibilities make the knitted textile possible to fit and adapt to any existing built structure or natural element. Making knitted textiles useful for increasing interest in urban spaces or as a facelift to buildings, facades or places.

With that said, even though knitted textiles have several properties that make them interesting for architectural applications, it is not suitable material for every structure. Without adding additional elements or in some way fixating the structure it cannot stand by itself. Deformable knitted structures need to be designed in combination with a structure(s) that can establish sufficient stiffness to act as a necessary outer or inner frame. It should also be pointed out that, while the properties and potentials listed above apply to knitted textiles, there are limitations in how they can be combined. Even so, this still leaves a lot of potential that could be utilised to generate intriguing new architecture.

5.4 Suggestions for future research

In this thesis, the presented application for textile architecture, as loosely fitted, knitted architectural windbreaks, interacting with the wind in urban space, is put forward as a new concept. It shows that such an application has a high potential to improve both aesthetics and wind comfort in urban spaces. However, the research should be seen mainly as a foundation on which future explorations can be built. As such, there are many future directions for knowledge building. The suggestions for future research presented here will, therefore, be limited to aspects that are important to consider for the realization of a working windbreak.

Firstly, the parameters that were the focus of this thesis pattern, stitches, and porosity, and how these factors affect the shape and wind, should be further explored. It would be useful to have more detailed information about all these aspects and what finetuning of these will bring to the design. Furthermore, it is interesting to know more about the effects of the curvature, shape, and motion of the knits, in relation to wind comfort. The bulging of the textile is likely contributing to the wider range of wind angles in which the prototypes were effective in terms of reducing wind velocities. But could this parameter be further developed and how much is this contributing to reducing perpendicular wind? In terms of the kinetic effects, the textile is extracting energy from the wind and is thereby set in motion. This exchange in energy will affect the motion of the wind, but it remains to be further studied whether it is noticeable or not. There is even a possibility that a fluctuation of a textile, in some settings, could increase uncomfortable turbulence.

Additionally, on the note of energy exchange, textile designers and researchers are developing different types of textiles that can be used to turn motion into electric energy. Combining that with loosely fitted, knitted architectural windbreaks interacting with the wind, there is also a possibility that such structures could be used to harvest wind energy in the future. Other types of energy production, such as piezo-electrics and wave energy, are also possible combinations.

During the studies presented in this thesis, it was observed that the knitted textile seems to have less tendency to flutter in the wind compared to some woven textiles. It is reasonable to think that the knitted structure’s ability to stretch and locally deform, in combination with its porosity, is decreasing flutter. As flutter could generate noise as well as strain the textile, it would be worth investigating this further.

In terms of wind reduction, it would be worth studying if it is possible to achieve a graded wind reduction through the pattern design, by utilising the knits possibility to vary the porosity and/or the wind-induced shape. For these explorations, digital tools would be important. It is suggested to use a combination of simulation methods, and models, for these (both particle and mesh-based), and to, sometimes, simplify the digital models to static representations. As such simulations will be computationally heavy it is also important to consider the required level of detail needed for each simulation. As real wind will be varying in direction as well as velocity, exact wind patterns and behaviour are likely not necessary in terms of pattern design. It is, however, important to know that the generated results are not incorrect. Data from the presented wind tunnel tests (paper C), could be used as a benchmark for digital simulation models.

Examples of other decisions and aspects to consider when designing a knitted structure like a windbreak that will influence the resulting design are:

- Mounting options. Should channels or holes for mast, struts, or cables be included in the knitting pattern? Should the edges of the textile be free to move or stiffened in some way (e.g., through edge cables)?

- The pattern design in terms of a need for pockets, channels, or holes. For mounting but also for visual appearance, obstacles on site, windows, or passages, etc.

- Type of yarn and yarn material. This includes decisions about durability, fire safety, etc.

- Desired stiffness. Is there a need for extra stiffening in sections of the knit? Should that then be achieved through increased density of stitches, another type of stitch, or additional yarn in the same or different materials? (Or even through weaving in or inserting other structural elements, such as cables or struts?)

- Size possibilities and restrictions. Should two or more sheets of textiles be combined, how is that best solved?

- Desired and expected wind. What winds should the structure be designed for, and how much wind reduction is desired? Is there a risk of too high winds and thus a need for the structure to be disassembled on such occasions?

- Acoustics. Is there a risk that the motion of the textile will cause noise? Could the knit be used to absorb sound?

Glossary

CFD
Computational Fluid Dynamics

CNC
Computer Numerical Control
The automated control of machining tools such as drills, 3D printers, or knitting machines by means of a computer

FEM
Finite Element Method

FVM
Finite Volume Method

FSI
Fluid Structure Interaction

Macro-level
Here referring to the scale of the whole textile or structure

Micro-level
In relation to knitted textiles, this is referring to the scale of the stitches/loops

SPH
Smoothed Particle Hydrodynamics.
A mesh-free simulation method for solid mechanics and fluid flow

Tensile structures
Pretensioned cable-net or membrane structures

Textile
Here defined as a material that:

1. Have a thickness that is much smaller than length and breadth (z << x or y).
2. Consists of fibres or structural members that in some way interlock and would unravel if one “tread” were to break.
3. Have very low bending stiffness.

Wind
Naturally occurring airflow

Figure Credits

Unless otherwise noted below, the illustration, diagram and photos are by Erica Hörteborn

Figure 2-2 Model produced during a workshop, held at Chalmers University of technology 2018, by Emil Adiels, Tim Finlay, Isak Näslund, Puria Safari and Chris Williams. Photograph by Emil Adiels.

