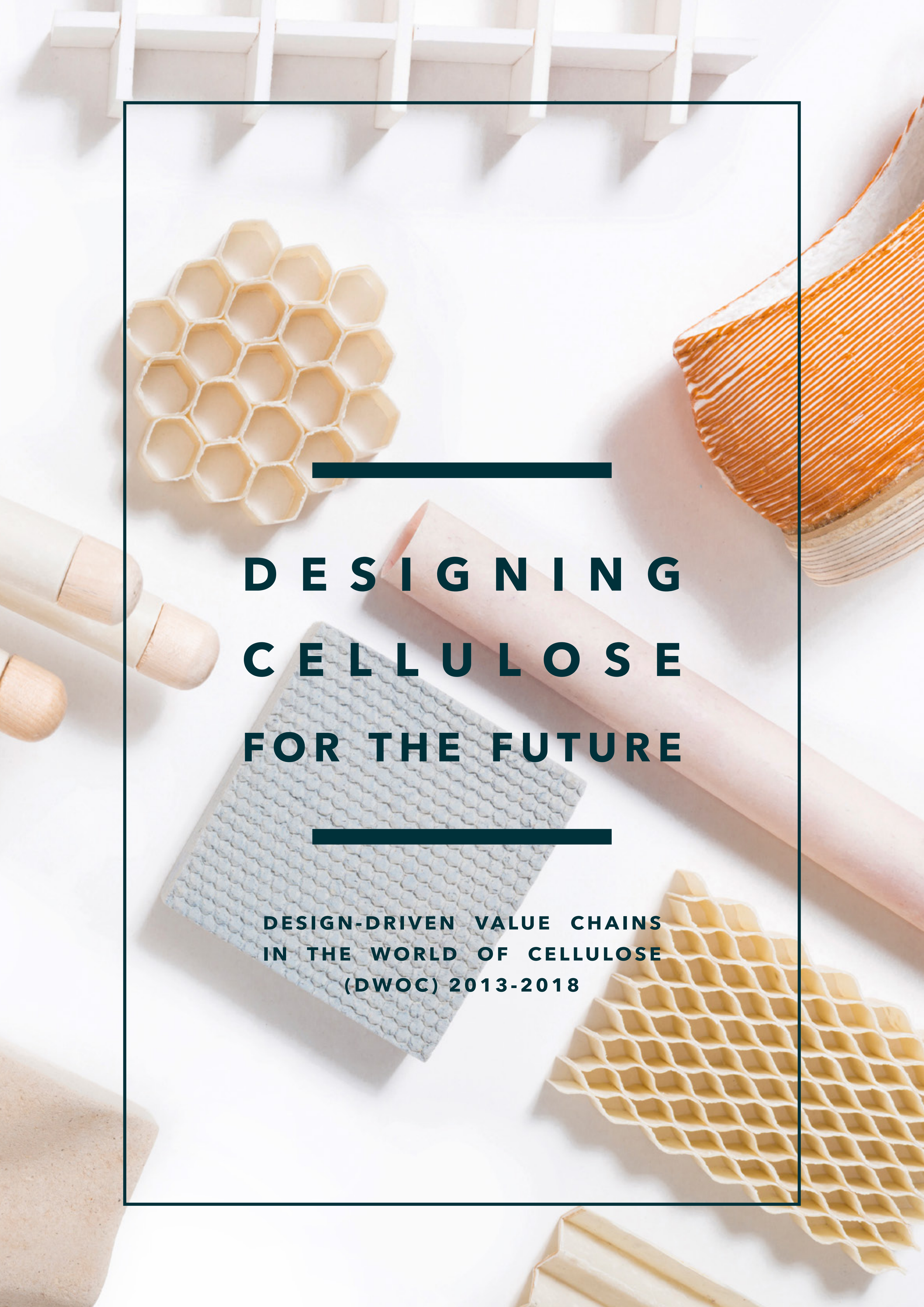

DESIGNING CELLULOSE FOR THE FUTURE

DESIGN-DRIVEN VALUE CHAINS IN THE WORLD OF CELLULOSE (DWOC) 2013-2018

KIRSI KATAJA
& PIRJO KÄÄRIÄINEN
(EDS.)

DESIGNING CELLULOSE FOR THE FUTURE

DESIGN-DRIVEN VALUE CHAINS
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Copy-Set
Helsinki 2018

DESIGN DRIVEN
VALUE CHAINS
IN THE WORLD
OF CELLULOSE
DWoC

VTT Aalto-yliopisto Aalto-universitetet Aalto University Tampere University of Technology University of Vaasa Tekes

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FIGURE 1
Experimenting with nanocellulose for tubular structures by Tiina Härkäsalmi.

INTRODUCTION

Since 2013, we have had the opportunity to work together on a special bio-material, cellulose, in a multidisciplinary research project called **Design-Driven Value Chains in the World of Cellulose** (**DWoC**). The central aim of the project has been to challenge the traditional way of using cellulose, to explore possible new applications for this material, and to experience at first hand how co-operation between designers, material engineers and business researchers can work in practice, and what kind of outcome we can expect.

In addition to advancing materials research, we have aimed to refresh the image of cellulose as a material for the sustainable future. We have also ambitiously targeted the birth of a new cellulose-based ecosystem in Finland. By using tools and methods from the fields of design and architecture, we have communicated the work-in-progress and the results of the project to a variety of audiences.

The DWoC project has been a great training exercise and valuable learning experience for us all. Now it is time to wrap it up, and to move on to new projects. Through this publication we would like to share our five-year experimental journey with you, and proudly present the main results of this unique collaboration project.

With compliments,
the DWoC team

PRESENTING THE DWoC - Facts and figures

FIGURE 2 Pulp.

‘The renewability of this raw material and the recyclability of cellulose end products makes cellulose a real supermaterial for the future.’

FIGURE 3 Wood chips.

WHY CELLULOSE?

As one of its most abundant materials, cellulose is a construction material of nature. It is a structural element of plant cell walls, and one of the three main components of wood (the others are hemicellulose and lignin).

Cellulose nanofibrils, (CNF), commonly termed nanocellulose, can be liberated from cellulose fibres using mechanical forces, chemical treatment, enzymes, or combinations of these. The most typical mechanical methods include homogenisation, microfluidisation, micro-grinding or cryocrushing. After fibrillation, the width of micro/nanofibrils is typically between 5 and 20 nm, and its length several micrometers. Micro/nanofibrils have high binding potential.

Cellulose is a biobased and bio-degradable product with multiple applications. Cellulosic fibres and fibrils are already widely utilised for paper and board, films, filters, absorbents, textiles, and non-woven materials for hygiene and home care. As wood-based cellulose is a renewable raw material, it is worth finding totally new, high added-value applications for it in addition to those in the traditional wood or paper and pulp industry.

Cellulose is a natural material, and users find it comfortable and friendly: breathable, warm and soft or strong, depending on the produced structure. It is also safe for users and causes no allergies. Cellulose can be processed and functionalised in various ways, and with the aid of these new, developed cellulose materials, we can improve our living environment in a sustainable way. Multi-use cellulose can be used to substitute fossil-based raw materials in, for example, textile products, architectural elements and various everyday objects. From cellulose we can manufacture products that are light, soft, hard, breathable, colourful, 3D-printable, absorbable, filterable, noise and heat insulating, or extremely durable (nanocellulose).

THE DWoC IN A NUTSHELL

Design Driven Value Chains in the World of Cellulose (DWoC) was a multi-disciplinary research project funded by **Tekes**, the Finnish Funding Agency for Innovation (now **Business Finland**), which focused on finding new, innovative applications for cellulosic materials. The DWoC project combined design thinking and design-driven prototyping with strong competence in technology development. The goal has been to make Finland a source of value-added cellulosic products and business concepts.

The project partners were: **VTT** Technical Research Centre of Finland, **Aalto University**, **Tampere University of Technology** and the **University of Vaasa**.

The project consisted of two phases: Phase I, 2013–2015; and Phase II, 2015–2018. The report of the first phase can be found at: http://www.vtt.fi/Documents/DWoC1.pdf

The total budget of the project was 11 M€.

About 110 people participated the research work over the years, and 54 manmonths of international researcher exchange was also realized. The research work in the project produced 40 scientific publications, 12 theses, 19 notifications of invention, 10 patent applications, and over 50 technology, product or business concepts. Three of the technologies were upscaled, and one start-up began operations already in January 2015.

Six seminars and 11 exhibitions were held; the exhibitions were attended by an overwhelming 70 000 people.

More information:
www.CelluloseFromFinland.fi

'Our aim throughout the project was to accelerate our knowledge refinement and by doing so, to reveal the distinctive attributes of the material, such as its recycling capabilities, and to combine these with new production processes to enable a breakthrough in innovations utilising cellulose.'

Ali Harlin, Research professor, VTT

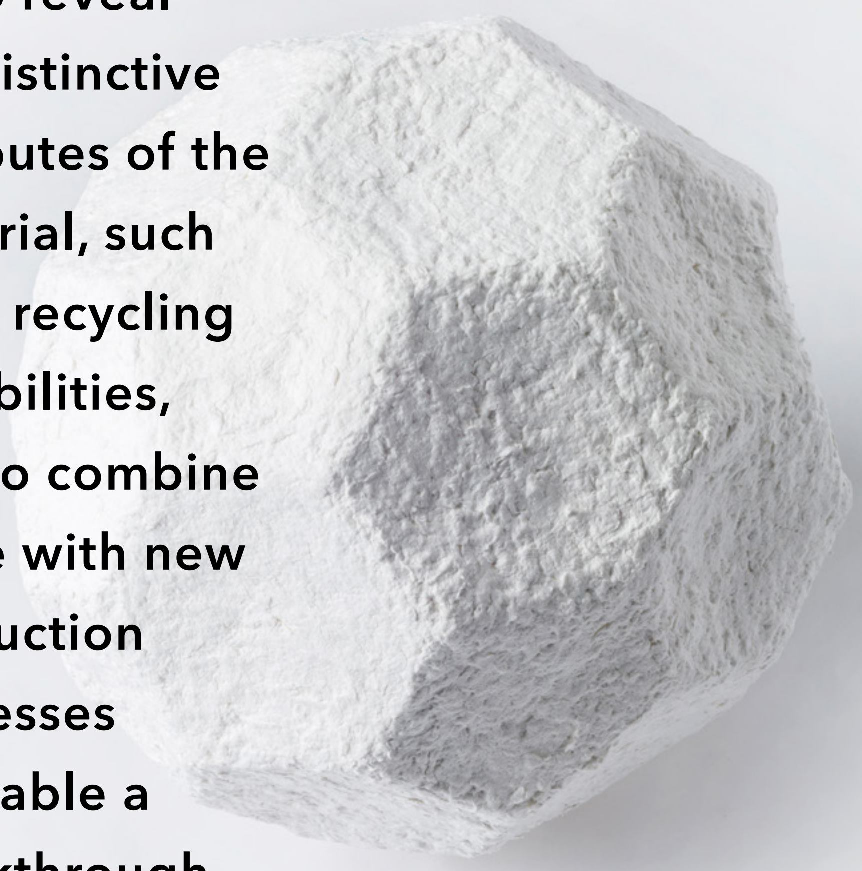


FIGURE 4
Sprayable biofibre-based acoustic coating by Tiina Härkäsalmi, prototyping in collaboration with Lumir Oy.

FIGURE 5
Cellulose in it's various forms, DWoC 2017.

'This research project is distinct from others in that it gives designers an active role in the development cycle, which allows entirely new and unusual positive human collisions that result in innovation.'

Erja Ämmälahti, Senior Advisor, Tekes

THE DWOC VISION

Wood cellulose has traditionally played a considerable role in Finnish industry, although the products have mainly been high volume with low added value, involving no design. The DWoC project was initiated to strengthen the role of Finland as a source of value-added cellulosic products and business concepts. The DWoC team has aimed to explore and challenge existing and emerging technologies, and to analyse and test the design and business potential of these findings. The target has been to accelerate the transformation of the current large-scale forest bioeconomy into a vivid ecosystem containing both large- and small-scale businesses, all capitalising on the numerous applications of cellulose. The DWoC vision sees Finland becoming an agent of this new circular economy on a global scale.

TO MAKE THIS HAPPEN, WE NEED

- to utilise cellulose in highly refined products such as textiles and those in the areas of fashion, interior decoration, health products, architecture, and construction.
- to accelerate the reform of the forest industry into a pervasive cellulose-based business ecosystem.
- to strengthen Finland's competitiveness by creating a new generation of highly competitive cellulose-based design products - Finland will become an agent of this new circular economy on a global scale.
- to inspire students of engineering, business and design to collaborate to find new, sustainable solutions for the utilisation of biomaterials.

ROAD MAPS 2030

Raija Koivisto, Anna Leinonen, Heidi Auvinen, Kirsi Kataja, Olli Salmi, Tiina Härkäsalmi, Jukka Itälä, Marjaana Tanttu

The structuring of a roadmap towards the **DWoC vision 2030** involved studying the contributing factors - drivers, markets and consumer needs, services, products and applications, and enabling technologies and materials. At the end of the first phase of the project (2013– 2015), three specific application areas of interest were identified and selected for more detailed analysis.

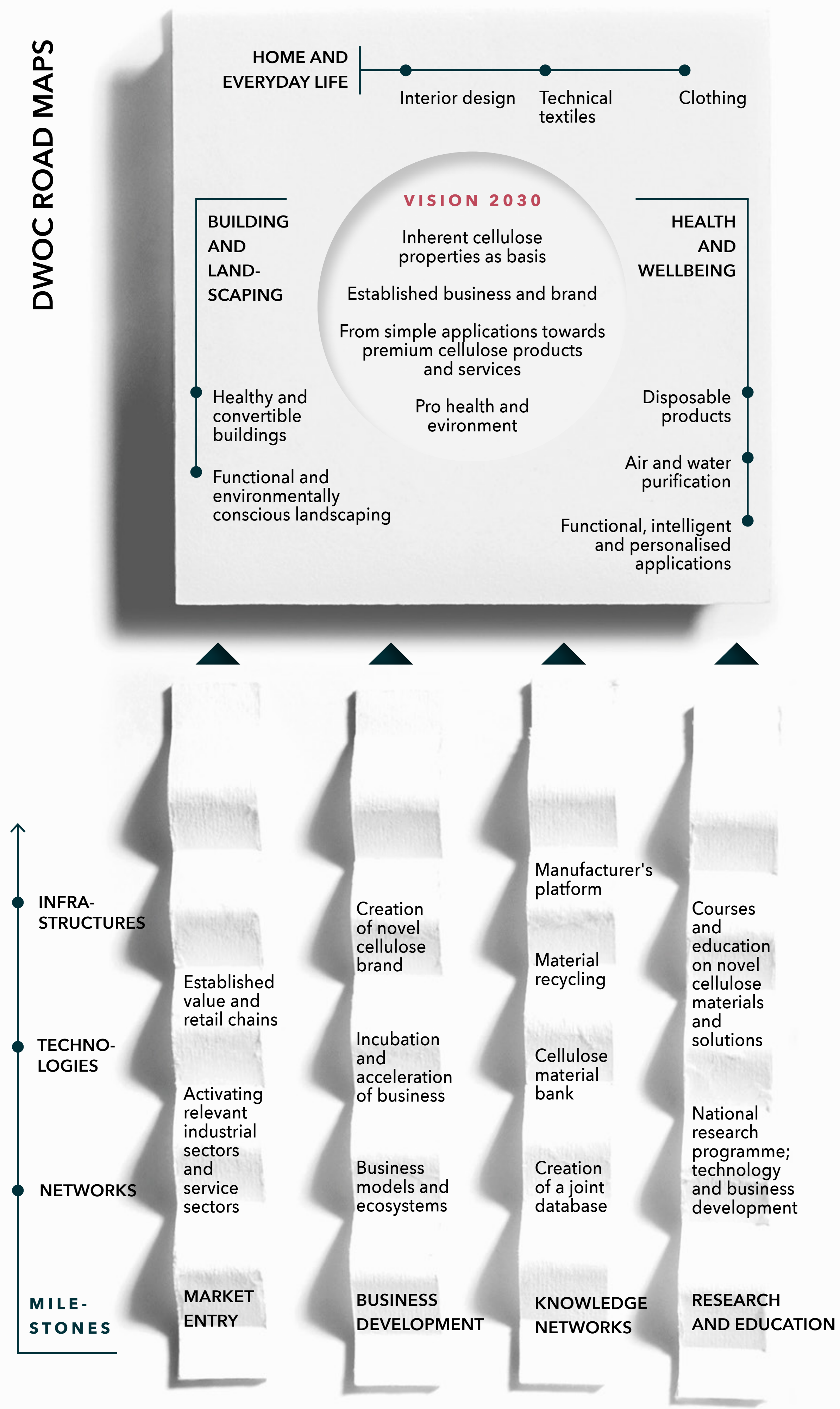
DETAILED ROADMAPS WERE THUS CREATED FOR:

- Home and everyday life (textiles)
- Building and landscaping
- Health and wellbeing

FIGURE 6
(page 12)
This roadmap is the result of Phase I. However, the actions were updated and redesigned during Phase II.

'The bioeconomy and the increase in consumption of sustainable products will in all likelihood increase the market share of biobased materials in the world. Products that satisfy people's basic needs such as clothes, hygiene products, foodstuffs, and housing and health products will always be in demand.'

— *Anna Suurnäkki, DWoC Project Manager 2015–2016* —



TOWARDS NEW BUSINESSES

Greg O'Shea, Ainomaija Haarla, Teemu Kautonen, Henri Hakala, Steffen Farny, Seppo Luoto, Kirsi Kataja, Tomi Erho

The overall aim of business research in Phase II of the DWoC was to explore and promote a new business ecosystem for cellulose-derived design products. The business research objectives of the project were

- to build an expansive business ecosystem based on cellulose by gathering a network of partners, and
- to increase the network's understanding of the economic benefits of the material by publishing and communicating cutting-edge research.

In addition to technical properties, the focus was on developing materials with an interesting design for versatile use in products, and for fulfilling future customers' demands (consumers or/and B2B). The most potential prototypes and materials were recognised through stakeholder interviews and teams' internal discussions. Clear favourable concepts to take forward include: wall elements, all-cellulose sandwich structures in general, 3D printing of textiles, non-wovens, strong nanocellulose tube structures, functional nanocellulose coatings, functional filaments, and foam technology-based all-cellulose elements or composite structures. The most favourable of these concepts to develop were described, and technology readiness levels assessed. Work included expanding some of these concepts in workshops with **Industrial Advisory Board** members and other external partners to find pathways towards commercialisation.

In general, two main pathways to commercialisation were identified. The first could be classified as **Technology transfer**, and involves partnering with large organisations of the cellulose ecosystem as part of a joint venture or some form of consortium. The second path - **Piloting technologies towards start-ups or spin-offs** - has been using a roadmap, which includes ideation, a demo, a pilot, a model, and start-up.

A good example of the second path is **Spinnova**, a spin-off company of VTT that began operations in January 2015. The core of its business idea is the pulp-based spinning method demonstrated in the DWoC project (Phase I). In 2017 Spinnova won the **Uusi puu** competition for wood-based solutions to challenges set by global mega trends. The **FabrikLink Network** also nominated Spinnova yarns as one of the Top 10 textile Innovations 2017.