Figure 2-3 Photos by the author, also in:
Hörteborn, E., Zboinska, M. A., Chernoray, V., & Ander, M. (2023). Architectural Knitted Windbreaks for Improved Wind Comfort in the City: A Wind Tunnel Study of Custom-Designed Porous Textile Screens. Buildings, 13(1), Article 1. https://doi.org/10.3390/buildings13010034

Figure 2-4 Christo and Jeanne-Claude, Running Fence, Sonoma and Marin Counties, California, 1972-76.
Photo: Jeanne-Claude © 1976 Christo and Jeanne-Claude Foundation.
Printed with permission

Figure 2-5 Photo by Linda Wallander

Figure 2-6 Photo by Ida Hesselmark

Figure 2-7 Illustration of weave made by Linda Wallander and Malin Borgny (slightly adjusted). Reprinted with permission, from:
Borgny, M., & Wallander, L. (2019). Textile Informed Structures—How to Braid a Roof Translating the logic of textile structure into the scale of architecture [MSc thesis]. Chalmers University of Technology.

Figure 2-8 Illustration by the author (slightly edited) previously published in:
Hörteborn, E., & Zboinska, M. A. (2021). Exploring expressive and functional capacities of knitted textiles exposed to wind influence. Frontiers of Architectural Research, 10(3), https://doi.org/10.1016/j.foar.2021.02.003

Figure 2-9 Illustration by the author (slightly edited) previously published in:
Hörteborn, E., & Zboinska, M. A. (2021). Exploring expressive and functional capacities of knitted textiles exposed to wind influence. Frontiers of Architectural Research, 10(3), https://doi.org/10.1016/j.foar.2021.02.003

Figure 2-10 Photo by the author also in:
Hörteborn, E., Zboinska, M. A., Chernoray, V., & Ander, M. (2023). Architectural Knitted Windbreaks for Improved Wind Comfort in the City: A Wind Tunnel Study of Custom-Designed Porous Textile Screens. Buildings, 13(1), Article 1. https://doi.org/10.3390/buildings13010034

Figure 2-11 Left and right, photo by Linda Wallander

Figure 2-12 Photo and illustration by the author previously published in:
Hörteborn, E., & Zboinska, M. A. (2021). Exploring expressive and functional capacities of knitted textiles exposed to wind influence. Frontiers of Architectural Research, 10(3), Article 3. https://doi.org/10.1016/j.foar.2021.02.003

Figure 2-13 Photo and illustration by the author previously published in:
Hörteborn, E., & Zboinska, M. A. (2021). Exploring expressive and functional capacities of knitted textiles exposed to wind influence. Frontiers of Architectural Research, 10(3), Article 3. https://doi.org/10.1016/j.foar.2021.02.003

Figure 2-14 Photo and illustration by the author previously published in:
Hörteborn, E., & Zboinska, M. A. (2021). Exploring expressive and functional capacities of knitted textiles exposed to wind influence. Frontiers of Architectural Research, 10(3), Article 3. https://doi.org/10.1016/j.foar.2021.02.003

Figure 2-15 Photo and illustration by the author previously published in:
Hörteborn, E., & Zboinska, M. A. (2021). Exploring expressive and functional capacities of knitted textiles exposed to wind influence. Frontiers of Architectural Research, 10(3), Article 3. https://doi.org/10.1016/j.foar.2021.02.003

Figure 2-16 Photo by the author previously published in:
Hörteborn, E., & Zboinska, M. A. (2021). Exploring expressive and functional capacities of knitted textiles exposed to wind influence. Frontiers of Architectural Research, 10(3), Article 3. https://doi.org/10.1016/j.foar.2021.02.003

Figure 2-17 Illustration by the author previously published in:
Hörteborn, E., & Zboinska, M. A. (2021). Exploring expressive and functional capacities of knitted textiles exposed to wind influence. Frontiers of Architectural Research, 10(3), https://doi.org/10.1016/j.foar.2021.02.003

Figure 2-18 Image by the author previously published in:
Hörteborn, E., & Zboinska, M. A. (2021). Exploring expressive and functional capacities of knitted textiles exposed to wind influence. Frontiers of Architectural Research, 10(3), https://doi.org/10.1016/j.foar.2021.02.003

Figure 2-19 Image by the author previously published in:
Hörteborn, E., & Zboinska, M. A. (2021). Exploring expressive and functional capacities of knitted textiles exposed to wind influence. Frontiers of Architectural Research, 10(3), https://doi.org/10.1016/j.foar.2021.02.003

Figure 2-20 Image by the author previously published in:
Hörteborn, E., & Zboinska, M. A. (2021). Exploring expressive and functional capacities of knitted textiles exposed to wind influence. Frontiers of Architectural Research, 10(3), https://doi.org/10.1016/j.foar.2021.02.003

Figure 2-22 Illustration by the author, also in:
Hörteborn, E., Zboinska, M. A., Chernoray, V., & Ander, M. (2023). Architectural Knitted Windbreaks for Improved Wind Comfort in the City: A Wind Tunnel Study of Custom-Designed Porous Textile Screens. Buildings, 13(1), Article 1. https://doi.org/10.3390/buildings13010034

Figure 2-24 Image from simulation created by Chris Williams, using a SPH approach.
Video retrieved: 17-09-2019, from: http://structure-geometry.eu/.
Re-printed with permission.

Figure 2-25 Illustration created by Jens Olsson, slightly edited, and reprinted with permission.
Olsson, J. (2022). Digital shaping: Meshless computational methods for form generation in architectural design [Chalmers University of Technology]. https://research.chalmers.se/en/publication/532425

Figure 3-4 Photo by Linda Wallander

Figure 3-5 Photo by Linda Wallander and Malin Borgny

Figure 3-6 Image by the author previously published in:
Hörteborn, E., & Zboinska, M. A. (2021). Exploring expressive and functional capacities of knitted textiles exposed to wind influence. Frontiers of Architectural Research, 10(3), https://doi.org/10.1016/j.foar.2021.02.003

Figure 3-7 Poster and still image from video by SEART

Figure 3-9 Photo by the author, also in:
Hörteborn, E., Zboinska, M. A., Chernoray, V., & Ander, M. (2023). Architectural Knitted Windbreaks for Improved Wind Comfort in the City: A Wind Tunnel Study of Custom-Designed Porous Textile Screens. Buildings, 13(1), Article 1. https://doi.org/10.3390/buildings13010034

Figure 4-1 digital model produced by workshop participants and photo by the author previously published in:
Hörteborn, E., Zboinska, M., Dumitrescu, D., Williams, C., & Felbrich, B. (2019). Architecture from textiles in motion. Form and Force, 2316–2323.

Figure 4-2 Photo by the author previously published in:
Hörteborn, E., & Zboinska, M. A. (2021). Exploring expressive and functional capacities of knitted textiles exposed to wind influence. Frontiers of Architectural Research, 10(3), https://doi.org/10.1016/j.foar.2021.02.003

Figure 4-3 chart produced by the author, also in:
Hörteborn, E., Zboinska, M. A., Chernoray, V., & Ander, M. (2023). Architectural Knitted Windbreaks for Improved Wind Comfort in the City: A Wind Tunnel Study of Custom-Designed Porous Textile Screens. Buildings, 13(1), Article 1. https://doi.org/10.3390/buildings13010034

Figure 4-4 chart produced by the author, also in:
Hörteborn, E., Zboinska, M. A., Chernoray, V., & Ander, M. (2023). Architectural Knitted Windbreaks for Improved Wind Comfort in the City: A Wind Tunnel Study of Custom-Designed Porous Textile Screens. Buildings, 13(1), Article 1. https://doi.org/10.3390/buildings13010034

Figure 4-5 chart produced by the author, also in:
Hörteborn, E., Zboinska, M. A., Chernoray, V., & Ander, M. (2023). Architectural Knitted Windbreaks for Improved Wind Comfort in the City: A Wind Tunnel Study of Custom-Designed Porous Textile Screens. Buildings, 13(1), Article 1. https://doi.org/10.3390/buildings13010034

Figure 4-6 chart produced by the author, also in:
Hörteborn, E., Zboinska, M. A., Chernoray, V., & Ander, M. (2023). Architectural Knitted Windbreaks for Improved Wind Comfort in the City: A Wind Tunnel Study of Custom-Designed Porous Textile Screens. Buildings, 13(1), Article 1. https://doi.org/10.3390/buildings13010034

Figure 4-7 illustrated photos by the author, also in:
Hörteborn, E., Zboinska, M. A., Chernoray, V., & Ander, M. (2023). Architectural Knitted Windbreaks for Improved Wind Comfort in the City: A Wind Tunnel Study of Custom-Designed Porous Textile Screens. Buildings, 13(1), Article 1. https://doi.org/10.3390/buildings13010034

Figure 4-8. Photo by Margarita Matiz Bergfeldt, SEART

References

Ahlquist, S. (2015). Social sensory architectures: Articulating textile hybrid structures for multi-sensory responsiveness and collaborative play. *Computational Ecologies: Design in the Anthropocene: Proceedings of the 35th Annual Conference of the Association for Computer Aided Design in Architecture*, *2*, 263–273. http://papers.cumincad.org/data/works/att/acadia15_263.pdf

Ahlquist, S. (2016). Sensory material architectures: Concepts and methodologies for spatial tectonics and tactile responsivity in knitted textile hybrid structures. *International Journal of Architectural Computing*, *14*(1), 63–82. https://doi.org/10.1177/1478077115625525

Akiwowo, K., Dennis, L., Weaver, G., & Bingham, G. (2019). The Living Archive: Facilitating Textile Design Research at Undergraduate Level Through Collaboration, Co-Creation and Student Engagement. *Journal of Textile Design Research and Practice*, *7*(2), 155–193. https://doi.org/10.1080/20511787.2019.1593297

Araújo, M., Fangueiro, R., & Hong, H. (2004). Modelling and simulation of the mechanical behaviour of weft-knitted fabrics for technical applications: Part III: 2D hexagonal FEA model with non-linear truss elements. *AUTEX Research Journal*, *Vol. 4*(1). http://repositorium.sdum.uminho.pt/

Armijos, S. J. (2008). *Fabric architecture: Creative resources for shade, signage, and shelter* (1st ed). W.W. Norton.

Aynsley, R. M. (1999). Shape and Flow: The Essence of Architectural Aerodynamics. *Architectural Science Review*, *42*(2), 69–74. https://doi.org/10.1080/00038628.1999.9696854

Bahadori, M. N. (1978). Passive Cooling Systems in Iranian Architecture. *Scientific American*, *238*(2), 144–155. JSTOR.

Barnes, M. R. (1999). Form Finding and Analysis of Tension Structures by Dynamic Relaxation. *International Journal of Space Structures*, *14*(2), 89–104. https://doi.org/10.1260/0266351991494722

Barozzi, M., Lienhard, J., Zanelli, A., & Monticelli, C. (2016). The sustainability of adaptive envelopes: Developments of kinetic architecture. *Procedia Engineering*, *155*, 275–284.

Bender, J., Müller, M., Otaduy, M. A., & Teschner, M. (2013). Position-based Methods for the Simulation of Solid Objects in Computer Graphics. *Eurographics (STARs)*, 1–22.

Bitog, J. P., Lee, I.-B., Hwang, H.-S., Shin, M.-H., Hong, S.-W., Seo, I.-H., Mostafa, E., & Pang, Z. (2011). A wind tunnel study on aerodynamic porosity and windbreak drag. *Forest Science and Technology*, *7*(1), 8–16. https://doi.org/10.1080/21580103.2011.559939

Blocken, B., Stathopoulos, T., & van Beeck, J. P. A. J. (2016). Pedestrian-level wind conditions around buildings: Review of wind-tunnel and CFD techniques and their accuracy for wind comfort assessment. *Building and Environment*, *100*, 50–81. https://doi.org/10.1016/j.buildenv.2016.02.004

Brečević, G., Brečević, R., Eskilsson, T., Francke, V., Gaetano, S. de, Hörteborn, E., Källman, J. F., König, L. J., Ljungström, H., Matiz, C., Moog, G., Tran, L., Norgren, T., Ollas, F., Sörenson, A., Stampe, E., Tamboly, A., Terry, J., Toijanen, A., & Wallander, T. (2022). *In Motion* [SEART Group exhibition, Stockholm, Sweden]. http://seart.se/IN_MOTION_PR.html

Brocklehurst, S. (2013, June 3). Faulty tower: The £10m white elephant. *BBC News*. https://www.bbc.com/news/uk-scotland-22509056

Broudy, E. (1993). *The Book of Looms: A History of the Handloom from Ancient Times to the Present*. UPNE.