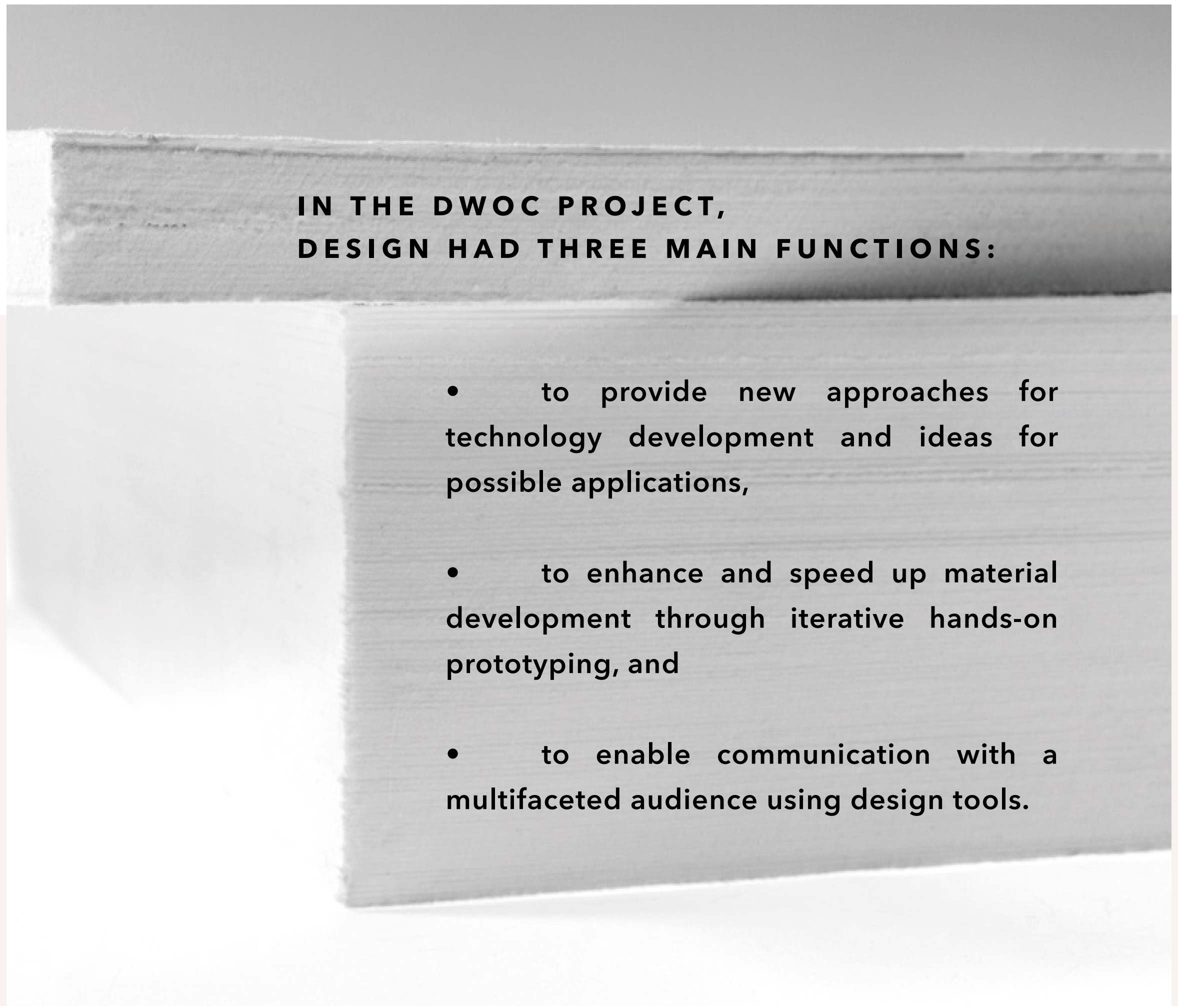
'Our vision is a more sustainable textile industry, in which cellulose-based materials are a cost-efficient, environmentally friendly and preferred option for brands, and are available to all consumers.'

Spinnova Ltd. https://spinnova.fi

FIGRURE 7
Example of all-cellulose composite boards glued with nanocellulose.
See also Glueing with nanocellulose, page 68.

COLLABORATION BETWEEN DESIGN, TECHNOLOGY AND BUSINESS

FIGURE 8 Strong structures from novel laminated material combining cellulose and nanocellulose. See Laminated structures for interior architecture, page 70. Design by Heidi Turunen.



IN THE DWOC PROJECT, DESIGN HAD THREE MAIN FUNCTIONS:

- to provide new approaches for technology development and ideas for possible applications,
- to enhance and speed up material development through iterative hands-on prototyping, and
- to enable communication with a multifaceted audience using design tools.

FIGURE 9 Strong block structures from cellulose and nanocellulose, see page 70.

'Designers should be involved in materials research and technology development in the early stages.'

Pirjo Kääriäinen, Professor, Aalto ARTS

The unique starting point for the DWoC was a new kind of multidisciplinary collaboration combining basic research, design, architecture, and business. The DWoC team has focused on exploring new ways of using cellulose whilst integrating a user-centred approach, technological development of materials and the development of business co-operation networks based on the circular economy. Possible cellulose products were tested through hands-on proto-typing and trial and error, and at the same time, we explored various potential application areas.

CELLULOSE-DRIVEN DESIGN APPROACH

- A synthesis of quantitative and qualitative material properties

Tiina Härkäsalmi, Jukka Itälä

One of the goals of the DWoC project was to develop wood-based cellulosic materials to be applied in novel application areas. For new materials to be commercialised, they have to fulfil the technical requirements of a product and support the creation of product personality, which means the synthesis of quantitative and qualitative aspects. A holistic design perspective is an interconnection between technical, perceptual and associative material characteristics, which can be divided into subcategories (**Figure 10**).

Functional parameters, together with material processability, sustainability and senso-aesthetic properties are considered simultaneously, and include the economic viability of solutions. Intrinsic technical properties include the qualities of the material itself, such as its density and mechanical, thermal and chemical properties. The processing properties are related to manufacturing processes such as the volume of production, the appropriateness of existing manufacturing techniques, and the cost of production. Moreover, the impacts on human health and the environment have to be taken into account throughout the life cycles. Perceptual qualities relate to the sensory impressions of the materials, including visual, tactile, and smell and sound characteristics. The visual performance and tactility of the materials are essential to fulfil end-users' expectations and needs. Associative characteristics entail intangible features that are typically culturally dependent. For example, in Finland, the forest has positive connotations, and wood-based materials are considered 'the green gold of the forest'. White is associated with innocence and purity.

Design can be seen as an integrative discipline and complementary to scientific research, thereby supporting materials research in interdisciplinary collaborations in particular not only by exploring applications for new technologies, but also by contributing to the creation of new knowledge from a more holistic point of view.

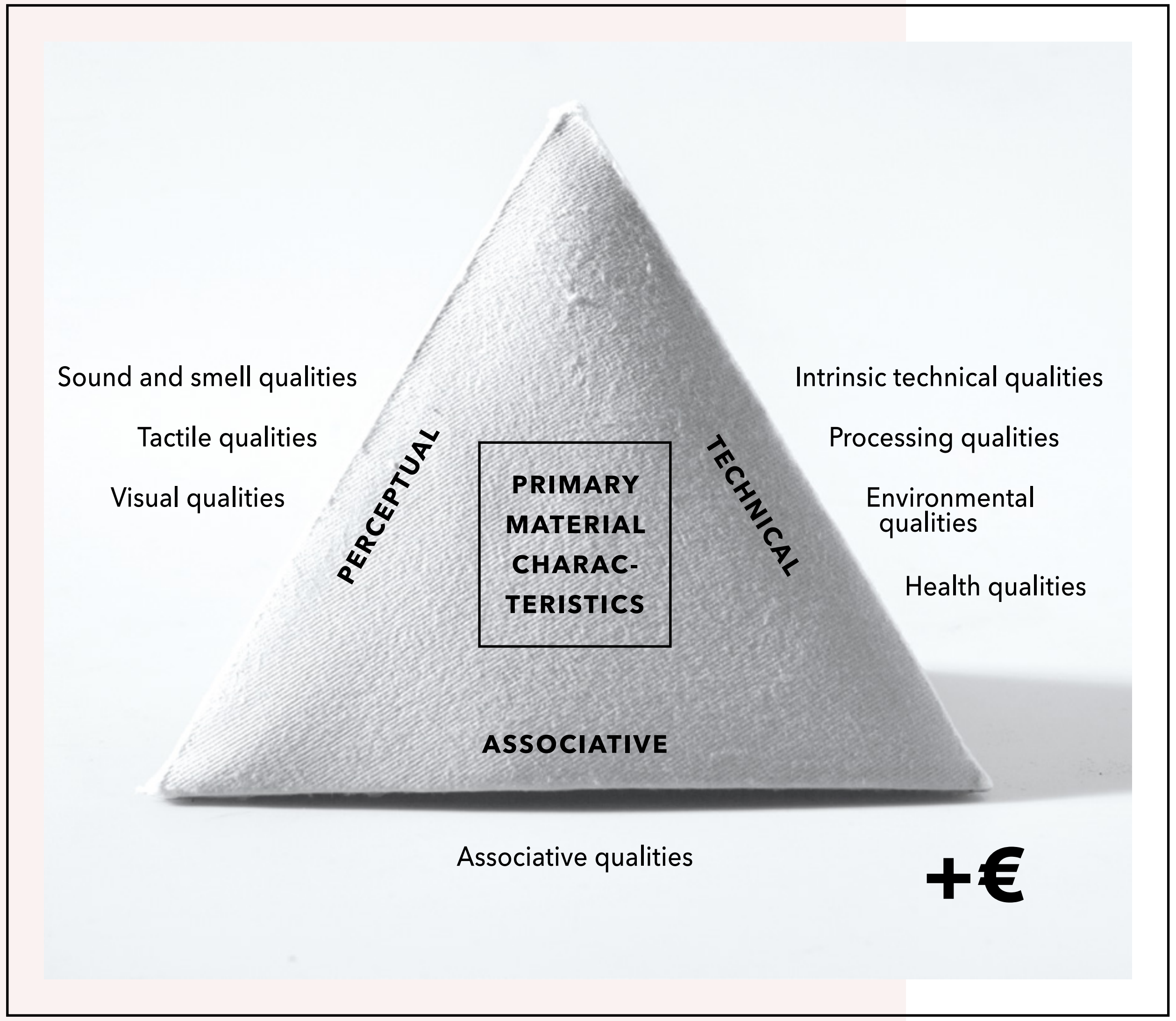


FIGURE 10 Meaningful primary material characteristics in design.

DESIGN RESEARCH MEETS MATERIAL SCIENCE

- Knowledge creation through iterative prototyping

*Tiina Härkäsalmi**

The development of new materials is typically executed by materials scientists and engineers, and in general, the research focuses on the technical aspects of the materials and processes. Integrating the design perspective into the technical development of materials is fairly uncommon. Science and engineering rely on quantitative methods, in contrast to the design approach, which commonly rests on the qualitative, human-centred approach. The key challenge is how to conjoin the specialised and theoretical scientific perspectives with the holistic and practical design standpoint in order to contribute to the creation of new coherent and complementary knowledge.

An illustrative example in the DWoC project was the interdisciplinary development of foam-forming technology that aimed to explore new ways of producing colourful 3D-shaped objects and to find the benefits and limits of the foam-forming process. The research explored foam-formed pulp at the same time as its possible application in sound insulation, and its contexts of use (acoustic indoor elements). It also studied process technologies through iterative design methodology entailing early phase prototyping in collaboration with design researchers and materials scientists and engineers.

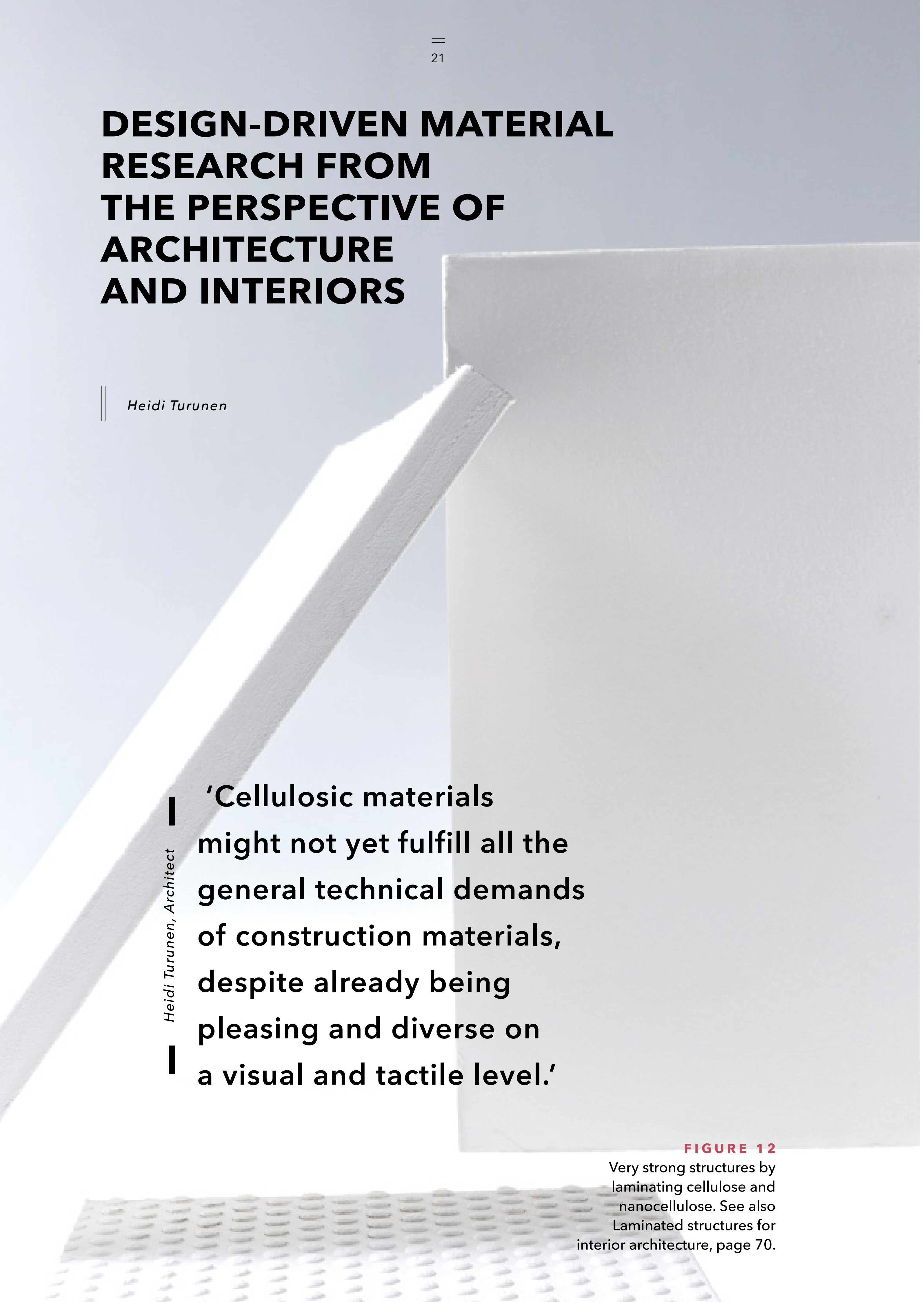
Iterative design methodology is based on a nonlinear, cyclical process, in which the prototyping, testing, analysis, and refining of a product or process are repeated stage by stage. The physical prototypes had designed structures on several different scales, ranging from macroscopic forms (m–cm scales) to surface texture (mm scale) and material pores (µm scale), and they embodied various kinds of technical and perceptual information on the interactions between wood-pulp fibres, the perforated mould and the forming process. In addition, the dyed pulp, together with the multi-scale forms provided interesting variations in visual quality, and the surface texture enhanced the material's tactile properties, giving a higher quality feel and enhanced rigidity. The iterative prototyping turned out to be an advantageous way of integrating knowledge from different disciplines, assisting communication, visualising the scenarios of use in acoustics and demonstrating the potential applications of foam-forming technology.

* Based on **Härkäsalmi, T., Lehmonen, J., Itälä, J., Peralta, C., Siljander, S., Ketoja, J.** 2017. Design-driven integrated development of technical and perceptual qualities in foam-formed cellulose fibre materials, Cellulose, pp. 5053-5068. DOI: 10.1007/s10570-017-1484-

'Science and engineering rely on quantitative methods contrary to the design approach, which commonly rests on the qualitative, human-centred approach.'

— *Tiina Härkäsalmi, Design rersercher* —

FIGURE 11
Acoustic panels from pulp, see 3D forms and surface structures from foam-forming, page 57.



DESIGN-DRIVEN MATERIAL RESEARCH FROM THE PERSPECTIVE OF ARCHITECTURE AND INTERIORS

Heidi Turunen

> **'Cellulosic materials might not yet fulfill all the general technical demands of construction materials, despite already being pleasing and diverse on a visual and tactile level.'**
>
> *Heidi Turunen, Architect*

FIGURE 12
Very strong structures by laminating cellulose and nanocellulose. See also Laminated structures for interior architecture, page 70.

Materials have an important cultural significance in people's living environments both when preparing for celebrations or just living everyday life. In addition, materials can acquire meaning by rooting people in places, and properly selected materials can improve the pleasure of living. Throughout the ages, natural or man-made materials have been processed to enable study on a practical level, and we have interacted with them to shape materials for protective shelters or buildings. This practical material research has created knowledge through shaping ambiences for the future.

As well as providing experience and cultural meaning, materials have many other tasks in living environments. For spatial applications, when new materials are developed, versatile technical aspects must be taken into account. Materials inherently interact with indoor and outdoor atmospheres. At the practical level, this means keeping heat, cold, moisture or water outside living areas and allowing air or light to pass through.

But materials can also be passive elements in surroundings, and carry loads. It is important that architects understand the technical capabilities of a material when designing spatial experiences for the users of buildings. This means that the right material will be designed in the right place, standing the test of time. In general, in dwellings and shelters that are not built for temporary use, the duration for the material, in the sense of time, wear and visuality, must be durable. People tend to explore surroundings through their senses, hence studying merely technical aspects is not enough to make meaningful spatial experiments. In general, materials can come very close to the experiencer, and depending on design, some can be experienced from a short distance. Because of this, materials can support spatial experience in a tactile but also a visual way.

Architecture can benefit from material research, particularly when designing environmentally friendly materials; materials that improve living conditions or even interact with their surroundings. When co-operating with design, the premise of the spatial experience can also be developed to create a more pleasant environment, to which the user can become attached and find meaningful.Cellulosic materials might not yet fulfill all the general technical demands of construction materials, despite already being pleasing and diverse on a visual and tactile level. The development of cellulosic materials can be seen as reaching towards the opportunity to make sustainable solutions for future inhabitants and users of buildings.

A CASE STUDY OF DESIGNERS AND SCIENTISTS COLLABORATING IN MATERIALS RESEARCH

Carlos Peralta

This research studied the dynamics of interdisciplinary collaboration in materials research and identified key aspects of its effectiveness. Its findings come from data collected from the direct observations of designers and scientists, a series of four collaborative workshops, and eleven in-depth interviews with designers, scientists (8) and project managers (3).

THE RESEARCH IDENTIFIED THESE KEY ASPECTS:

- To set up and communicate a clear policy for patenting, IPR, confidentiality and authorship credit, it is necessary to guarantee open and fluid collaboration.
- To foster the integration of research teams, time must be allocated and specific activities undertaken at the beginning of the project. Having a ~ 1 to 1 ratio of scientists and designers is also necessary to produce a better research output. Also, it has been identified that collaboration increases if project managers actively encourage people to collaborate.
- Enabling the physical proximity of the researchers is crucial, as this makes collaboration more efficient and fosters informal work interactions.
- The ideal personality traits and attitudes of collaborators are open-mindedness, flexibility, willingness to change, enthusiasm, a hands-on approach and an attitude that demonstrates interest.
- Steps must be taken to bring designers up to speed with specific techno-scientific knowledge as soon as the collaboration starts. It is also crucial that scientists are made aware of the designers' capability at the beginning of the research.
- Planning a sufficient supply of materials is fundamental, especially considering that designers require substantially larger amounts of raw materials while undertaking research activities than scientists.
- Joint ideation and prototyping sessions are essential for successful research. "Thinking and doing together" increases the quality of material research output, as it enables the integration of designers' and scientists' research and problem-solving tools.
- A shared understanding of project goals and targets is considered central to making collaboration suc-cessful. Also, a design-driven approach to materials development should be employed, as it enables the integration of designerly and scientific approaches while fostering innovative research with high application potential.