Cermak, J. E. (1975). Applications of Fluid Mechanics to Wind Engineering—A Freeman Scholar Lecture. *Journal of Fluids Engineering*, *97*(1), 9–38. https://doi.org/10.1115/1.3447225

Chen, J., Huang, Y., Zhang, N., Zou, H., Liu, R., Tao, C., Fan, X., & Wang, Z. L. (2016). Micro-cable structured textile for simultaneously harvesting solar and mechanical energy. *Nature Energy*, *1*(10), Article 10. https://doi.org/10.1038/nenergy.2016.138

Chilton, J. (2000). *Heinz Isler*. Telford.

Chilton, J., & Chuang, C.-C. (2017). Rooted in Nature: Aesthetics, Geometry and Structure in the Shells of Heinz Isler. *Nexus Network Journal*, *19*(3), 763–785. https://doi.org/10.1007/s00004-017-0357-5

Cirio, G., Lopez-Moreno, J., & Otaduy, M. A. (2017). Yarn-Level Cloth Simulation with Sliding Persistent Contacts. *IEEE Transactions on Visualization and Computer Graphics*, *23*(2), 1152–1162. https://doi.org/10.1109/TVCG.2016.2592908

Cornelis, W. M., & Gabriels, D. (2005). Optimal windbreak design for wind-erosion control. *Journal of Arid Environments*, *61*(2), 315–332. https://doi.org/10.1016/j.jaridenv.2004.10.005

Creswell, J. W. (2014). *Research design: Qualitative, quantitative, and mixed methods approaches* (4th ed). SAGE Publications.

Cuvilliers, P. (2020). *The constrained geometry of structures: Optimization methods for inverse form-finding design* [Thesis, Massachusetts Institute of Technology]. https://dspace.mit.edu/handle/1721.1/127853

Davidson, L. (2018). *An Introduction to Turbulence Models*. Chalmers University of Technology. http://www.tfd.chalmers.se/~lada/postscript_files/kompendium_turb.pdf

Day, A. S. (1965). An introduction to dynamic relaxation(Dynamic relaxation method for structural analysis, using computer to calculate internal forces following development from initially unloaded state). *The Engineer*, *219*, 218–221.

Dean, D. (1996). *Museum Exhibition: Theory and Practice*. Taylor & Francis Group.

Deleuran, A. H., Schmeck, M., Quinn, G., Gengnagel, C., Tamke, M., & Thomsen, M. R. (2015). The Tower: Modelling, Analysis and Construction of Bending Active Tensile Membrane Hybrid Structures. *Proceedings of IASS Annual Symposia*, *2015*(23), 1–13.

Dimmig, A. (2014). Fabricating a New Image: Imperial Tents in the Late Ottoman Period. *International Journal of Islamic Architecture*, *3*(2), 341–372. https://doi.org/10.1386/ijia.3.2.341_1

Dong, Z., Luo, W., Qian, G., & Wang, H. (2007). A wind tunnel simulation of the mean velocity fields behind upright porous fences. *Agricultural and Forest Meteorology*, *146*(1), 82–93. https://doi.org/10.1016/j.agrformet.2007.05.009

Dumitrescu, D., Nilsson, L., Persson, A., & Worbin, L. (2014). Smart textiles as raw materials for design. *Proceedings Shape Shifting*.

Eggler, M. (2009). Divide and Conquer: Ludwig Mies van der Rohe and Lilly Reich's Fabric Partitions at the Tugendhat House. *Studies in the Decorative Arts*, *16*(2), 66–90. https://doi.org/10.1086/652505

Elnokaly, A. M. (2014). CFD Analysis of tensile conical membrane structures as microclimate modifiers in hot arid regions. *Civil Engineering and Architecture*, *2*(2), 92–102. https://doi.org/DOI: 10.13189/cea.2014.020204

Felbrich, B. (2020, February 21). *Flexhopper* [Internet hosting for software development]. GitHub: FlexCLI. https://github.com/HeinzBenjamin/FlexCLI (Original work published 2017)

Foqué, R. (2010). *BUILDING KNOWLEDGE IN ARCHITECTURE*. ASP.

Fox, M. (2016). *Interactive Architecture: Adaptive World*. Princeton Architectural Press.

Francis, N., & Sparkes, B. (2011). 3—Knitted textile design. In A. Briggs-Goode & K. Townsend (Eds.), *Textile Design* (pp. 55–87e). Woodhead Publishing. https://doi.org/10.1533/9780857092564.1.55

Fraser, M. (2013). *Design research in architecture: An overview*. Ashgate.

Freiberger, M. (2007). *Perfect buildings: The maths of modern architecture*. Plus+ magazine.

Fridh, K., Zetterblom, M., & Femenias, P. (2019). *Sound absorbing textile surfaces in the urban landscape – collaborative research in textile and architectural design*. Urban materiality.

Garcia, M. (2006). Prologue for a history and theory of architextiles. *Architectural Design*, *76*(6), 12–20.

Glück, M., Breuer, M., Durst, F., Halfmann, A., & Rank, E. (2001). Computation of fluid–structure interaction on lightweight structures. *Journal of Wind Engineering and Industrial Aerodynamics*, *89*(14–15), 1351–1368. https://doi.org/10.1016/s0167-6105(01)00150-7

Guan, D., Zhang, Y., & Zhu, T. (2003). A wind-tunnel study of windbreak drag. *Agricultural and Forest Meteorology*, *118*(1), 75–84. https://doi.org/10.1016/S0168-1923(03)00069-8

Gupta, S. S., Tan, Y. Y., Chia, P. Z., Pambudi, C. P., Yogiaman, C., & Tracy, K. J. (2019). Knit Tensegrity Shell. *Form and Force. Presented at the 60th Anniversary Symposium of the*

International Association for Shell and Spatial Structures IASS Symposium 2019 9th International Conference on Textile Composites and Inflatable Structures Structural Membranes 2019, *2019*, 523–531.

Hauberg, J. (2011). *Research by design: A research strategy*.

Heisler, G. M., & Dewalle, D. R. (1988). 2. Effects of windbreak structure on wind flow. *Agriculture, Ecosystems & Environment*, *22–23*, 41–69. https://doi.org/10.1016/0167-8809(88)90007-2

Henrysson, E. (2012). *Conceptual design and analysis of membrane structures* [Master thesis, Chalmers University of Technology]. http://publications.lib.chalmers.se/records/fulltext/168816/168816.pdf

Henrysson, E., Olsson, J., Fisher, A., & Ander, M. (2016). Conceptual design and analysis of membrane structures. *29th Nordic Seminar on Computational Mechanics*, S8:2:c.

Highum, K. (Director). (2016, October 19). *Janet Echelman: Breaking Down Boundaries with Art*. https://creativecloud.adobe.com/sv/discover/article/breaking-down-boundaries-with-art

Hörteborn, E. (2020). *Textile architecture informed by wind* [Chalmers University of Technology]. https://research.chalmers.se/en/publication/519746

Hörteborn, E. (2022). *(In)Formed by wind* [Exhibition]. SPARK Malmö. https://www.sparkmalmo.org/exhibitions

Hörteborn, E., & Zboinska, M. A. (2021). Exploring expressive and functional capacities of knitted textiles exposed to wind influence. *Frontiers of Architectural Research*, *10*(3), 669–691. https://doi.org/10.1016/j.foar.2021.02.003

Hörteborn, E., Zboinska, M. A., Chernoray, V., & Ander, M. (2023). Architectural Knitted Windbreaks for Improved Wind Comfort in the City: A Wind Tunnel Study of Custom-Designed Porous Textile Screens. *Buildings*, *13*(1), Article 1. https://doi.org/10.3390/buildings13010034

Hörteborn, E., Zboinska, M., Dumitrescu, D., Williams, C., & Felbrich, B. (2019). Architecture from textiles in motion. *Form and Force*, 2316–2323.

Hosain, M. L., Domínguez, J. M., Bel Fdhila, R., & Kyprianidis, K. (2019). Smoothed particle hydrodynamics modeling of industrial processes involving heat transfer. *Applied Energy*, *252*, 113441. https://doi.org/10.1016/j.apenergy.2019.113441

Hosain, M. L., & Fdhila, R. B. (2015). Literature Review of Accelerated CFD Simulation Methods towards Online Application. *Energy Procedia*, *75*, 3307–3314. https://doi.org/10.1016/j.egypro.2015.07.714

Janson, U. (1998). *Vägen till verket: Studier i arkitekt Jan Gezelius arbetsprocess*. Chalmers Univ. of Technology.

Kabošová, L., Foged, I., Kmeť, S., & Katunský, D. (2019). Hybrid design method for wind-adaptive architecture. *International Journal of Architectural Computing*, *17*(4), 307–322. https://doi.org/10.1177/1478077119886528

Kane, F., Akiwowo, K., Morgan, L., & Tyrer, J. (2015). Textile Design Research: From Chemistry to Craft Towards Sustainable Design Innovation. *The Value of Design Research, 11th International European Academy of Design Conference*.

Kirstein, T. (2013). *Multidisciplinary Know-How for Smart Textiles Developers*. Elsevier Science & Technology.

Koch, K.-M., Habermann, K. J., & Forster, B. (2004). *Membrane structures: Innovative building with film and fabric*. Prestel Publishing.

Kormaníková, L., Achten, H., Kopřiva, M., & Kmeť, S. (2018). Parametric wind design. *Frontiers of Architectural Research*, *7*(3), 383–394. https://doi.org/10.1016/j.foar.2018.06.005

Kotnik, T., & Schwartz, J. (2011). The Architecture of Heinz Isler. *Journal of the International Association for Shell and Spatial Structures*, *52*(3), 185–190.

Kronenburg, R. (2015). 1—Introduction: The development of fabric structures in architecture. In J. I. de Llorens (Ed.), *Fabric Structures in Architecture* (pp. 1–21). Woodhead Publishing. https://doi.org/10.1016/B978-1-78242-233-4.00001-2

Kronenburg, Robert. (2014). *Architecture in motion: The history and development of portable building*. Routledge, Taylor & Francis Group.

Krüger, S. (2009). *Textile architecture = Textile Architektur*. Jovis.

La Magna, R., Fragkia, V., Längst, P., Lienhard, J., Noël, R., Šinke Baranovskaya, Y., Tamke, M., & Ramsgaard Thomsen, M. (2018). Isoropia: An Encompassing Approach for the Design, Analysis and Form-Finding of Bending-Active Textile Hybrids. *Proceedings of IASS Annual Symposia*, *2018*, 1–8. https://www.researchgate.net/publication/326836434_Isoropia_an_Encompassing_Approach_for_the_Design_Analysis_and_Form-Finding_of_Bending-Active_Textile_Hybrids

Lackey, L. M. (2008). What is Exhibition for? Considering the Purposes of Art Display in a Saturday Art School Context. *Art Education*, *61*(4), 33–39. https://doi.org/10.1080/00043125.2008.11652066

Liddell, I., & Heppel, P. (2001). Turning with the Wind. *Civil Engineering (08857024)*, *71*(7), 38. Business Source Premier.

Liu, B., Qu, J., Zhang, W., Tan, L., & Gao, Y. (2014). Numerical evaluation of the scale problem on the wind flow of a windbreak. *Scientific Reports*, *4*(1), Article 1. https://doi.org/10.1038/srep06619

Liu, D., Christe, D., Shakibajahromi, B., Knittel, C., Castaneda, N., Breen, D., Dion, G., & Kontsos, A. (2017). On the role of material architecture in the mechanical behavior of knitted textiles. *International Journal of Solids and Structures*, *109*, 101–111. https://doi.org/10.1016/j.ijsolstr.2017.01.011

Liu, M. B., & Liu, G. R. (2010). Smoothed Particle Hydrodynamics (SPH): An Overview and Recent Developments. *Archives of Computational Methods in Engineering*, *17*(1), 25–76. https://doi.org/10.1007/s11831-010-9040-7

Liu, Y., Chai, H., & Yuan, P. F. (2020). Knitted Composites Tower—Design Research for Knitted Fabric Reinforced Composites Based on Advanced Knitting Technology. *Design in the Age of Humans - Proceedings of the 25th CAADRIA Conference*, 55–64. http://papers.cumincad.org/cgi-bin/works/paper/caadria2020_064

Llorens, J. I. de. (2015). *Fabric structures in architecture*. Woodhead Publishing.