FIGURE 13
Designers and scientists in a collaborative workshop.

Carlos Peralta, Design Researcher

'To set up and communicate a clear policy for patenting, IPR, confidentiality and authorship credit, open, fluid collaboration is essential.'

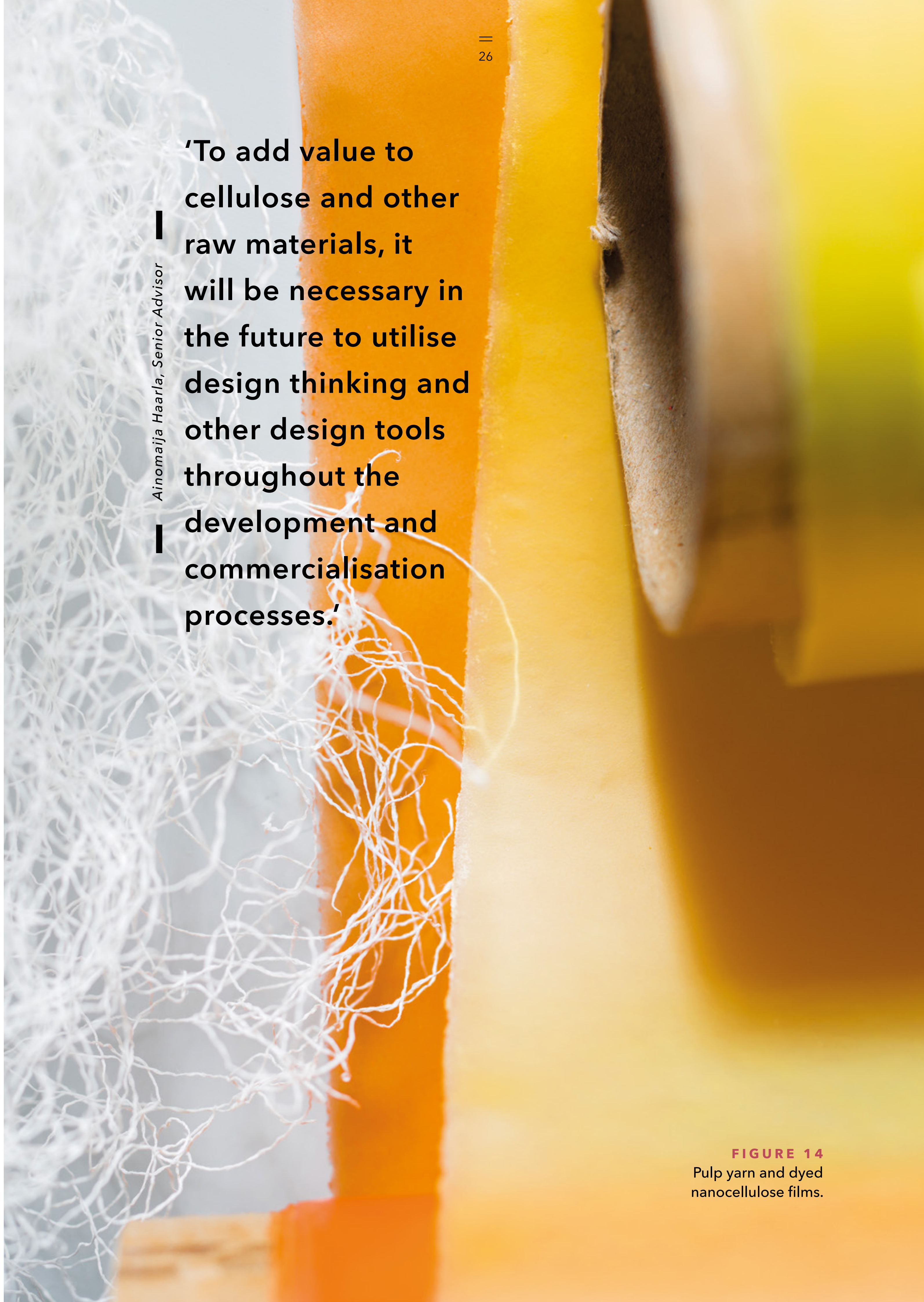
DESIGN-DRIVEN APPROACH IN MATERIALS RESEARCH FROM THE BUSINESS PERSPECTIVE

Ainomaija Haarla,
Pirjo Kääriäinen

In the 1990s, the digital media increasingly took over the print media, and as a result, the paper and pulp industry had to find new end-uses for the raw materials of wood; cellulose, hemicellulose and lignin. At the same time, consumers were searching for more ecological solutions. However, the growth in demand for packaging materials and hygiene products was not sufficient to compensate for the fall in demand for cellulose. Recently, we have seen the introduction of various biorefinery concepts according to which several other biomaterial-based products are produced on the same site as the main product – pulp – utilising side and waste streams from the main process. To date, out-of-the-box thinking and design in particular have played a minor role in the renewal of the forest industry.

The timing of the DWoC project has been perfect. Today we know much more about natural super materials such as cellulose, hemicellulose and lignin than we did a decade ago: we know more about their structure, nature, behaviour, and how they can be processed. Recent research has been both intensive and wide-ranging, in particular that relating to nanocellulose and lignin. At the same time, future-oriented designers have been searching for new ecological, sustainable and recyclable materials, and selecting them for endless applications to satisfy the needs of consumers both today and in the future. We now understand that material know-how is essential in the design phase in our way towards a circular economy. To add value to cellulose and other raw materials, in the future it will be necessary to utilise design thinking and other design tools throughout the development and commercialisation processes.

We are now at the beginning of our new collaborative journey. Obtaining the most promising initiatives, testing them on the laboratory scale, and then piloting them will take time. One of the end-use applications with the greatest potential is textiles, but many more will follow. The road from the idea and first trials to the ready product and profitable business is long and unsecure. Achieving real results will also demand patience from funders. Step-by-step, we are proceeding towards a new wood raw material-based bio materiality, and luckily we do not lack raw material: on the contrary, Finnish forests are taken good care of and produce much more wood than we use today.



'To add value to cellulose and other raw materials, it will be necessary in the future to utilise design thinking and other design tools throughout the development and commercialisation processes.'

Ainomaija Haarla, Senior Advisor

FIGURE 14
Pulp yarn and dyed nanocellulose films.

RESULTS

HOME AND EVERYDAY LIFE: TEXTILES

Textiles play an important role in our everyday lives, not only as clothing or home textiles, but also as hygiene products or more technical applications. Currently the industry is in transition towards more sustainable production processes and business models, and new material innovations are seen as one of the main solutions. For example, wood-based fibre yarns have possible applications in non-wovens or composites, and pulp-based wet-laid non-wovens could be produced using wood fibre yarn instead of synthetic or viscose fibres.

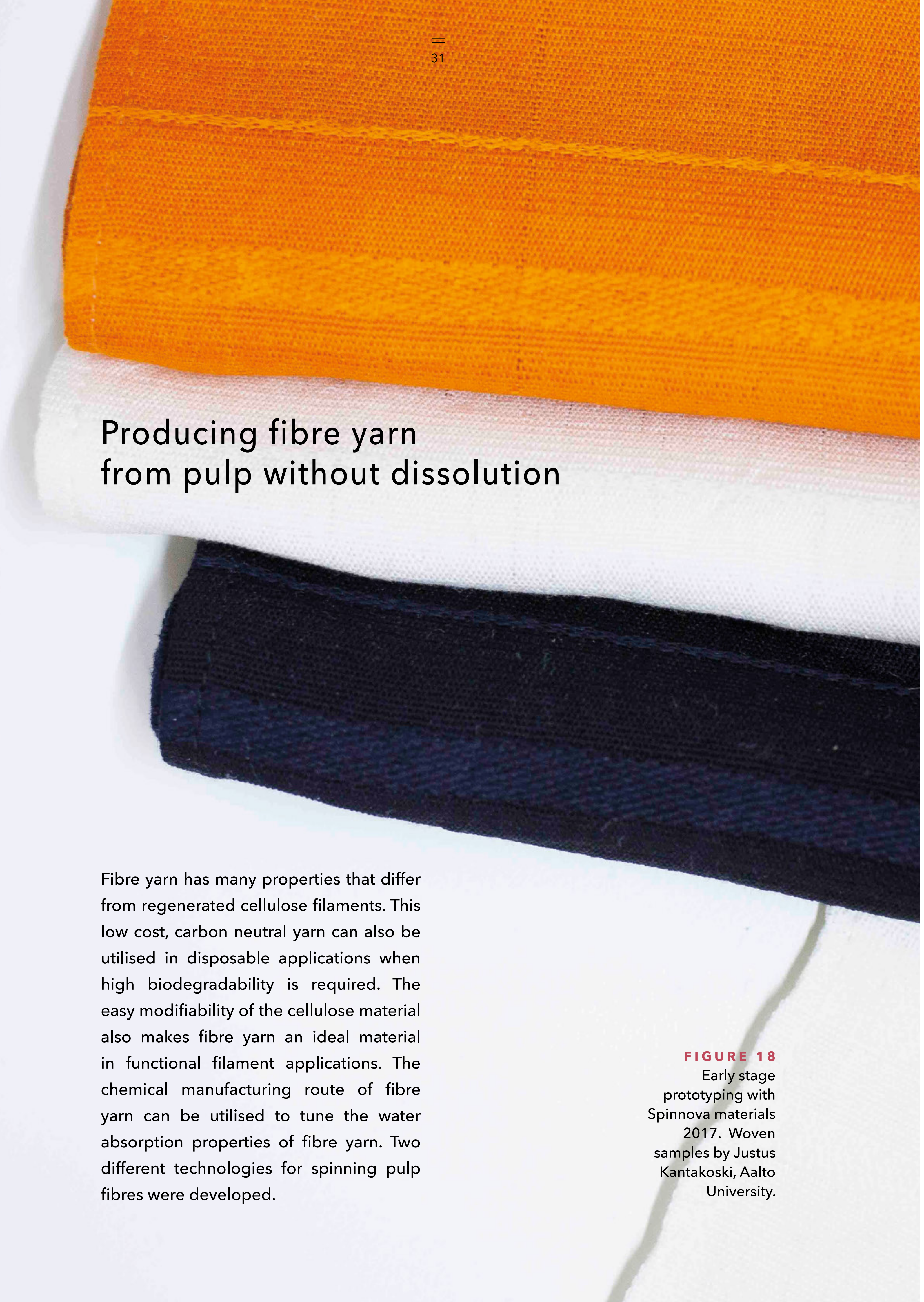
FIGURE 16
Textiles from recycled cotton and cardboards, produced using Ioncell technology. The brown color comes from lignin. Designed by Marjaana Tanttu, 2014. See also How to wear old newspaper, page 44.

FIGURE 17 Continuous nanocellulose-based filaments, see also page 35.

Towards water-stable and functional cellulosic filaments

In the first phase of the DWoC, the aim of the work was to develop filament manufacturing technologies of native cellulose materials using several different emerging technologies. In the second phase, the most promising technologies were selected and further developed to improve the mechanical and chemical performance of filaments, and to develop functional cellulose filaments. Both pulp-based filaments and nanocellulose-based filaments were developed.

The project examined four different methods to enhance mechanical properties (strength and ductility) and the water stability of cellulose-based filaments. These methods were: crosslinking cellulose fibres or fibrils, gas-phase modification of CNF filaments with hydrophobic chemicals, improving the wet strength of fibre filaments with partial dissolution with NMMO, and UV-crosslinkable CNF by grafting benzophenone onto TEMPO-oxidised CNF.



Producing fibre yarn from pulp without dissolution

Fibre yarn has many properties that differ from regenerated cellulose filaments. This low cost, carbon neutral yarn can also be utilised in disposable applications when high biodegradability is required. The easy modifiability of the cellulose material also makes fibre yarn an ideal material in functional filament applications. The chemical manufacturing route of fibre yarn can be utilised to tune the water absorption properties of fibre yarn. Two different technologies for spinning pulp fibres were developed.

FIGURE 18
Early stage prototyping with Spinnova materials 2017. Woven samples by Justus Kantakoski, Aalto University.

I

Spinning pulp fibres with a rheology modifier - Spin-off company Spinnova

Edited by *Kirsi Kataja*
Researchers *Juha Salmela, Johanna Liukkonen, Jarmo Kouko, Ville Klar, Thomas Widmaier*

A new technique for producing man-made yarns directly from wood fibre suspension by a wet spinning process was introduced by **VTT** already before DWoC began. In this method, fibre suspension using a rheology modifier, dispersion agent, and other additives such as surface active agents, is wet-extruded through a nozzle to form filament yarn. After this, the water is removed. This method has the potential to produce low-cost yarn with adequate mechanical properties and has a very low environmental impact.

The initial technology was further developed in DWoC during 2014. Laboratory-scale yarn production machinery was constructed and developed. Several fibre types were tested as a raw material for yarn making. In addition to process parameters, crosslinking chemicals, a rheology modifier and strength additives were further researched and tested.

In the final developed technology, fibre suspension was extruded on a forming wire using a special nozzle, and wet pressing with moving wire was used to remove the excess water from the yarn. Cross-linking gel was needed around the fibres to create wet strength for the wet pressing stage.

After the excellent research results, a spin-off company of VTT – **Spinnova** – began operations in January 2015, and has since developed this method further.

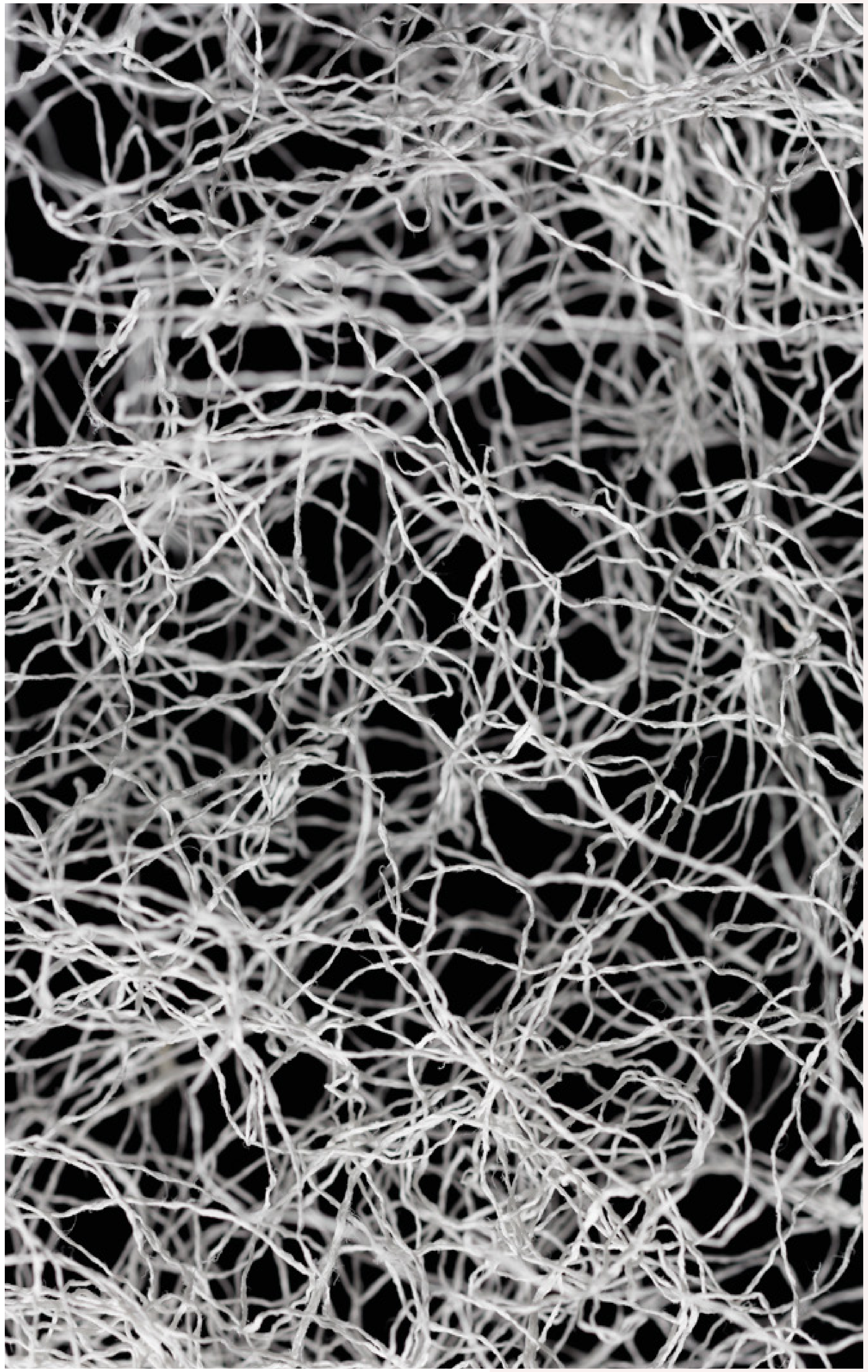


FIGURE 19 DES fibre yarn.

II

Spinning pulp fibres with deep eutectic solvents (DES fibre yarn)

Tiia-Maria Tenhunen, Hannes Orelma, Hille Rautkoski, Ville Klar, Minna Hakalahti, Jaakko Pere, Tuomas Hänninen, Ali Harlin

In addition to spinning pulp fibres with a rheology modifier, another approach to manufacturing pulp-based filament yarn has been developed. The initial hypothesis of the mechanism for this other approach was to swell the pulp fibre surfaces and thereby assist the interactions of fibres in the extrusion through the nozzle to produce filament yarn. Deep eutectic solvent (DES), composed of choline chloride (ChCl) and urea showed to be a suitable medium for pulp fibre yarn formation. This eutectic mixture can disperse pulp fibres and form a gel-like suspension that can be further spun into fibre yarns using the extrusion method. Our research produced clear evidence of swelling, and no dissolution of cellulose took place in the process, meaning that the cellulose I structure remained intact.

The developed filament production method uses dry-jet wet spinning, and is easily up-scalable with simultaneous spinning jets. This enables a great amount of fibre yarn filaments to be made in a short time. The prepared filament is made water resistant by combining a non-toxic crosslinking additive (5–10%) with a short heat treatment. This method allows continuous filament production, and the filament can be cut into staple fibre if required. The produced filament exhibits native wood cellulose structure with no losses of hemicelluloses.

TECHNICAL DATA: Filament diameter is between 60 μm and 120 μm, and the length-mass is 170-250 dtex (depending on the utilised nozzle diameter). The filament is fully recyclable and manufacturing costs are low. The properties of DES fibre yarn are very different to those of the earlier described pulp yarn produced with the rheology modifier. The DES fibre yarn has high porosity and high water absorption capacity (500%), and still has high wet strength, up to 60% of that recorded in dry conditions (130 MPa with an elongation of 17%). The surface of the fibre yarn is easily modified using chemical modification strategies.

POTENTIAL APPLICATIONS: Reinforcing biocomposite materials, giving strength and elasticity to non-woven textiles (see Non-woven textiles by foam forming page 41), water absorbing structures, and substrates for affinity capture applications. See Hormone capturing, page 108.

Nanocellulose-based filaments by wet and dry spinning

Meri Lundahl, Ling Wang, Gisela Cunha, Ester Rojo, Ville Klar, Yingfeng Shen, Ali Harlin, Pezhman Mohammadi, Markus Linder, Hannes Orelma, Ilari Filpponen, Orlando Rojas

We demonstrated several methods for preparing cellulosic filaments with native cellulose I crystalline structures during the first phase of the project. The aim was to develop high performance, continuous filaments (fibre yarns) using native cellulose nanofibrils (CNF). Crystalline regions in CNF have been reported to have Young's modulus as high as 138 GPa. Thus, the high crystallinity and the presence of cellulose I suggests that CNF-based fibres have a superior mechanical performance to that of existing cellulosic materials (cotton and regenerated cellulose fibres with cellulose II, for example). Such favourable performance can be augmented if CNF is aligned properly during the spinning process. Long CNF-based filaments were produced using several spinning technologies.

The team produced monomaterial filaments (only CNF), coaxial filaments (CNF core and polymer surface), hybrid filaments (using recombinantly produced genetically engineered fusion proteins and CNF) and composite filaments (enzymatically fibrillated cellulose and crosslinker polymer). Some of the concepts, i.e the most suitable for upscaling to continuous spinning, were selected for the second phase of the DWoC project. In the second phase, we identified three main challenges in filament production: water stability, making the yarn suitable for textile products, and the upscaling of the production process for high throughput.

We wet-spun the monofilaments from nanofibrillated cellulose using different kinds of pretreatments. The properties of the ensuing filaments were influenced by the pretreatment and solids content of the nanofibrils. To solve the challenge of water stability, we used benzophenone-modified nanofibrils to produce filaments that became stable in water via UV-triggered crosslinking. Another approach was to use a water-repellent additive or coating for the filaments. In order to produce larger filament batches, we developed a coaxial spinning method, which incorporated a supportive, recyclable polymer shell around the nanocellulose hydrogel during wet-spinning.

A laboratory-scale concept for conductive filaments was also developed.

MATERIAL CHARACTERISTICS: The filaments are rather stiff and surfaces considerably rough. Thickness can be controlled by varying the diameter of the wet-spinning nozzle or the solids content of the nanocellulose hydrogel. Round or flat cross-sectional shapes can be obtained by drying the filament with or without squeezing on a winder, respectively. The filaments with pretreated fibrils in particular absorb water strongly and fully disperse in water over time. UV-crosslinked filaments can easily be handled, even in water.

TECHNICAL DATA: The dry tensile strength of a monofilament can reach approximately 300 MPa. By using pretreatment, Young's modulus can be increased from 15.5 ± 1.7 GPa to 21.3 ± 5.5 GPa, while elongation at break decreases from 6.9 ± 0.9 % to 2.8 ± 0.5 %. However, the pretreated filaments retain less than 1% of their strength in wet conditions, and untreated filaments retain close to 2%. Wet strength can be increased above 80% of dry strength via UV-crosslinking.

POTENTIAL APPLICATIONS: The filaments can be used in applications in which the combination of high strength, stiffness and lightness is important. For example, they could be used to reinforce biocomposite materials. In addition, the filament can be chopped and used in nonwovens. This was already demonstrated by preparing a non-woven sample by foam forming.

FIGURE 20 Different kinds of nanocellulose-based filaments.

Filaments from enzymatically fibrillated pulp

Steven Spoljaric, Jukka Seppälä

In order to enhance spinnability and impart strength and water stability, we blended enzymatically fibrillated pulp (EFP) with selected crosslinking chemicals to prepare spinning dopes. The filaments were either directly spun into an acetone bath, or were spun in air. No additional concentration or removal of water was necessary following crosslinking.

TECHNICAL DATA: The dry tensile strength of the monofilament was 40 ± 6 MPa, and elongation at break was 1–5%. Wet tensile strength was 65 ± 4 MPa, and elongation 17± 2%. The reference values for dry cotton yarn are 625 ± 225 MPa and 3-8%, and for wet cotton yarn 590 ± 150 MPa and 9 ± 2%.

POTENTIAL APPLICATIONS: The great potential of this type of filament is its applicability in combined processes in which the spun filament yarn is, for example, knitted in to the ready-made product during the same process. By utilising heating, appropriate viscosity can be achieved, allowing the monofilaments to go from spinning to knitting almost instantaneously. By combining the spinning process with a manufacturing process, the production chain can be significantly shortened. This in turn can reduce the costs, lead times, and environmental impacts of production.

FIGURE 21 (page 38)
Filaments from nanocellulose.

Improving the wet strength of fibre filaments using partial dissolution with NMMO

Hannes Orelma, Hille Rautkoski, Antti Korpela

We developed a post-treatment method for improving the wet strength of cellulose filaments by partial dissolution and regeneration with NMMO. NMMO was applied to the filament structure using two different methods, including NMMO-methanol impregnation and NMMO-melt treatment. NMMO-melt partially dissolved only the outer layer of a filament, whereas NMMO-methanol treatment cross-linked the whole filament structure. Using these tools, the filament properties can be tuned for different end uses.

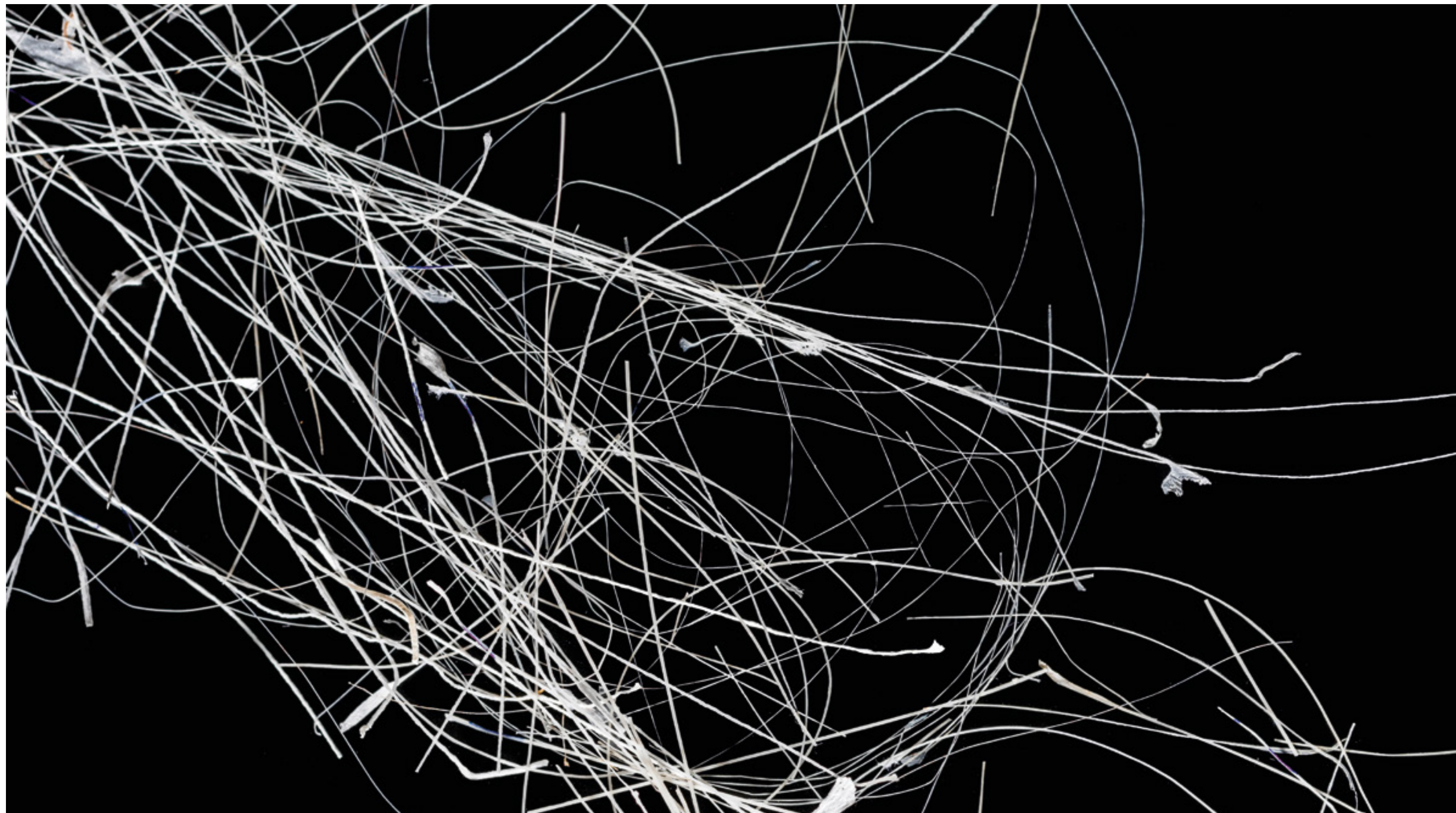
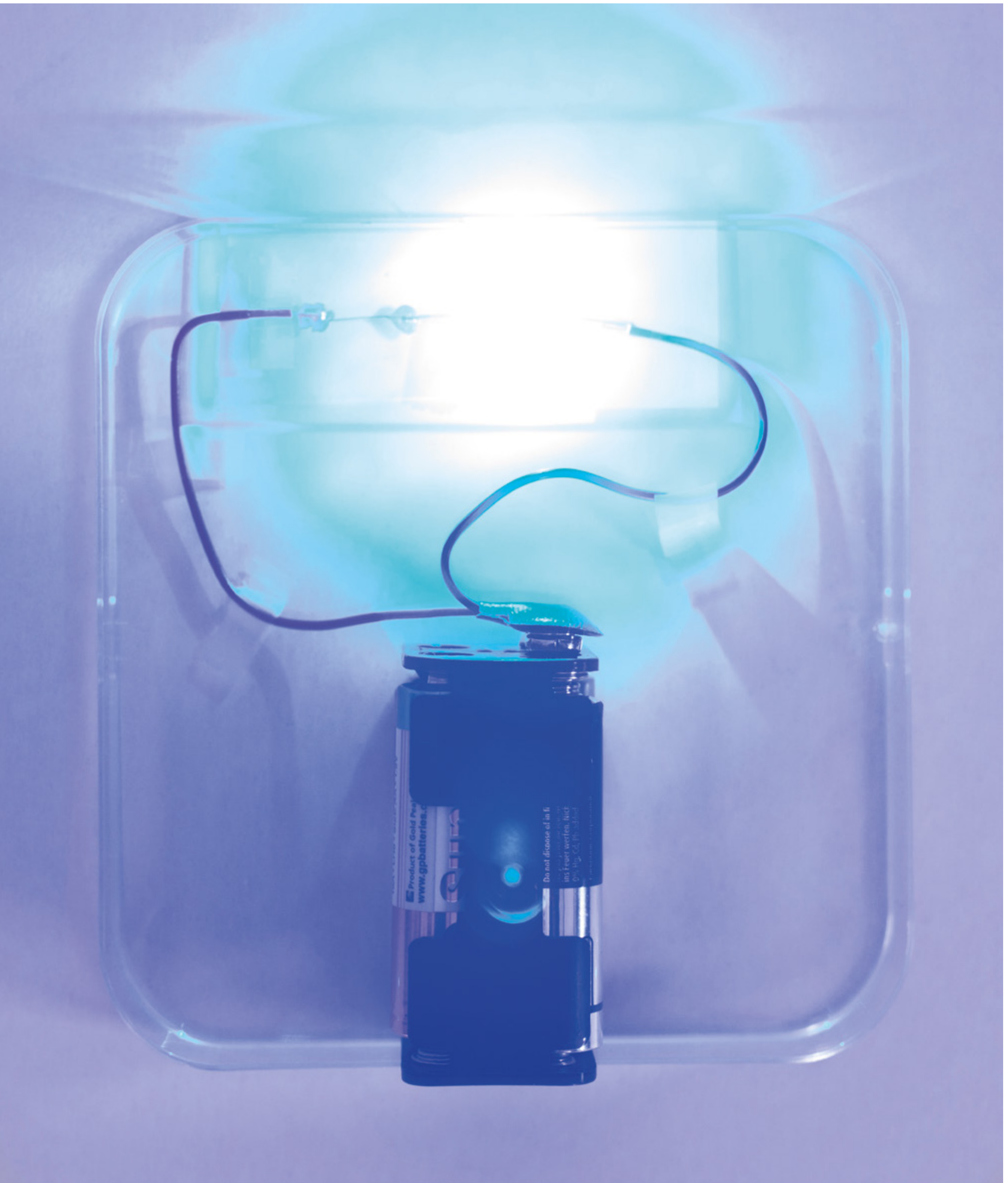


FIGURE 22
Conductive filament. The 1 cm long filament sample is on the top left in the circuit.



Gas-phase modification of CNF filaments using hydrophobic chemicals

Gisela Cunha,
Ling Wang,
Orlando Rojas

We adopted a straightforward gas-solid approach to hydrophobise CNF wet-spun filaments, using selected chemicals. The modified CNF filaments presented not only a hydrophobic character but, in some cases, showed lipophobicity, which also denotes an amphiphobic character.

Conductive filaments

Ling Wang,
Orlando Rojas,

Conductive filaments were successfully produced in a two-step process. Ligno cellulose nanofibres (LCNF) were first made into filaments, after which carbon fibres (CF) with high porosity were treated using one-step carbonization.

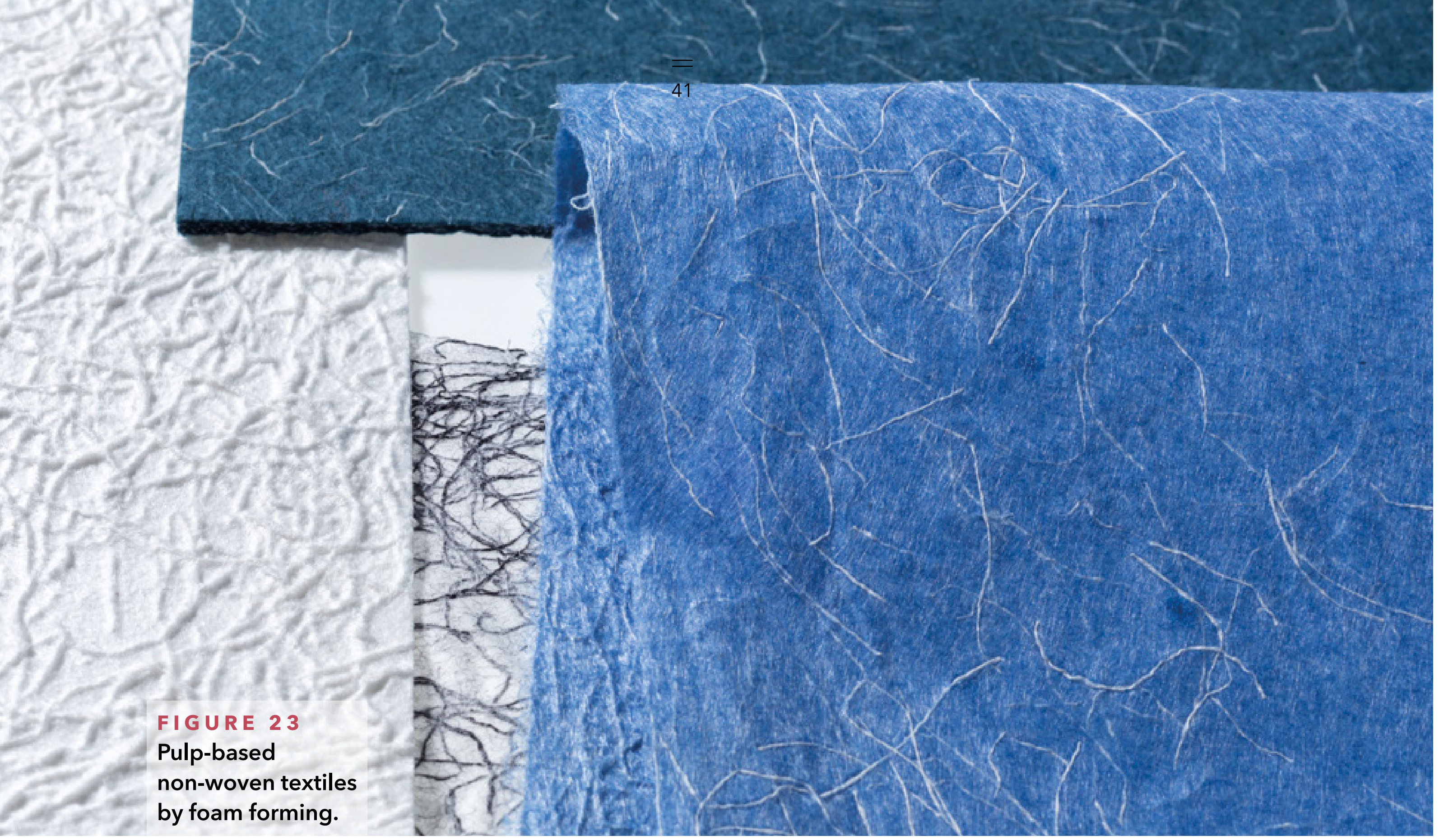


FIGURE 23
Pulp-based non-woven textiles by foam forming.

Non-woven textiles by foam forming

Jukka Ketoja, Atsushi Tanaka, Jani Lehmonen

Foam forming enables the production of a vast variety of fibre-based materials. Feeding the fibre foam into a porous fabric and sucking out the liquid phase leaves a fibre network, which forms the skeleton of the non-woven fabric. Multi-scale structural features affect both the technical and perceptual qualities of the material.

We combined cellulose yarns and fibres into different types of non-wovens, ranging from thin textiles to thick elastic materials. The material characteristics vary greatly depending on the type of yarns and fibres, their relative proportions and how tightly the material units are bound together. The basic fibre components have been pulp yarn (by DES process), commercial paper yarn, viscose fibres, pine or birch kraft pulp and some added latex.

TECHNICAL DATA: Materials with yarn are generally quite light, with densities varying in the range of 150–300 kg/m3. The obtained strengths showed a considerable scatter, 0.2–2.8 MPa with a reference value of 6.8 MPa for a pure pine kraft sheet with latex. We found a similar scatter in the breaking strain with some highly extensible samples.

POTENTIAL APPLICATIONS: The non-woven fabrics can be utilised in, for example, technical textiles, commodity products, composite applications, and interior decoration.

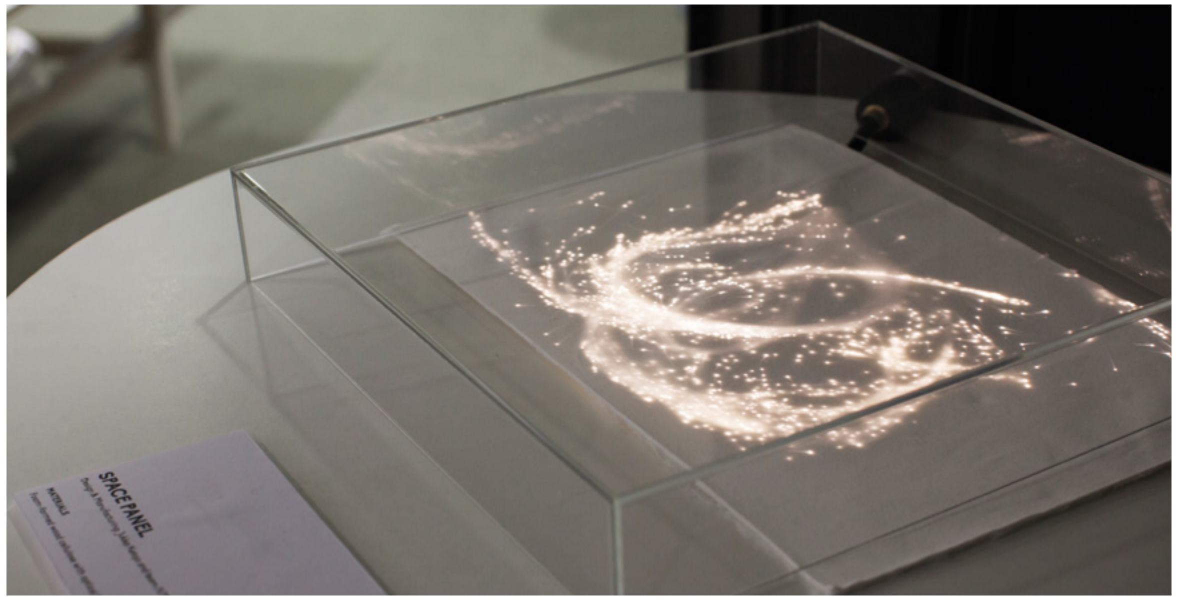


FIGURE 24
'Space panel'; optical fibres integrated into foam-formed pulp board production process.