McLaughlin, T. (2000). Sevicing the Dome Environment. In M. Barnes & M. Dickson (Eds.), *Widespan Roof Structures* (pp. 129–132). Thomas Telford.

Mehdizadeh, S., Zimmermann, A., & Tessmann, O. (2023). RotoColumn. In C. Gengnagel, O. Baverel, G. Betti, M. Popescu, M. R. Thomsen, & J. Wurm (Eds.), *Towards Radical Regeneration* (pp. 476–486). Springer International Publishing. https://doi.org/10.1007/978-3-031-13249-0_38

Michalski, A., Haug, E., Bradatsch, J., & Bletzinger, K.-U. (2009). Virtual Design Methodology for Lightweight Structures—Aerodynamic Response of Membrane Structures. *International Journal of Space Structures*, *24*(4), 211–221. https://doi.org/10.1260/026635109789968245

Michalski, A., Kermel, P., Haug, E., Löhner, R., Wüchner, R., & Bletzinger, K.-U. (2011). Validation of the computational fluid–structure interaction simulation at real-scale tests of a flexible 29 m umbrella in natural wind flow. *Journal of Wind Engineering and Industrial Aerodynamics*, *99*(4), Article 4. https://doi.org/10.1016/j.jweia.2010.12.010

Monticelli, C. (2015). *Membrane claddings in architecture* (pp. 449–480). www.scopus.com

Morgan, L., Kane, F., Tyrer, J., & Shen, J. (2018). Laser Shibori: A Digital Moulding Technique Supporting Circular Textile Design in Three Dimensions. *Journal of Textile Design Research and Practice*, *6*(1), 5–22. https://doi.org/10.1080/20511787.2018.1493836

Mossé, A. (2018). Gossamer timescapes: A design-led investigation into electro-active and light responsive textiles for the home. *Smart Materials and Structures*, *27*(7), 074009. https://doi.org/10.1088/1361-665x/aac537

Moya, R., Salim, F., & Williams, M. (2014). Pneumosense Project. *Rethinking Comprehensive Design: Speculative Counterculture, Proceedings of the 19th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2014)*, 369–378.

Moya, R., Salim, F., Williams, M., & Sharaidin, K. (2013). *Flexing Wind*. http://papers.cumincad.org/cgi-bin/works/paper/ecaade2013_169

Müller, M., Heidelberger, B., Hennix, M., & Ratcliff, J. (2007). Position Based Dynamics. *J. Vis. Comun. Image Represent.*, *18*(2), Article 2. https://doi.org/10.1016/j.jvcir.2007.01.005

Nimmo, A., Wright, S., & Coulson, D. (2011). Delivering London 2012: Temporary venues. *Proceedings of the Institution of Civil Engineers*, *164*(6), 59–64. ProQuest Central.

Norén Isaksen, T. (2013). Bernadotte Architecture: The Palaces and Capitals of King Carl XIV Johan of Sweden and of Norway. *The Court Historian*, *18*(1), 23–46. https://doi.org/10.1179/cou.2013.18.1.002

Olsson, J. (2022). *Digital shaping: Meshless computational methods for form generation in architectural design* [Doctoral Thesis, Chalmers University of Technology]. https://research.chalmers.se/en/publication/532425

Olsson, J., Ander, M., & Williams, C. J. K. (2021). The Use of Peridynamic Virtual Fibres to Simulate Yielding and Brittle Fracture. *Journal of Peridynamics and Nonlocal Modeling*, *3*(4), 348–382. https://doi.org/10.1007/s42102-021-00051-4

Olsson, J., Ander, M., & Williams, C. J. K. (2022). The numerical simulation of standard concrete tests and steel reinforcement using force flux peridynamics. *Structural Concrete*. https://doi.org/10.1002/suco.202200153

Otto, F., & Rasch, B. (2006). *Finding form: Towards an architecture of the minimal* (5th Edition). Axel Menges.

Otto, F., Vrachliotis, G., Kleinmanns, J., Kunz, M., & Frohn, M. (2017). *Frei Otto—Thinking by Modelling* (P. Kurz, Ed.; 1. Auflage). Spector Books.

Penwarden, A. D. (1973). Acceptable wind speeds in towns. *Building Science*, *8*(3), 259–267. https://doi.org/10.1016/0007-3628(73)90008-X

Piker, D. (2017, March 22). *Kangaroo solver*. Kangaroo Group on Grasshopper Forums. https://www.grasshopper3d.com/forum/topics/kangaroo-working?groupUrl=kangaroo&commentId=2985220%3AComment%3A1718553&groupId=2985220%3AGroup%3A120977

Popescu, M., Rippmann, M., Liew, A., Reiter, L., Flatt, R. J., Van Mele, T., & Block, P. (2020). Structural design, digital fabrication and construction of the cable-net and knitted formwork of the KnitCandela concrete shell. *Structures*. https://doi.org/10.1016/j.istruc.2020.02.013

Raine, J. K., & Stevenson, D. C. (1977). Wind protection by model fences in a simulated atmospheric boundary layer. *Journal of Wind Engineering and Industrial Aerodynamics*, *2*(2), 159–180. https://doi.org/10.1016/0167-6105(77)90015-0

Ramsgaard Thomsen, M., Sinke Baranovskaya, Y., Monteiro, F., Lienhard, J., La Magna, R., & Tamke, M. (2019). Systems for transformative textile structures in CNC knitted fabrics – Isoropia. *Softening the Habitats - Tensinet Symposium 2019*, 95–110. https://doi.org/10.30448/ts2019.3245.08

Ramsgaard Thomsen, M., & Tamke, M. (2009). Narratives of making: Thinking practice led research in architecture. *Communicating (by) Design 2009*, 1–8.