FIGURE 25
Lamp shade produced by foam forming and mold technology. Mold design by Anastasia Ivanova.

FIGURE 26
Textile filaments, yarns and fabric from old newspapers. Fabric designed by Marjaana Tanttu.

How to wear old newspaper - Fabrics from waste cellulose

Yibo Ma, Marjaana Tanttu, Shirin Asaadi, Michael Hummel, Herbert Sixta

Ioncell is a new, sustainable technology for producing high-quality textile fibres. The process uses an environmentally friendly solvent called ionic liquid, developed by a team of researchers from **Aalto University** and the **University of Helsinki**. This process can turn wood pulp, used cotton textiles, or even old newspapers and cardboard into new high-quality textile fibres without using harmful chemicals.

As material recycling and upcycling are becoming an important topic in our society, the recycling of cotton textiles and card-board were tested already during the first phase of the DWoC. In the second phase the task was even more challenging. We spun Ioncell fibres from a deinked newsprint/(DBNH)OAc dope using a dry-jet wet spinning method. The fila-ment jets were coagulated in water. The fila-ments were cut into 40 mm-long staple fibres before they were washed. These fibres were blended with commercial viscose fibres, carded, drafted together, and ring-spun into a yarn from a 50:50 blend of Ioncell newsprint fibres and viscose. The spun yarn was knitted, leading to the final product.

MATERIAL CHARACTERISTICS: Ioncell newsprint fibres are strong even when wet. They feel soft and are shiny in appearance. The cross section is circular. The fibres have good water absorbency.

POTENTIAL APPLICATIONS: Using newsprint as raw material for cellulosic fibre spinning offers new possibilities to upgrade waste material to high-value-added products. Fibres spun from newsprint are suitable for textile application, bio-composite applications and other technical fibres.

TECHNICAL DATA:

FIBER	CONDITIONED										WET					
	Titer dtex	±	Diameter µm	±	Tenacity cN/tex	±	Stress MPa	±	Elong. %	±	Tenacity cN/tex	±	Stress MPa	±	Elong. %	±
Ioncell Newsprint	1.34	0.17	10.7	3.8	36.8	2.4	553	35	10.0	1.1	34.4	3.9	516	58	11.2	1.5
Ref. Viscose	1.30	0.10			23.8	2.4			18.7	2.1						
Ref. Tencel®	1.31	0.11			40.5	1.6			14.4	1.6						
YARN	Count tex	±			Tenacity cN/tex	±			Elong. %	±						
Ioncell Viscose	93	32			7.5	2.5			7.6	0.9						

HEALTH AND WELLBEING

Consumers and governments are increasingly demanding products that are recyclable or biodegradable and made from renewable raw materials, using environmentally friendly manufacturing processes. Future materials have to be safe to wear and use, and their use should not be harmful to nature, as microplastics are today. For example, nanocellulose is biocompatible and can be processed into extremely light, strong structures. We also tested another approach, the all-cellulose concept in, for example, the prototyping of footwear.

FIGURE 27
Prototype bicycle with white nanocellulose structures 2017.

FIGURES 28 AND 29
Extremely light, strong tubular structures from nanocellulose, see page 47.

Exploring the formability of nanocellulose for solid structures

Tiina Härkäsalmi

Fibrillated nanocellulose can be processed using moulding technology into extremely light, strong 3D forms, structures and constructions that are based on the chemical bonding of cellulosic fibres. These explorations were used to challenge and test materials in ways that would create new knowledge on the formability of fibrillated nanocellulose in solid 3D objects and identify interesting design uses in new application areas.

In the beginning, the material itself, fibrillated nanocellulose, was the starting point for explorations with a more opportunistic and intuitive approach, and there were no strictly predefined methods and systems. Thus, preconceived ideas do not limit the creative process, which is nonlinear and iterative by nature. In the first phase, the explorations were used to challenge and test materials in ways that would bring forth new knowledge of the formability of fibrillated nanocellulose in solid 3D objects entailing different colours, forms, structures and compounds. The material was dyed with reactive textile dyes using the cold pad-batch method. We chose three main forms: hemispheres, tubes and sheets, which we used for all-cellulose constructions. These are easy to customise in terms of technical qualities, shape, size, and colour, and they offer wide-ranging opportunities for further development, especially in products that have to be recyclable and biodegradable.

Hollow, colourful, solid nanocellulose structures, as well as all-cellulose composite structures (multilayered) were produced with the developed moulding method. Structures included various 3D forms such as tubes, polygonal forms, honeycombs and corrugated sheets. Light, strong cellulose-based structures can be moulded without chemicals and these properties are based on the chemical bonding of cellulosic fibres. A layer-by-layer or mono-layer method and the use of different CNF, CMF, pulp, and CMC combinations enable high variations of tailored properties. Topography can be tuned with sanding (basic tools can be used, the material does not cause wearing of the tools) and the surface can be also structured.

MATERIAL CHARACTERISTICS

TECHNICAL PROPERTIES: light and strong, tailorable material properties. E.g. birch tube: diameter 16.5 mm, thickness 0.61; length 95 mm, weight 3.99 g, density ~ 810 g/m2, strength/stress ~ 80 MPa

MANUFACTURING PROCESSES: a layer-by-layer or mono-layer method, high shrinkage in drying process > special requirements for form and mould design

SENSORIAL PROPERTIES:
▹ **Visual:** opaque, non-reflective, light absorbing, high variety of colourfulness, high intensity of colours
▹ **Smell:** odourless (dry/wet)
▹ **Touch:** from smooth to rough depending on the mould surface or surface finishing, hard/semi-hard, warm handle, wood-like touch
▹ **Sound:** "clattering"

SUSTAINABILITY: 100% renewable material, easily recyclable/reusable, (bioeconomy, circular economy), biodegradable and compostable, mono-material, non-toxic, traceability (certified pulp)

HEALTH: non-outgassing, non-allergenic, non-toxic, odourless

FIGURE 30
Colour palette for reactive-dyed nanocellulose by Tiina Härkäsalmi 2016.

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FIGURE 31
Cellulose nanofibril sheets with pulp filaments.

FIGURE 32
Corrugated sheet structures from nanocellulose.

FIGURE 33
Light, durable honeycomb structures from nanocellulose.

FIGURE 34
Tubular structure.

FIGURE 35
Corrugated sheet structures from nanocellulose.

FIGURE 36
Composite sheets based on nanocellulose.

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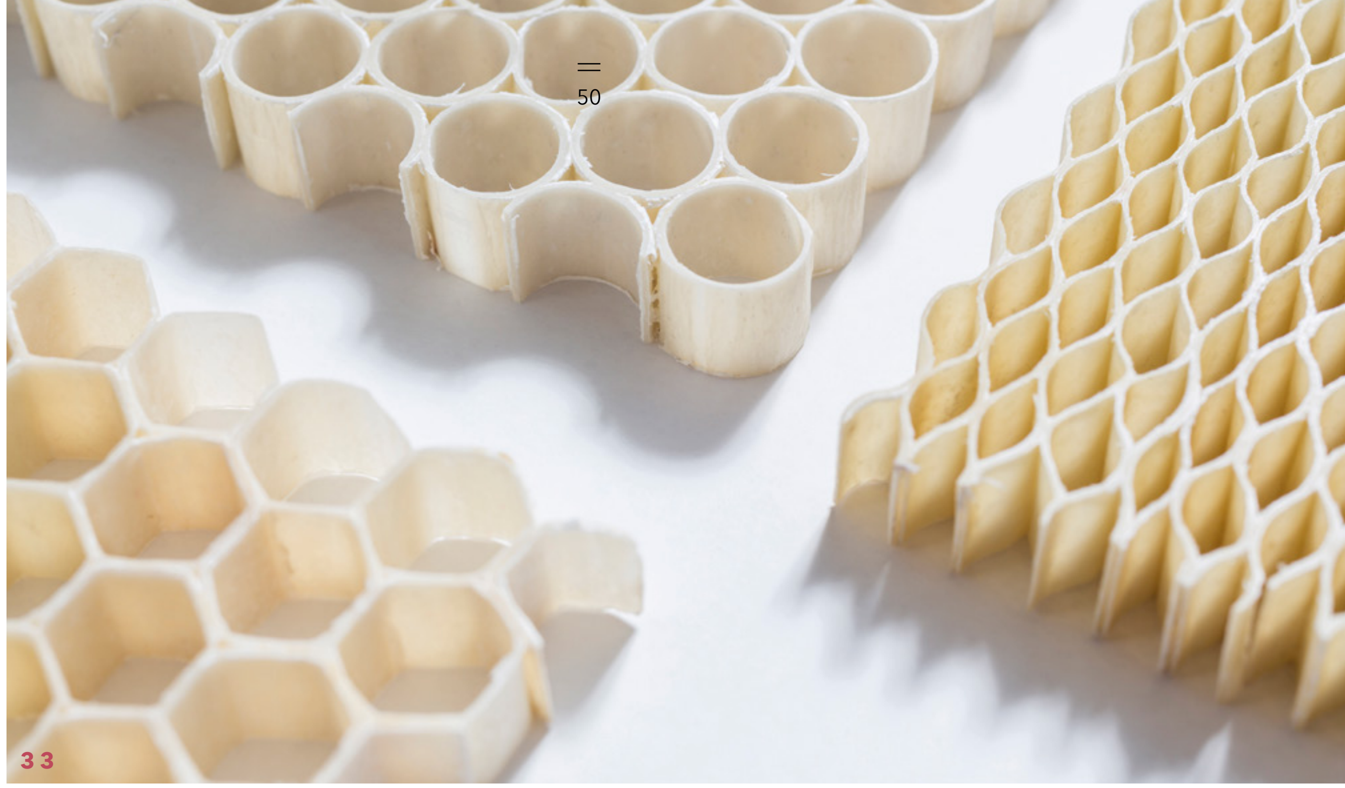

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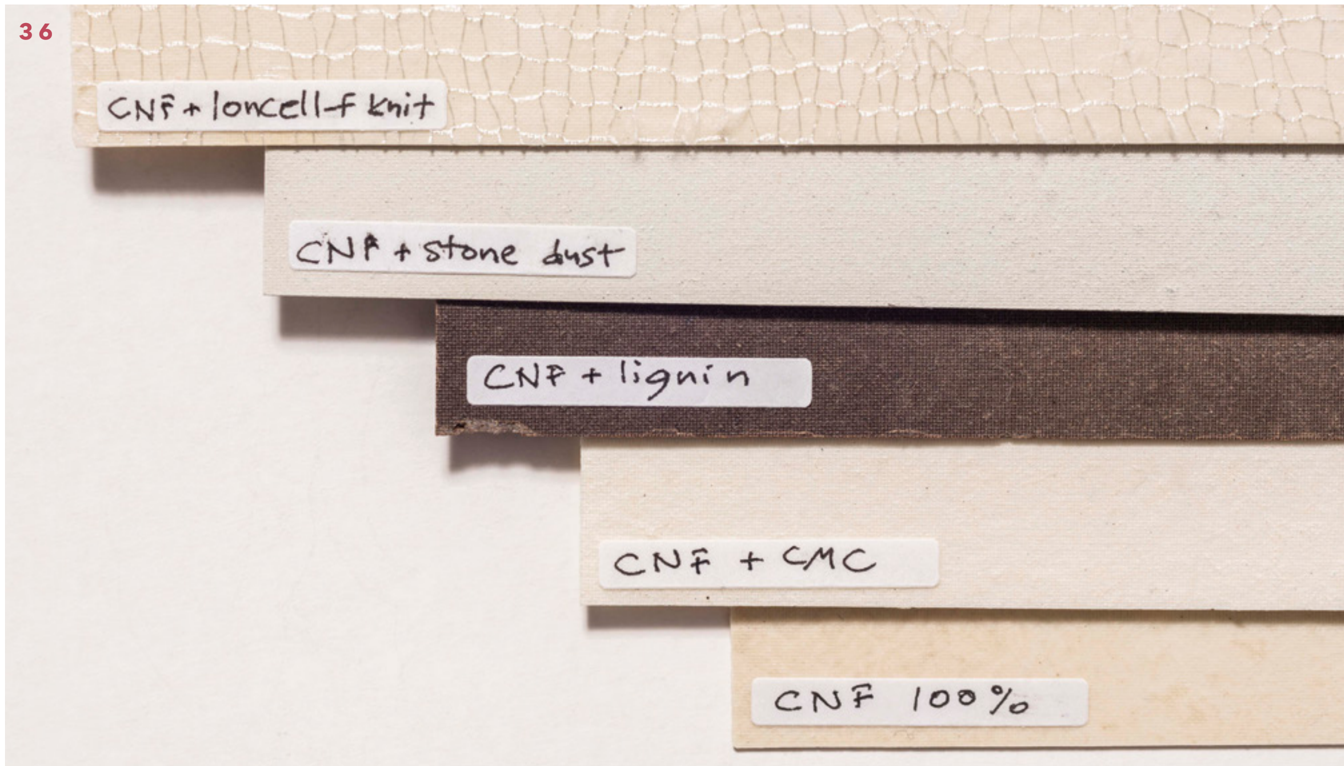

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FIGURE 37
Concept kayaking paddle.

FIGURE 38
Concept stool no. 2 with Ioncell fabric.

FIGURE 39
Concept stool no1.

FIGURE 40
Prototype bicycle with load-bearing nanocellulose structure (white tubes). The CNF tubes were produced by Tiina Härkäsalmi. The prototype was made by Kim Antin and Tuomas Pärnänen. The mechanical strength of CNF tubes was tested by Mauno Kemppainen and Steven Spoljaric.

All-cellulose shoe: Novel wood-based materials in footwear

Saara Kinnunen, Jukka Ketoja,
Atsushi Tanaka, Kari Kammiovirta, Kirsi Kataja

There is a need to find alternatives to commonly used footwear materials, such as chrome-tanned leather, oil-based synthetic materials or cotton, which are too often harmful to the environment. Ecological wood-based materials could be one solution.

The purpose of the **All-Cellulose Shoe** was to test and develop selected wood-based materials on the demo product. The material development was design-driven and carried out together with material researchers.

The main aim was to find a suitable material for the upper part of footwear. This material must be strong, elastic, water- and heat-resistant, and breathable. It was developed in various ways, beginning with a thin, easily breakable wood fibre-based non-woven (foam-formed) material. It was clear already at this point that the developed material was not likely to achieve all the qualities that the upper part of a shoe should have. Therefore, a decision was made to concentrate on developing strength and elasticity. For the final demo (see **Figure 42**) the thickness was adjusted to give good strength but not to form wrinkles in the toe area. Pulp based filaments (see Spinning pulp fibres with deep eutectic solvents, page 34) gave strength and elasticity to the base material, which consisted of pulp and viscose fibres. Birch fibres were replaced with pine fibres because they are longer.

In order to make the material even stronger and to prevent it breaking when the shoe was removed from the last, a type of cellulose derivative, coloured with textile pigment, was applied to the surface of the non-woven material by a 3D printer.

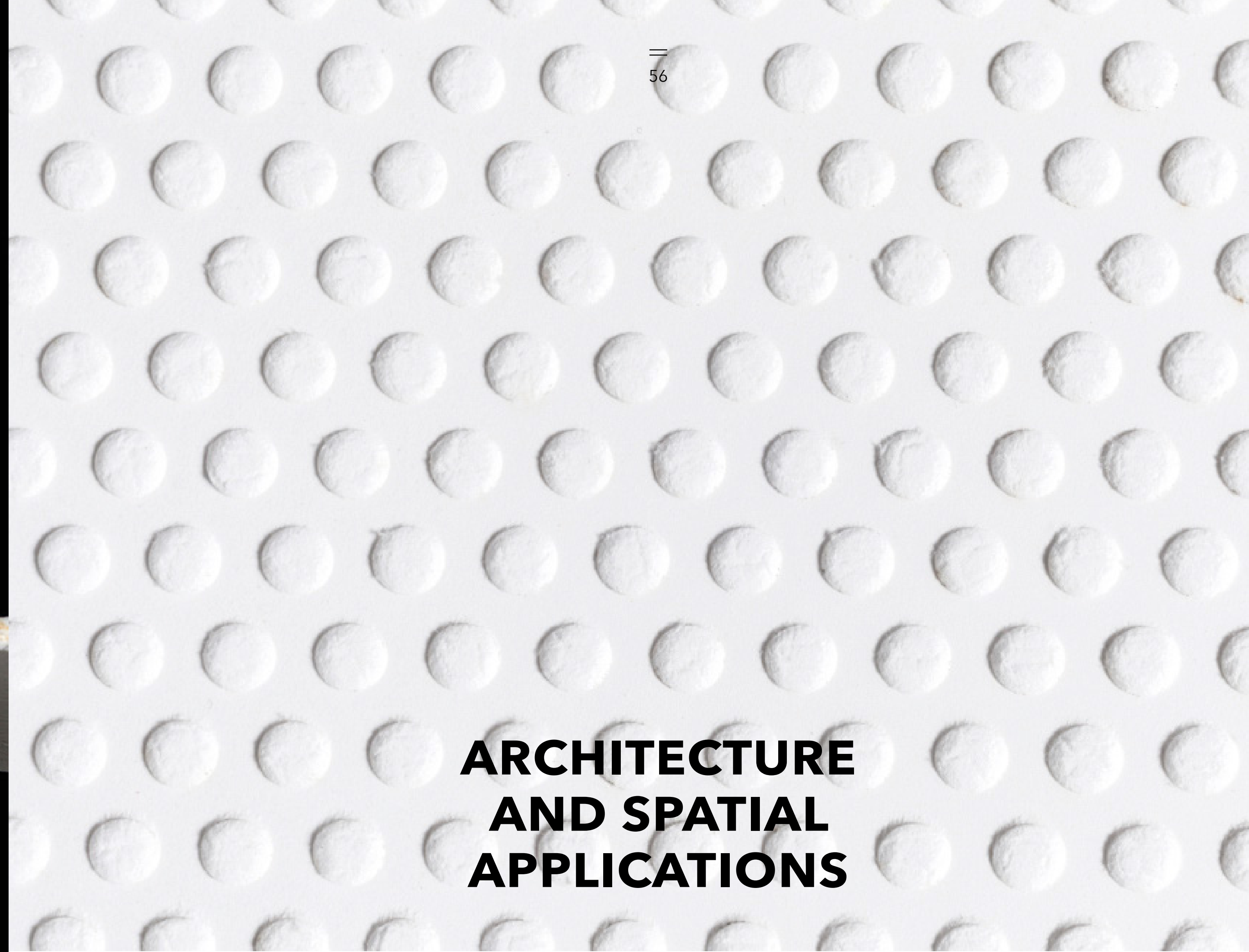
Traditionally, the toe puff and heel counter of a shoe are made from leather or plastics. In this research, we used microfibrillated cellulose paste (MFC) to reinforce the structure of the shoe. MFC was also used as a glue in all demos.

The materials endured the shoemaking process, despite being doused in water, heated, glued, sewn, and handled by heavy machines. Even though the materials are yet not strong enough to be used in commercial footwear, they turned out to be versatile and proved to have potential.

FIGURE 41
Protoyping was an essential part of the design-driven material research. Photo by Saara Kinnunen.

FIGURE 42
All-cellulose demo shoes. Design and photo by Saara Kinnunen.

More info in the Bachelor's Thesis:
Saara Kinnunen, All-Cellulose-Shoe, Wood-Based Materials in Footwear, HAMK, 2017

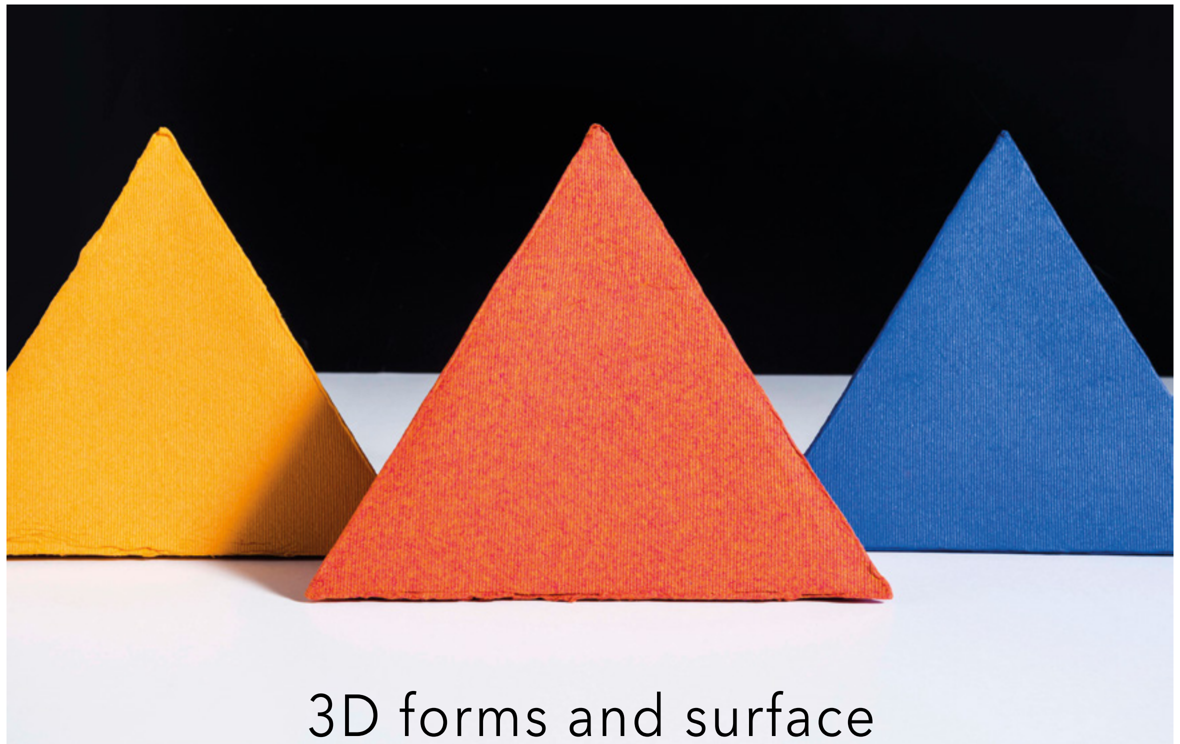


ARCHITECTURE AND SPATIAL APPLICATIONS

The combination of recently emerged manufacturing methods and the intensive research on wood-based materials will also enhance future sustainable solutions in architecture. New cellulose-based elements and all-cellulose structures can be lightweight and recyclable. Good acoustic properties and easily convertible visuality make these new applications especially interesting for interior architecture.

FIGURE 43 Laminated all-cellulose board with structured surface, see page 68.

FIGURE 44 (page 55) Laminated all-cellulose material pressed to 3D form, see page 68.



3D forms and surface structures from foam forming

Tiina Härkäsalmi, Jukka Itälä, Jani Lehmonen, Jukka Ketoja

FIGURE 45
Acoustic panels from pulp. Designed by Tiina Härkäsalmi.

Foamed pulp can be used in the production of sound absorbing and insulating panels. Due to its special structural and rheological properties, the interaction between the foam, fibre material and the structural details of the mould determine the final product properties. The unique porous structure (tunable proportion of large pores) obtained through foam forming enables material properties such as density, stiffness, gas or liquid permeability, heat insulation or sound absorption to be tailored.

The non-linear design process consisted of iterative loops between the different panel designs of the shell-like forms with both curved and edgy profiles and moulds and different surface textures. The moulds were manufactured using different technologies and materials such as plywood for hill-like structures; polystyrene, which was perforated by laser cutting and vacuum-formed into the correct shape; a metal wire material with sharp regular bends in its structure; and a 3D-printed PLA mould for a sharp-edge form. The surface texture can be varied by, for example, changing the density and size of the holes in the plastic mould. On the other hand, a metal wire moud can also produce a unique textile-like texture, in which traces of the wire appear as textile yarns. Sufficiently small and dense dewatering channels cause the sub-mm-scale regular texture to disappear.

Early dyeing of pulp with reactive dyes before the actual foam-forming process enables good colour penetration, and ensures uniform and integral colouring of the end-product. In addition, the dyed pulp enables a multitude of different colours, which are obtained by mixing batches of different basic colours. Multi-scale 3D forms entailing sub-mm-scale surface textures and micro-scale fibre network structures can be easily customised. Foam-forming allows regular flow patterns with which the desired surface texture can be easily formed. This is particularly beneficial for fibre-based applications in which perceptual properties related to the material surface are essential. Typical examples are interior elements, panelling (e.g. vehicle interiors) or furniture. In addition to acoustics and visual performance, the surface texture may also affect other technical properties such as light scattering and surface strength, which are important for interior design.

The material's density, stiffness, permeability, heat insulation, and sound absorption can be tailored. The form of the panels can be customised on multiple scales by moulding with, for instance, laser-cut and vacuum-formed plastic moulds, or a 3D-printed mould. Multiple colour variants can be produced by mixing pulp from just a few different colour batches.

All-cellulose panels are easy to recycle after use. The foam-forming process is simple and requires a relatively light infrastructure. The mouldability of the material enables tailored solutions.

MATERIAL CHARACTERISTICS

PHYSICAL PROPERTIES:

- **Stiffness:** semi-rigid
- **Structure:** closed
- **Surface:** textures
- **Transparency:** opaque
- **Surface hardness:** semi-hard, soft

ACOUSTIC PROPERTIES: sound-absorbing, sound-diffusing, sound-reflecting

SUSTAINABILITY PROPERTIES: bio-degradable, recyclable, lightweight, low carbon footprint, single/mono material

POTENTIAL APPLICATIONS: Interior acoustic elements. It is possible to manufacture multifunctional products that can tackle various needs in construction and renovation. The dyed pulp and form together provided an interesting variation to the material's visual qualities. Moreover, the surface texture enhanced its tactile properties and gave the material a feel of higher quality.

FIGURE 46
First prototypes of 3D foam formed pulp 2014. Design by Tiina Härkäsalmi and Jukka Itälä

FIGURE 47
Second cycle of 3D foam formed pulp 2014. Designed by Tiina Härkäsalmi and Jukka Itälä

FIGURE 48
Third cycle of 3D foam-formed pulp 2017. Designed by Tiina Härkäsalmi in collaboration with Eeva Suorlahti.

FIGURE 49
UV- printed foam-formed pulp boards (resembling plasterboards). The board surface looks and feels like a textile surface because the wire pattern is copied to the foam surface. The print pattern strengthens the impression of textile surface. The researched aspects by means of design were the printing quality of thin and overlapping coloured lines and appearance when printing on the wire patterned surface. Print designed by Heidi Turunen.

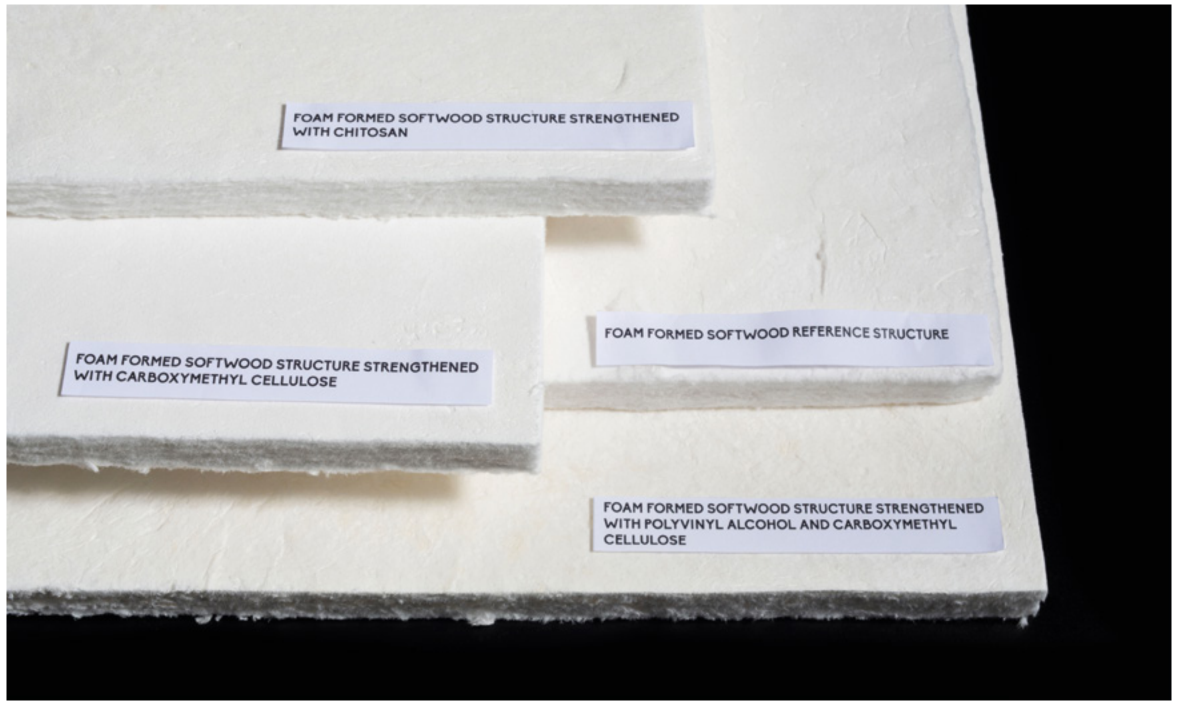


FIGURE 50 Researching the strengthening of foam panels.

Foam-formed interior elements

Jani Lehmonen, Jukka Ketoja, Atsushi Tanaka, Heidi Turunen, Anastasia Ivanova

Foam-forming technology enables the production of a vast variety of fibre-based materials. Through this research, we produced a new type of board from pulp by foam forming and pressing. The material of these boards contained only pulp and a small amount of additives (such as a foaming additive).

MATERIAL CHARACTERISTICS: The density profile of these foam-formed pulp boards (resembling plasterboard) can be adjusted. The board surface can be designed as printed or patterned.

TECHNICAL DATA: The bending stiffness for the commercial peeled plasterboard reference was 1.13 ± 0.13 MPa, and correspondingly for the foam-formed pulp board, 2.95 ± 0.43 MP. The maximum deflection for the commercial peeled plaster board was 0.5 ± 0.1 mm and correspondingly for the foam-formed pulp board 14.45 ± 0.38 mm.

POTENTIAL APPLICATIONS: Pulp-based alternative for traditional plasterboard. Decorative and functional elements.

FIGURES 51 - 53
Different kinds of interior element demos using foam forming and pressing. Designed by Heidi Turunen.

Conductive (heating) non-woven textiles and 3D elements

Sanna Siljander, Pasi Keinänen,
Anna Räty, Atsushi Tanaka,
Jani Lehmonen, Anastasia Ivanova

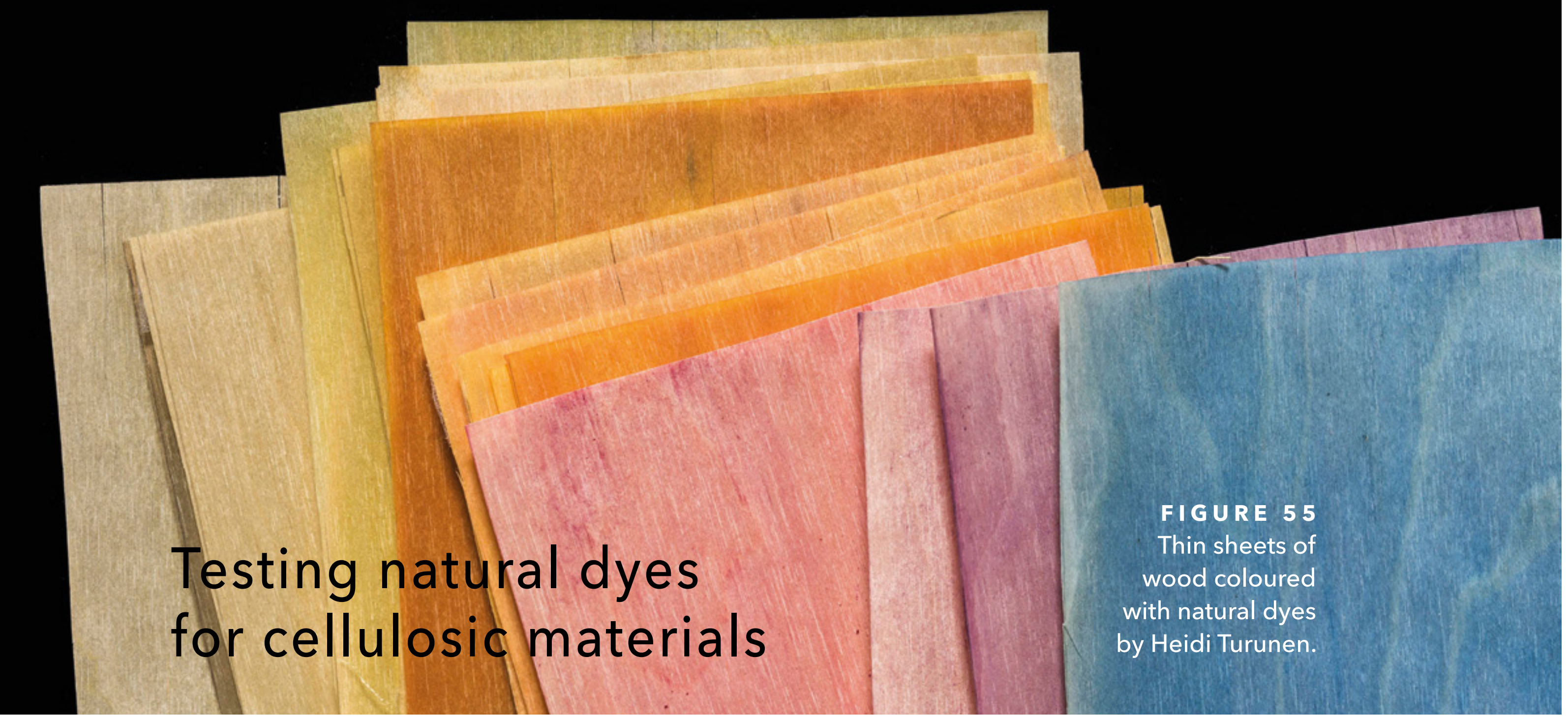
The aim of our research was to achieve optimum conductive properties in cellulose-based non-woven textiles, using a minimum amount of materials and chemicals, and a minimum number of processing steps. In the development process, we used sonication to homogenise the dispersion of carbon nanotubes (CNTs) and nanocellulose. The dispersion was mixed with matrix fibres (e.g. cellulose pulp and viscose staple fibres), using foam forming. The resulting conductive material can be in the form of either a non-woven textile or a thick 3D-shaped element.

MATERIAL CHARACTERISTICS: The materials and processes used made every single cellulose fibre in the created material structure conductive. The maximum achievable temperature of a heating structure is already adjusted in the production process by the amount of carbon nanotubes. CNTs act as a fire retardant.

TECHNICAL DATA: Heating of total volume – no hotspots. No fire hazard. The maximum temperature can be customised. Low voltage (e.g. 9V) can be used in the products, which means that they are safe and easy to install. Rapid cooling. No chemical reactions.

POTENTIAL APPLICATIONS: There are various possibilities for using this invention in different applications. The conductive non-woven element can also be used inside different structures. Examples: Boat cabin walls, car interior panels, personal heaters in offices.

FIGURE 54
Heating element 'Salmiakki'.
Designed by Anastasia Ivanova.



Testing natural dyes for cellulosic materials

FIGURE 55 Thin sheets of wood coloured with natural dyes by Heidi Turunen.

Heidi Turunen

Natural dyes, derived mainly from plants, have traditionally been used for textiles. Historical recipes include compounds which are today considered harmful, and many recipes have been updated. There is a growing interest in utilising natural dyes and finishings not only for soft materials, but also for interior elements and objects. In this project we dyed all sorts of cellulose-based material samples, using natural colours. The experiments were conducted on nanocellulose in the form of film and sphere, pine wood, birch veneer, pulp sheets, pulp fibre filaments and yarns, and fabrics made from cotton or flax. The colour sources were for example birch, lupine, nettle, onions, tancy, webcap, madder and cochineal. The dying followed the traditional process: we added the colourants to boiling water and used mordants to attach the colour.

MATERIAL CHARACTERISTICS: The hues were soft and natural. We were able to generate different types of tones, and as estimated, the soaking time affected the intensity of the colour. The shades of the samples were almost equal, despite the use of cellulosic materials. Nanocellulose dyed remarkably well, but the intensity of the tone increased due to shrinkage during the drying phase. The colours were fastened by using suitable mordants for each colourant. However, their durability against light, humidity and rubbing should be further researched, and the recipes might require adjustments to optimise the process for each material.

POTENTIAL APPLICATIONS: Natural dyes could also be a sustainable, safe way to colour various cellulosic or wooden materials on an industrial scale in the future. Application areas could be almost anywhere where cellulosic materials are used.

Glueing with nanocellulose

Jaakko Pere, Jyri Roppola, Vesa Kunnari

All-cellulose structures such as soft/hard, soft/film, hard/film cellulose structures, can be easily glued with enzymatically fibrillated nanocellulose (HefCel). We developed an adhesion test method for two unlike cellulosic material surfaces. The test results show an important correlation between fibre-based material porosity and adhesion gained with nanocellulose particle suspension: the higher the porosity, the better the bond strength between two adherents.

POTENTIAL APPLICATIONS: Glueing all-cellulosic structures for end-use in dry conditions.

Cellulose nanofibril-based coating as fire retardant

Jaakko Pere, Vesa Kunnari, Timo Kaljunen

We developed a material combination of microfibrillated cellulose (HefCel) and inorganic nano-scale pigments, which can act as a fire retardant on a wooden surface. HefCel acts as a binder. The material contains no additional chemicals.

MATERIAL CHARACTERISTICS: The developed fire retardant material is easy to apply to wood, using a brush, roller or spray. Importantly, unlike most traditional fire retardants, it is safe for both the environment and humans. It dries when heat and airflow of less than 60s for single layer is used. A surface layer of thickness less than 100 microns is capable of protecting wood from ignition during a 180 second flame exposure.