Ramsgaard Thomsen, M., Tamke, M., Karmon, A., Underwood, J., Gengnagel, C., Stranghöner, N., & Uhlemann, J. (2016). Knit as bespoke material practice for architecture. *Posthuman Frontiers: Data, Designers, and Cognitive Machines : Proceedings of the 36th Annual Conference of the Association for Computer Aided Design in Architecture*, 280–289. http://papers.cumincad.org/cgi-bin/works/Show?acadia16_280

Saadatian, O., Haw, L. C., Sopian, K., & Sulaiman, M. Y. (2012). Review of windcatcher technologies. *Renewable and Sustainable Energy Reviews*, *16*(3), 1477–1495. https://doi.org/10.1016/j.rser.2011.11.037

Sabin, J. E. (2013). myThread Pavilion: Generative Fabrication in Knitting Processes. *Adaptive Architecture: Proceedings of the 33th Annual Conference of the Association for Computer Aided Design in Architecture*, 347–354. http://papers.cumincad.org/data/works/att/acadia13_347.content.pdf

Sabin, J. E., Dillon Pranger, Clayton Binkley, Kristen Strobel, & Jingyang (Leo) Liu. (2018). Lumen. *Recalibration: On Imprecision and Infidelity: Proceedings of the 38th Annual Conference of the*

Association for Computer Aided Design in Architecture, 444–455. http://papers.cumincad.org/cgi-bin/works/Show?_id=acadia18_444

Santina Di Salvo. (2018). Kinetic Solutions for Responsive and Communicative Building Skin. *Advanced Materials Research*, *1149*, 86–97. https://doi.org/10.4028/www.scientific.net/AMR.1149.86

Scherer, A. L. (2021). *CONCRETE FORM[ing]WORK: Design, Fabrication, Simulation and Correlation of Parametrically Patterned Flexible Formwork and Concrete*.

Schmeck, M., & Gengnagel, C. (2016). Calibrated Modeling of Knitted Fabric as a Means of Simulating Textile Hybrid Structures. *Procedia Engineering*, *155*, 297–305. https://doi.org/10.1016/j.proeng.2016.08.032

Schön, D. A. (2003). *The reflective practitioner: How professionals think in action.* (Main Library Johanneberg q Schön; Repr.[= New ed.]). Arena; Chalmers Library Print Collection.

Schumacher, M., Schaeffer, O., Vogt, M.-M., & Scheuermann, A. (2010). *MOVE - Bewegliche Bauteile und Komponenten in der Architektur: Architecture in Motion - Dynamic Components and Elements*. Walter de Gruyter GmbH.

Scott, J. (2012). Knitting Moves: Bio-inspired Transformable Textiles for knitted Architecture | Studies in Material Thinking. *Studies in Material Thinking*, *07*. https://www.materialthinking.org/papers/77

Scott, J. (2016). Programmable Knitting. *Posthuman Frontiers: Data, Designers, and Cognitive Machines : Proceedings of the 36th Annual Conference of the Association for Computer Aided Design in Architecture*, 276–281. http://eprints.whiterose.ac.uk/106974/

Semper, G. (2010). *The four elements of architecture and other writings.* Cambridge University Press.

Shadloo, M. S., Oger, G., & Le Touzé, D. (2016). Smoothed particle hydrodynamics method for fluid flows, towards industrial applications: Motivations, current state, and challenges. *Computers & Fluids*, *136*, 11–34. https://doi.org/10.1016/j.compfluid.2016.05.029

Shelley, M. J., & Zhang, J. (2011). Flapping and bending bodies interacting with fluid flows. *Annual Review of Fluid Mechanics*, *43*, 449–465.

Sinke, Y., Thomsen, M. R., Tamke, M., & Seskas, M. (2022). Strategies for Encoding Multi-dimensional Grading of Architectural Knitted Membranes. In C. Gengnagel, O. Baverel, G. Betti, M. Popescu, M. R. Thomsen, & J. Wurm (Eds.), *Towards Radical Regeneration* (pp. 528–542). Springer International Publishing. https://doi.org/10.1007/978-3-031-13249-0_42

Spencer, D. J. (2001). *Knitting Technology: A Comprehensive Handbook and Practical Guide*. Taylor & Francis.

Stathopoulos, T. (2009). Wind and comfort. *5th European and African Conference on Wind Engineering, EACWE 5, Proceedings*. https://www.semanticscholar.org/paper/Wind-and-Comfort-Stathopoulos/cdc2942e6d5f37737992c4c2db0c2373620fed81

Tamke, M., Sinke Baranovskaya, Y., Monteiro, F., Lienhard, J., La Magna, R., & Ramsgaard Thomsen, M. (2021). Computational knit – design and fabrication systems for textile structures with customised and graded CNC knitted fabrics. *Architectural Engineering and Design Management*, *17*(3–4), 175–195. https://doi.org/10.1080/17452007.2020.1747386

Tennekes, H., & Lumley, J. L. (1972). *A first course in turbulence*. MIT Press.

Thomsen, M. R., & Bech, K. (2011). FCJ-130 Embedding response: Self production as a model for an actuated architecture. *The Fibreculture Journal*, *19*, 31–46.

Veenendaal, D., West, M., & Block, P. (2011). History and overview of fabric formwork: Using fabrics for concrete casting. *Structural Concrete*, *12*(3), 164–177. https://doi.org/10.1002/suco.201100014

Verbeke, J. (2013). This is research by design. In *Design research in architecture: An overview.* (pp. 137–159). Ashgate. https://doi.org/10.4324/9781315258126-8

Wang, D., & Groat, L. N. (2013). *Architectural research methods* (Second Edition). John Wiley & Sons, Incorporated.