POTENTIAL APPLICATIONS: Can be used as a fire retardant on wood (or other similar cellulosic surfaces) in dry conditions.

We have filed a patent application for the concept. Research activities to commercialise the technology are ongoing.

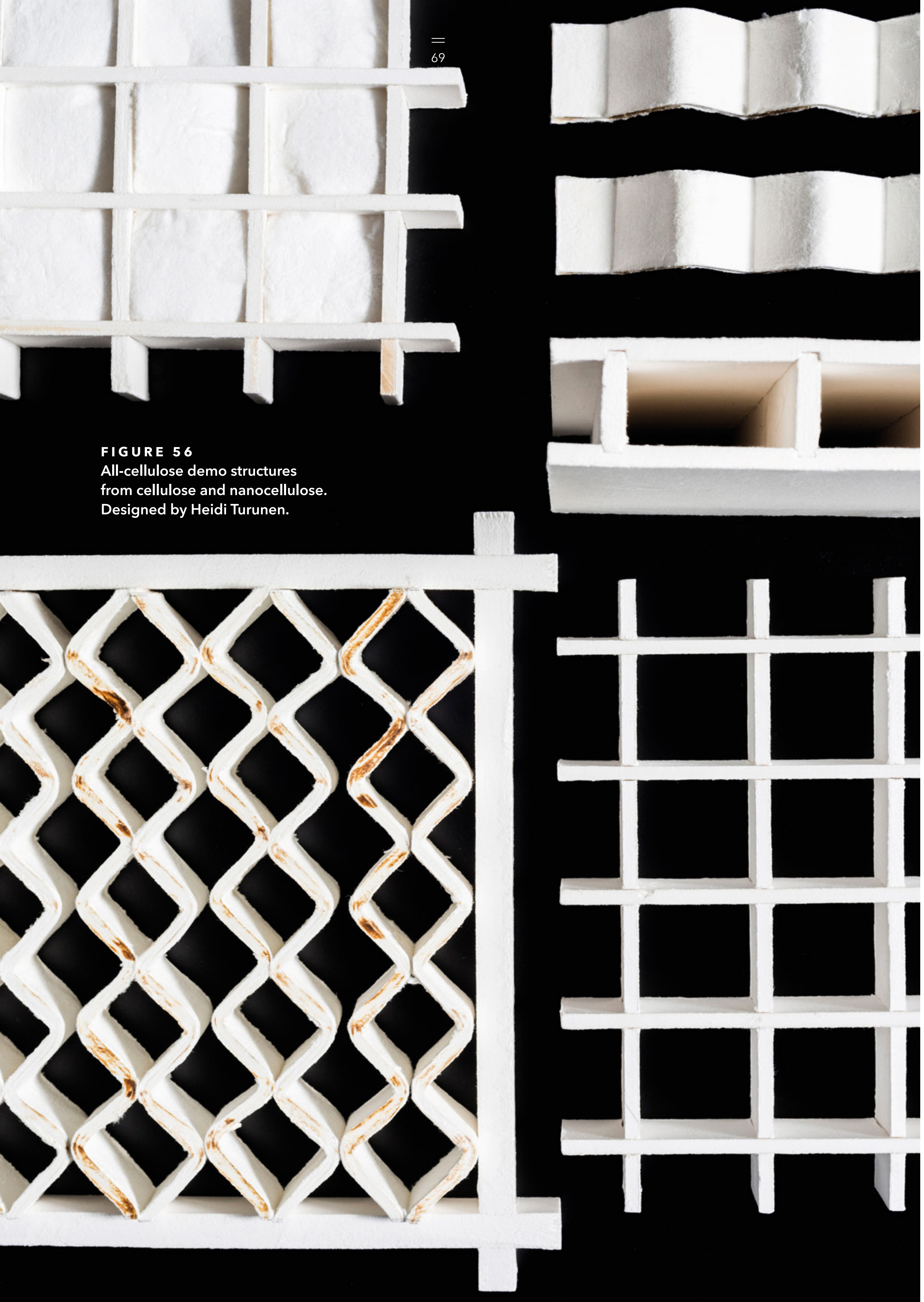


FIGURE 56
All-cellulose demo structures from cellulose and nanocellulose. Designed by Heidi Turunen.

Laminated structures for interior architecture

Vesa Kunnari, Heidi Turunen, Timo Kaljunen, Jaakko Pere, Ali Harlin, Ulla Salonen, Vuokko Liukkonen, Jyri Roppola (TUT, student), Kirsi Kale (Omnia, student)

This is a method of producing a novel laminated material structure that combines nanocellulose and cellulose. No additional glue is needed. The method has been demonstrated by creating interior architectural design elements.

MATERIAL CHARACTERISTICS: The material is strong and light. Various finishing possibilities include embossed patterns, printed pictures and painted surfaces. Wet material can be shaped into 3D forms. The material can be drilled or sawn using conventional woodworking tools. It is totally bio-based and biodegradable.

TECHNICAL DATA: The bending strength of this novel structure is 28 N/mm2, which is higher than the strength of the tested reference materials chipboard (8 N/mm2), gypsum board (EH, 10 N/mm2), MDF (26 N/mm2) and softwood plywood (22 N/mm2).

ECONOMY: Competitive raw material price, simple production process.

POTENTIAL APPLICATIONS: Interior architectural design elements, an alternative to domestic partition walls made from gypsum and chip board, office partition walls that are light and sound absorbing, and furniture.

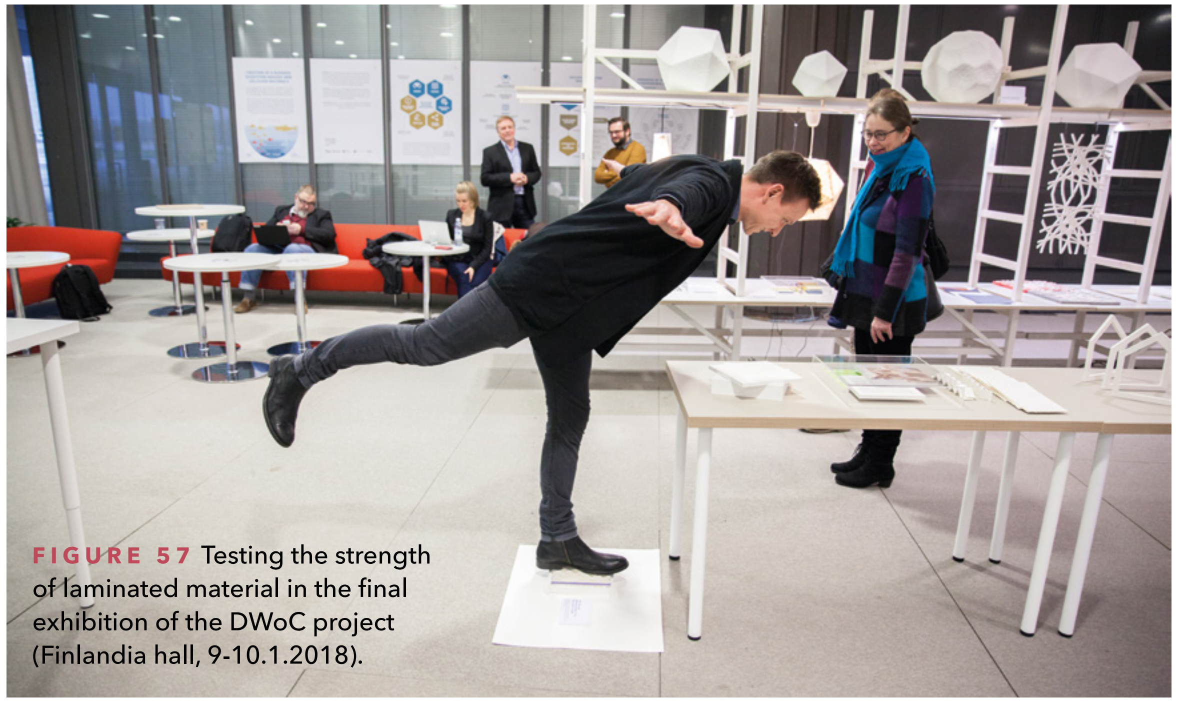


FIGURE 57 Testing the strength of laminated material in the final exhibition of the DWoC project (Finlandia hall, 9-10.1.2018).

Dyed and printed nanocellulose films

Heidi Turunen, Vesa Kunnari, Jaakko Pere, Pauliina Varis, Timo Kaljunen

Cellulose micro/nanofibrils have high binding and film-forming potential. Earlier projects have upscaled this feature to produce films on a pilot scale with different characteristics. In this project, we studied the design-driven production of dyed and printed films to determine their potential, and to inspire innovative future applications. Dyed nanocellulose films were produced on the **VTT SutCo line**, using film-making technology based on a patent shared by **Aalto University** and **VTT**. The prints were produced using one of two techniques; silk screen prin- ting or an office inkjet printer.

MATERIAL CHARACTERISTICS: Films may have different characteristics depending on the fibre origin and processing method. Without dyeing, their appea- rance varies from completely transparent to translucent. Prior to film preparation, micro/nanofibrils can be easily dyed for visual effects. Films are up to ten times stronger than copy paper, but somewhat more brittle.

POTENTIAL APPLICATIONS: Micro/ nanofibril films can provide naturally excellent barriers against oxygen and grease in, for example, food packaging. By chemical surface functionalisation, these films can be tailored for different end uses. Dyed and printed films can be used in many applications that demand visually aesthetic properties.

FIGURE 58
Inkjet printed nanocellulose films. Printed microscope images of willow bark by Jinze Dou, Aalto University. Designed by Heidi Turunen.

FIGURE 59
Dyed or screen-printed nanocellulose films. Pattern and color design Pauliina Varis.

FIGURE 60
Wooden Rag Rug. Horizontal timber strips with various widths painted using coloured nanocellulose. Designed by Heidi Turunen.

Cellulose nanofibril coating as paint

Jaakko Pere, Vesa Kunnari, Heidi Turunen

Cellulose micro/nanofibrils have an inherent ability to bind to wood and to various small-scale particles such as colour pigments. These features have been combined by applying colour to wood surfaces using only nanocellulose as a binder.

MATERIAL CHARACTERISTICS: CNF have different characteristics, depending on the fibre origin and processing method. Their appearance as dried layers may optically vary from completely transparent to translucent. Micro/nanofibrils can be easily dyed for visual effects. Films and structures made from nanofibrils in general have tensile strength comparable to aluminium, although their surface appears paper-like. They are also completely recyclable. Micro/nanofibril paint can be washed away from surfaces using water. Using nanofibril manufacturing technology developed at VTT, the paint application solid is between 10% and 15%, and drying time is comparable to that of traditional water-based paints.

POTENTIAL APPLICATIONS: Micro/nanofibril coating as paint may provide a new eco-friendly interior decoration option for surface treatment. Non-permanent markings that are removed using water spray and a cloth in, for example, construction, stencils, temporary protection during transport, or dressing paint, could apply this technology. This technology will be developed further to provide enhanced water tolerance.

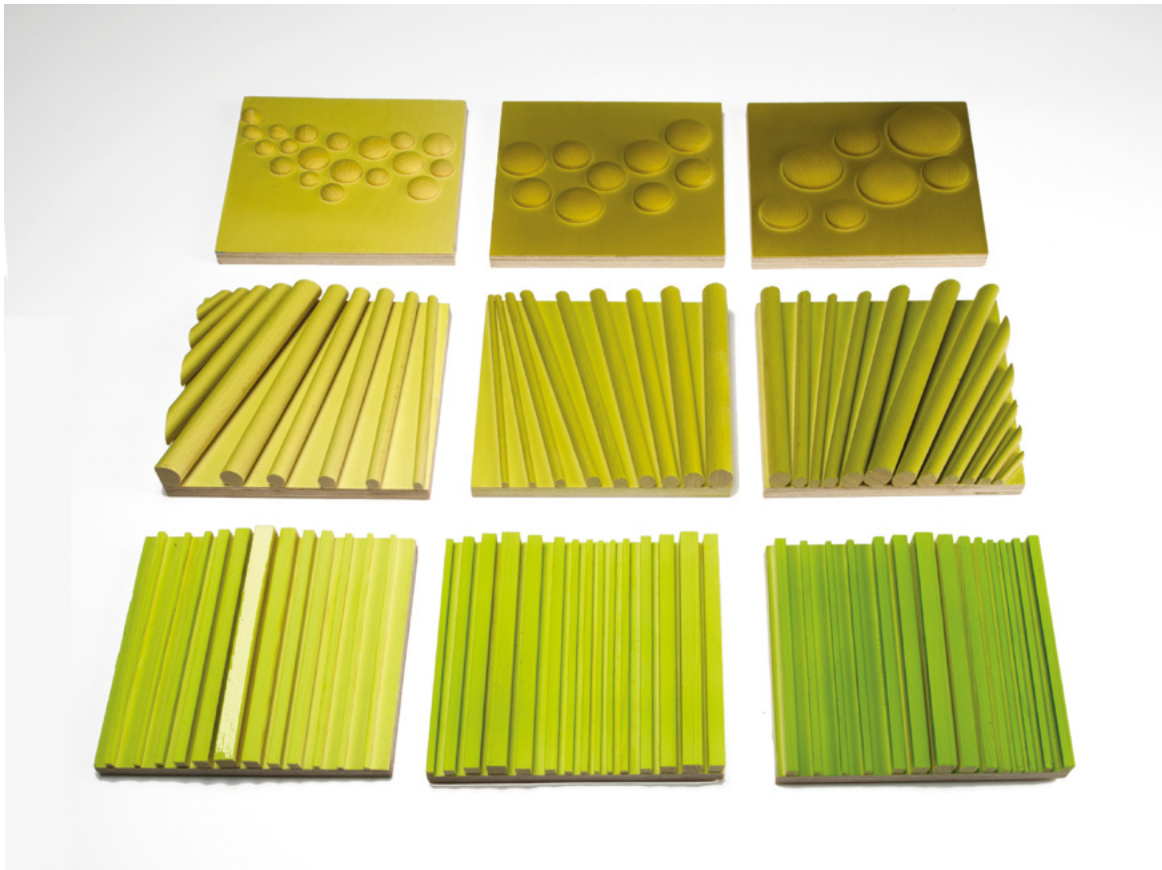
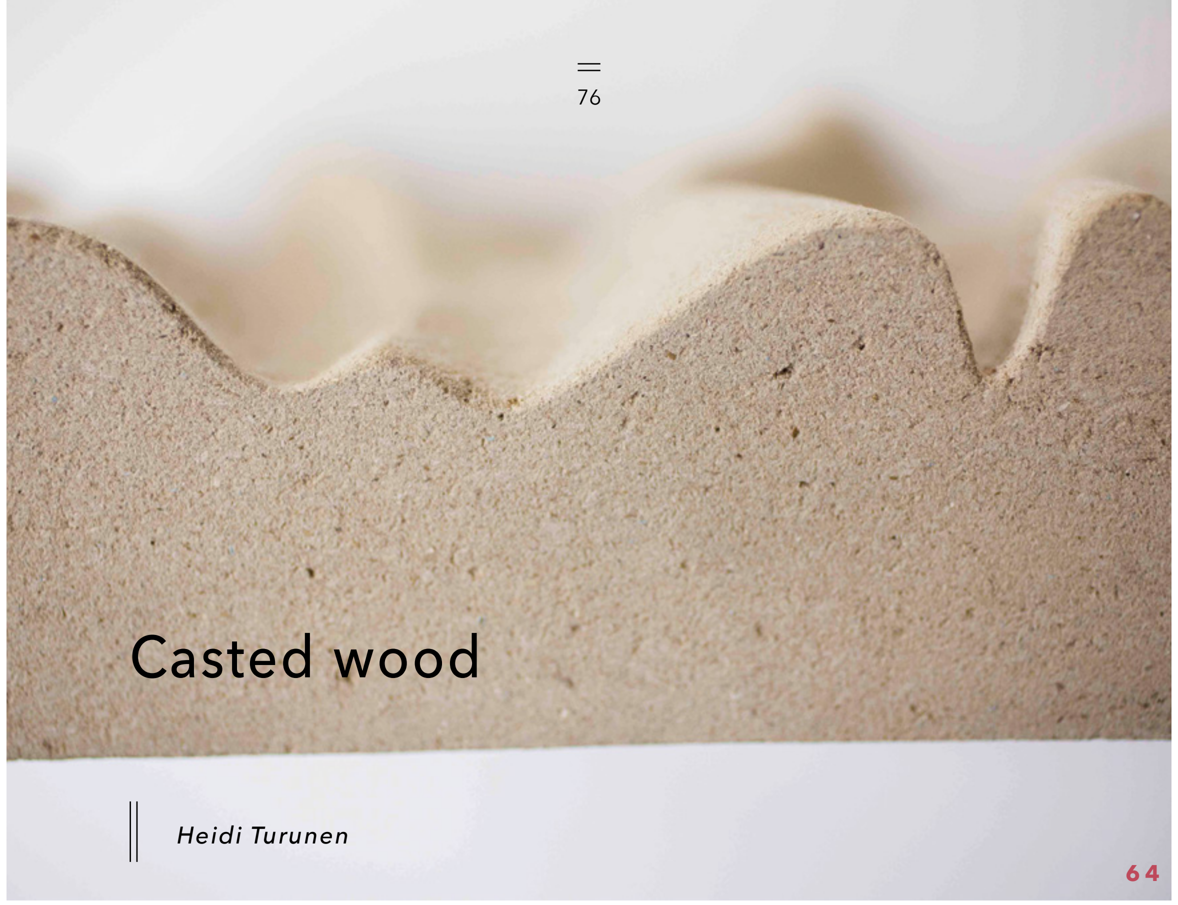


FIGURE 61 Wooden reliefs painted with coloured nanocellulose. Design of reliefs by Heidi Turunen. Photo by Anne Kinnunen.