Wang, H. (2015). A chebyshev semi-iterative approach for accelerating projective and position-based dynamics. *ACM Transactions on Graphics*, *34*(6), 246:1-246:9. https://doi.org/10.1145/2816795.2818063

Wensveen, S., & Matthews, B. (2014). Prototypes and Prototyping in Design Research. In *Routledge Companion to Design Research* (Paul A. Rodgers and Joyce Yee, pp. 262–276). Routledge.

West, M. (2016). *The fabric formwork book: Methods for building new architectural and structural forms in concrete.* Routledge.

Williams, C. (1990). Travelling waves and standing waves on fabric structures. *Structural Engineer*, *68*(21/6).

Wu, Y.-C., Yang, A.-S., Tseng, L.-Y., & Liu, C.-L. (2011). Myth of ecological architecture designs: Comparison between design concept and computational analysis results of natural-ventilation for Tjibaou Cultural Center in New Caledonia. *Energy and Buildings*, *43*(10), 2788–2797. https://doi.org/10.1016/j.enbuild.2011.06.035

Zboinska, M. A. (2021). Architectural Research in Hybrid Mode: Combining Diverse Methods within Design-Based Architectural Research Inquiry. *ARENA Journal of Architectural Research*, *6*(1), 7. https://doi.org/10.5334/ajar.291

Zhou, X. H., Brandle, J. R., Mize, C. W., & Takle, E. S. (2005). Three-dimensional aerodynamic structure of a tree shelterbelt: Definition, characterization and working models. *Agroforestry Systems*, *63*(2), 133–147. https://doi.org/10.1007/s10457-004-3147-5

Equations for fluid dynamics

The mathematical description of wind is given by the Navier–Stokes equations:

Conservation of mass:

$$\frac{D\rho}{Dt} = \frac{\partial \rho}{\partial t} + \mathbf{v} \cdot \nabla \rho = -\rho \nabla \cdot \mathbf{v} = 0 \tag{a}$$

Conservation of momentum:

$$\underbrace{\overbrace{\rho}^{\text{“mass”}} \frac{D\mathbf{v}}{Dt}}_{\text{acceleration}} = \underbrace{\nabla \cdot \left\{ \left(-p + \left(\zeta - \frac{2}{3}\mu \right) \nabla \cdot \mathbf{v} \right) \mathbf{I} + 2\mu \frac{1}{2} \left(\nabla \mathbf{v} + (\nabla \mathbf{v})^{\mathrm{T}} \right) \right\}}_{\text{Internal force}} + \underbrace{\rho g}_{\text{external force}} \tag{b}$$

Where p is the pressure, μ is the viscosity and ζ is the bulk viscosity. The density, ρ, is constant for an incompressible fluid (as in the case of wind around buildings). (The del operator, ∇, written out in Table A.)

As can be seen in the term $\nabla \cdot \mathbf{v}$ is a scalar describing the change in velocity in the three main direction, or that mass is conserved. $\nabla\mathbf{v}$ is the change in velocity all velocity components in the x, y and z-direction (i.e. 9 components). The term $\frac{1}{2}\left(\nabla \mathbf{v} + (\nabla \mathbf{v})^{\mathrm{T}} \right)$ in equation (b) is the rate of shear strain, $\boldsymbol{\gamma}$:

$$\boldsymbol{\gamma} = \frac{1}{2}\left(\nabla \mathbf{v} + (\nabla \mathbf{v})^{\mathrm{T}} \right) = \frac{1}{2}\left(\frac{\partial v_y}{\partial x} + \frac{\partial v_x}{\partial y} \right) \tag{c}$$

This could be compared to the vorticity equation:

$$\boldsymbol{\omega} = \frac{1}{2}\left(\nabla \mathbf{v} - (\nabla \mathbf{v})^{\mathrm{T}} \right) = \frac{1}{2}\left(\frac{\partial v_y}{\partial x} - \frac{\partial v_x}{\partial y} \right) \tag{d}$$

Figure A aims to explain vorticity, through a 2d example (inspired by (Williams, 1990)). You can see that by adding the two circled expressions (similar to equation (c)) the fluid gets “squeezed”, resulting in shear strain. By subtracting one term you create a rotation, resulting in vorticity (equation (d)).

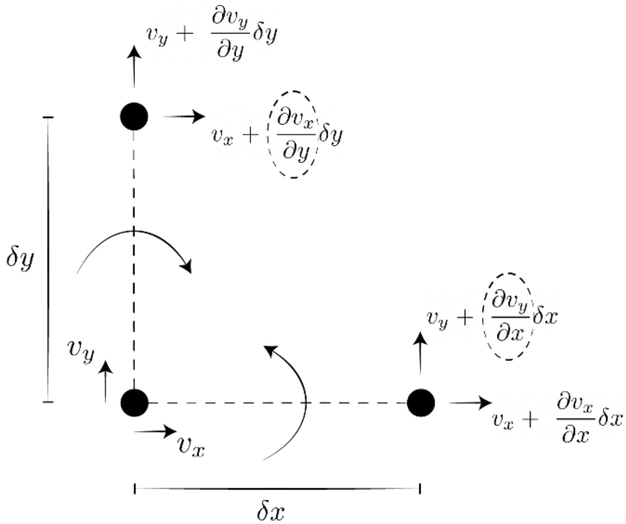


Figure A illustrating three fluid particles and their velocities at different positions. Note that the circled expressions are the ones that effects the rate of shear strain and vorticity, it is also the terms that rotates the fluid particles.

Table A The del operator

The del operator, ∇:

$$\nabla = \left(\frac{\partial}{\partial x} i + \frac{\partial}{\partial y} j + \frac{\partial}{\partial z} k\right)$$

thus

$$\nabla \cdot \mathbf{v} = \frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z}$$

and

$$\nabla \mathbf{v} = \begin{bmatrix} \frac{\partial v_x}{\partial x} & \frac{\partial v_x}{\partial y} & \frac{\partial v_x}{\partial z} \\ \frac{\partial v_y}{\partial x} & \frac{\partial v_y}{\partial y} & \frac{\partial v_y}{\partial z} \\ \frac{\partial v_z}{\partial x} & \frac{\partial v_z}{\partial y} & \frac{\partial v_z}{\partial z} \end{bmatrix}$$