FIGURE 62
Balls made of wood dust mixed with nanocellulose by Heidi Turunen

FIGURES 63, 64
Casted wood. Designed by Heidi Turunen



Casted wood

Heidi Turunen

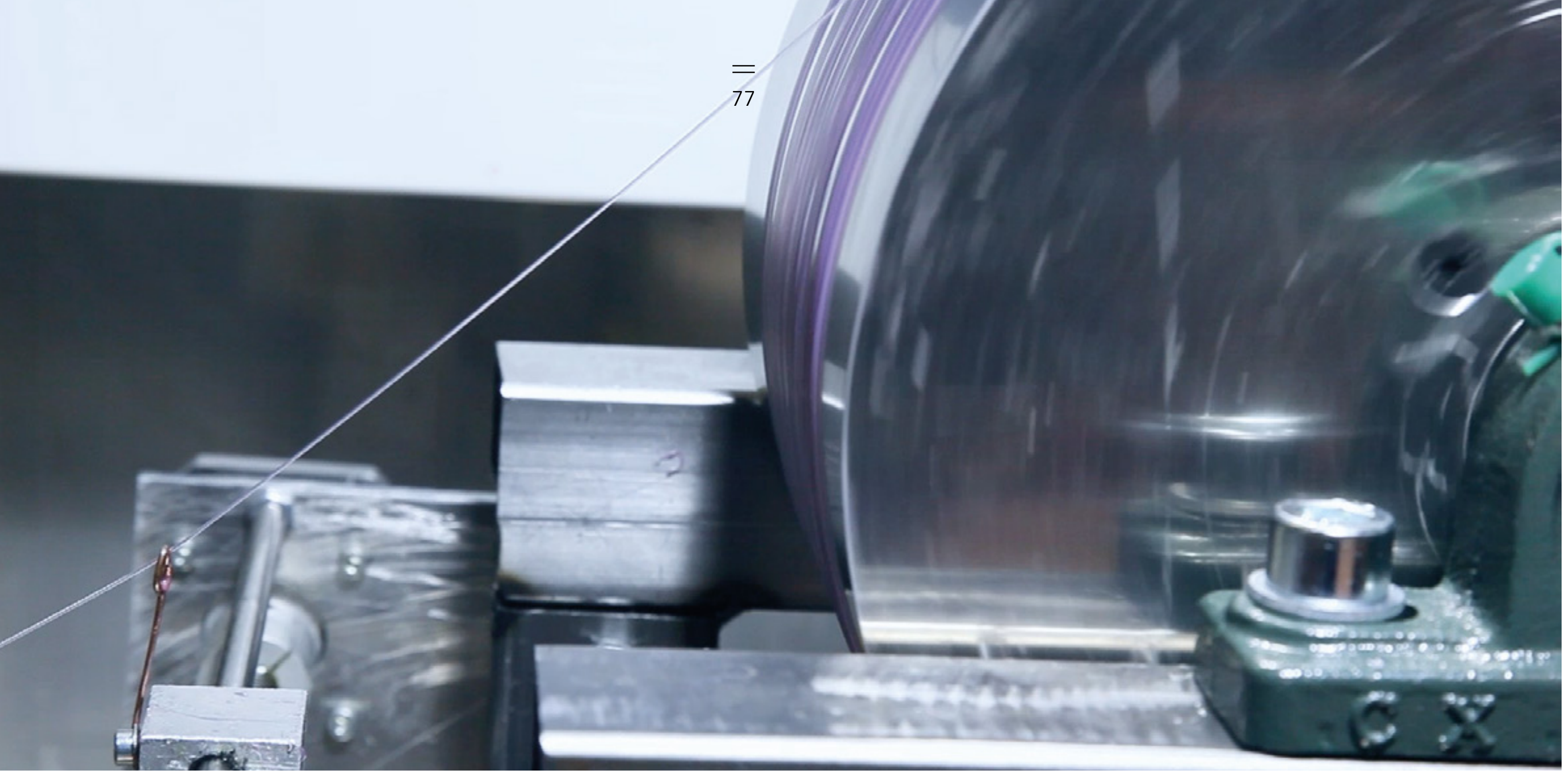
64

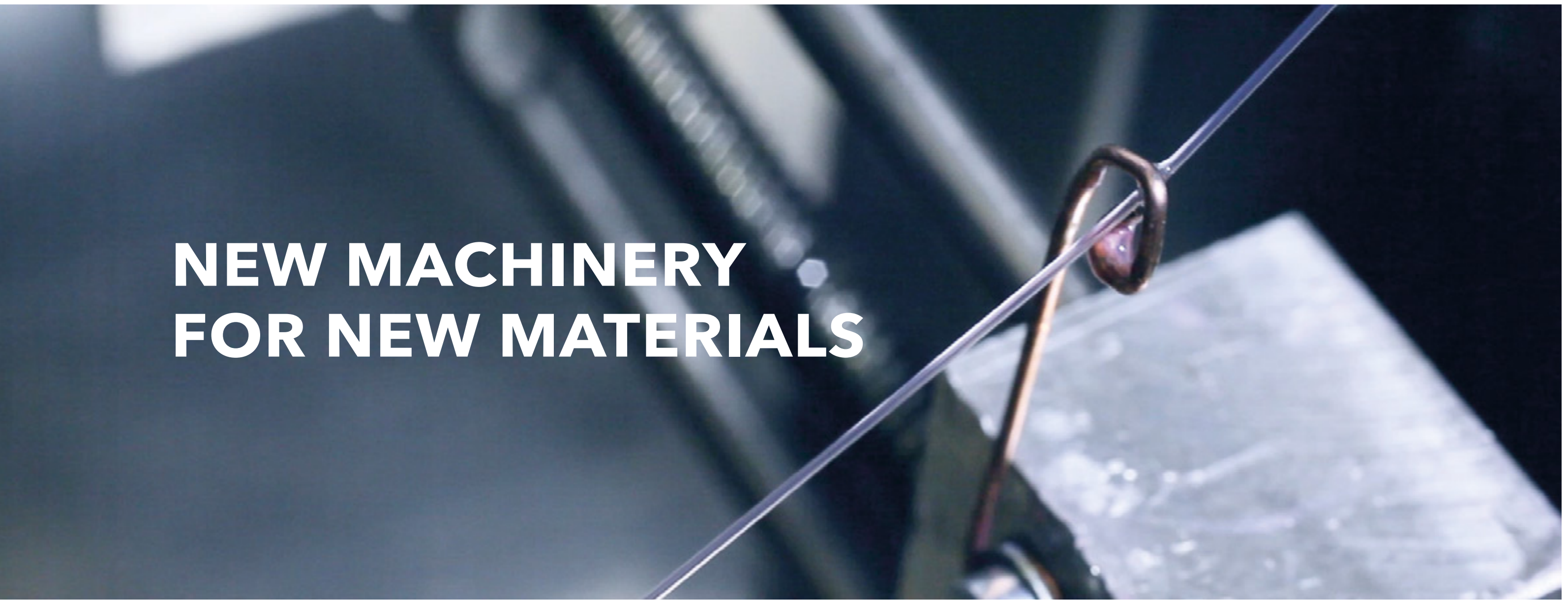
Nanocellulose is mixed with wood dust or coarse sawdust to produce the material for casting. A watery material combination may be poured into designed moulds, resulting in hard predetermined shapes after the water has evaporated. The cast pieces can be reproduced by reusing the moulds. Machining is not necessary, though light surface grinding may be necessary, depending on the applications. The shaping possibilities, when using moulds, are somewhat similar to the cast materials in general. Completely wood-based material combination has a low environmental impact and is recyclable.

MATERIAL CHARACTERISTICS: The surface structures of the material can be designed using moulds or by alternating the granularity of the wooden ingredient. The material can be dyed by, for example, using natural mineral pigments or natural colours. The tone of the dyed material is soft, due to the inherent beige colour of the wood. The surface of the material feels warm as do wooden surfaces.

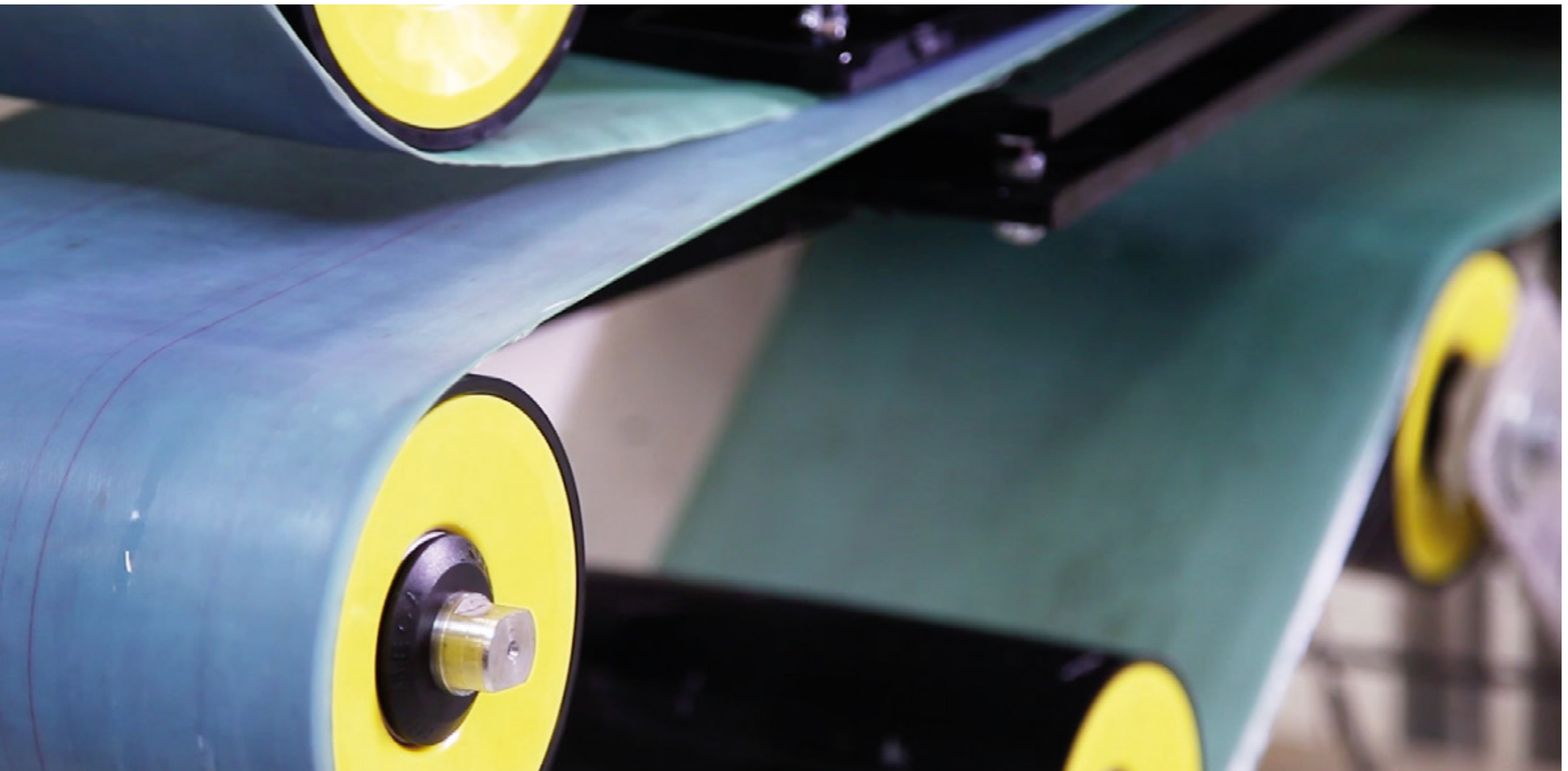
TECHNICAL DATA: The shrinkage of the casted material and the strength of the dried material depend on the mixing ratio of the raw material. However, its shrinkage is relatively lower than that of nanocellulose, at just a few per cent. Its acoustic features are presumably close to the properties of wooden material.

POTENTIAL APPLICATIONS: When wooden materials are used in a malleable form, application areas expand. The outcomes can be used in various products such as wall reliefs for artwork, sound-directing designed objects, applications in the sports or toy industry, jewellery, shoes, disposable applications in gardens, interior decoration products, furnishings, or products related to the construction industry.





NEW MACHINERY FOR NEW MATERIALS



Many of the wood-based cellulosic materials researched in the DWoC project are entirely new. As such, most of them are not directly usable in established industrial manufacturing processes and machinery. For instance, many of the spinning dopes cannot be directly used in conventional spinning lines as the time scales for filament and yarn formation are completely different. While in their simplest form, filaments can be produced by simple extrusion, these types of spinning approaches are often suboptimal in terms of both filament properties and production rates.

To address these issues early, we developed new process machinery and approaches at the same time as spinning raw materials. Many prototypes were constructed to identify bottlenecks and challenging functions in the manufacturing process. The early identification of these critical areas is crucial, as addressing them later on is far more costly.

The prototypes were iteratively improved throughout the DWoC project. They also enabled us to study the influence of critical process parameters and their optimisation. **Figure 65** illustrates the adopted development process model.

Machinery development in the DWoC can be roughly divided into two categories: filament spinning and 3D-printing, which are discussed in more detail in Sections Spinning machinery, page 79, and Machinery for 3D printing, page 83, respectively. The main target in the development of the spinning machinery was to upscale production rates while maintaining or even improving the properties of the yarn/filament. Regarding 3D printing, we tested various extruders (both commercial and own designs) and developed a testing platform to efficiently test the 3D printability of a wide range of cellulosic raw materials.

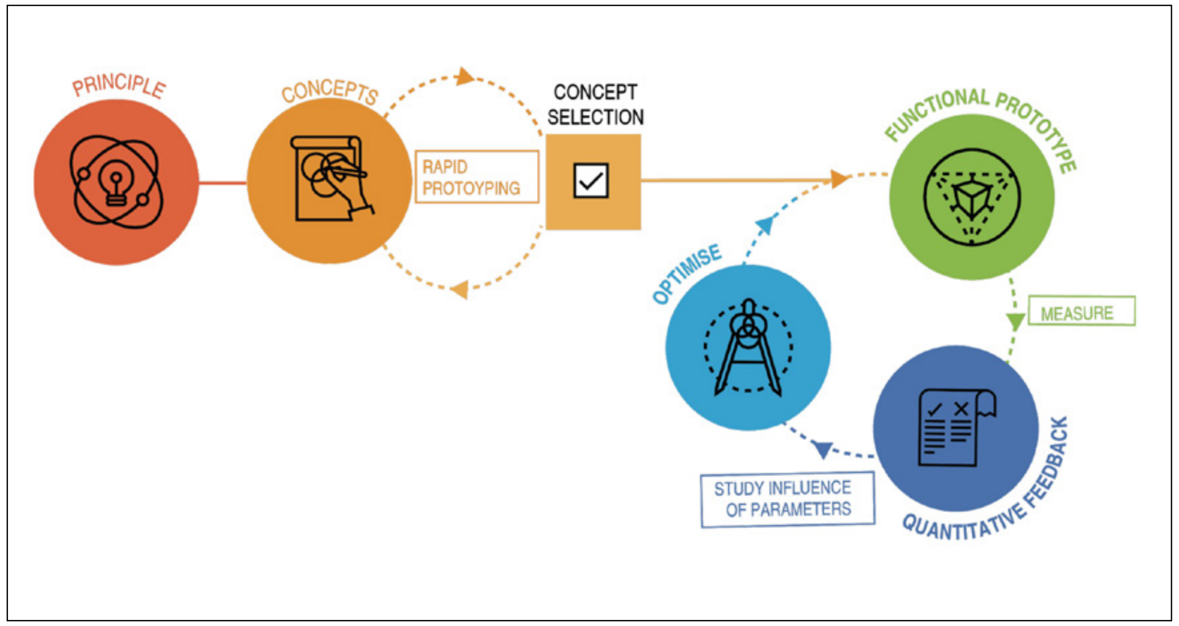


FIGURE 65 Process model used in machine development.

Spinning machinery

In the first phase of the DWoC project, we tested, developed and successfully demonstrated several approaches to filament spinning. In the second phase we set out to further develop these technologies in terms of both the materials and processes. As regards upscaling and spinning machinery development, we worked on three approaches;

- Wet spinning of CNF
- Coaxial wet spinning with a CNF core
- Dry-jet wet spinning of DES (Deep Eutectic solvent) treated pulp

The aim of upscaling was to assess the technological readiness and scalability of the spinning methods. Furthermore, to test the yarns and filaments as parts of larger structures such as non-wovens, textiles or composites, we needed to produce them at higher production rates.

The spinning dope characterisation as well as the filament/yarn analysis met-hods are described in detail earlier in this report. For each spinning approach, 2–5 prototypes were constructed. The fidelity of the prototypes ranged from very rough to fully functional. The different spinning line prototypes were iteratively improved throughout the DWoC project, resulting in improved fibre yarn and filament properties, as well as increased production rates. Each spinning approach and the related development is briefly introduced below.

FIGURE 66 Photograph of coaxial spinning line prototype. Photo by Ville Klar.

Coaxial wet spinning with a CNF core

Meri Lundahl, Ling Wang,
Ville Klar, Hannes Orelma,
Petri Kuosmanen, Orlando Rojas

One of the main challenges with spinning CNF is that it develops wet strength much slower than, for example, cellulose solutions. In the process domain, this translates into having to be very gentle with incipient filament to maintain the continuity of the spinning process. To tackle this problem, we studied how a supportive outer polymer could be used to enable facile processing of the incipient filament with higher draw ratios.

We developed several prototypes for this approach, which are illustrated in **Figures 66** and **67.** Depending on the coagulation speed of the supportive polymer, the incipient filament could either be immediately picked up by a rotating roll, or transported on a conveyor belt. The rotating roll was heated to expedite the drying of the filament. Various mechanisms were studied for the traversing movement of the filament guides. Eventually, the best approach with slowly coagulating sheath polymers was to move the roll itself instead of using guides. This approach subjected the incipient structure to the least amount stress.

Although these prototypes were used to produce significant quantities of filament, their mechanical properties were lower than those of the pure CNF filaments reported in literature. Furthermore, the roll-based drying method resulted in filaments of a ribbon-like shape. These factors prevented deeper investigations of the coaxial filaments as part of larger structures such as textiles and composites.

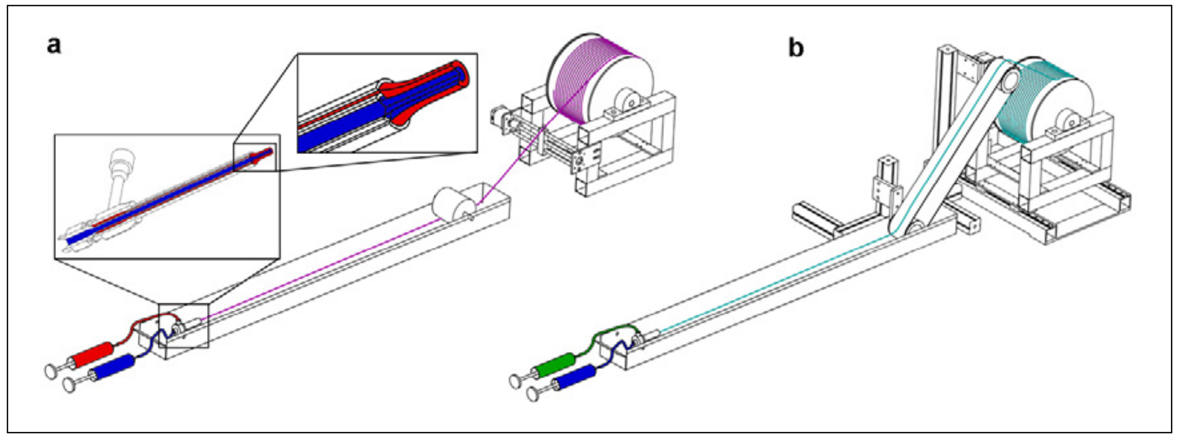


FIGURE 67 Schematic views of spinning lines without (a) and with (b) a conveyor belt.

Dry-jet wet spinning of DES (Deep Eutectic Solvent)-treated pulp

Ville Klar, Hannes Orelma, Hille Rautkoski, Tiia-Maria Tenhunen, Ali Harlin, Petri Kuosmanen

The **DES method** for producing fibre yarns was developed in the first phase of the DWoC. The softwood pulp fibres are mixed with a DES. The DES pre-treatment results in a gel-like spinnable suspension, which can be solidified by removing the DES with a suitable solvent such as ethanol. These structures are unlike conventional cellulosic monofilaments or yarns, and therefore we refer to them as fibre yarns.

We developed a series of prototypes related to this wood fibre yarn spinning process. Similarly to CNF, the incipient fibre yarn had low wet strength, which meant we could not employ conventional wet spinning approaches. After rapid prototyping, an inclined channel approach showed most promise so we chose this as the main concept. The novel feature of the spinning approach is that unlike traditional wet spinning or dry-jet wet spinning, the dope is extruded onto an inclined channel instead of a stationary bath.

Inclined ethanol stream serves three purposes. Firstly, it enables gentle, controlled drawing of the incipient fibre yarn. In early testing, various rolls and godets were tested and we found that the incipient fibre yarn structure lacked the wet strength to ensure continuous spinning. Secondly, the ethanol stream enabled expedited removal of the DES from the incipient yarn. Thirdly, inclined ethanol stream is a gentle way of simultaneously removing DES and transporting the yarn to a pick-up roll. This idea, with successful tests, led to the invention disclosure.

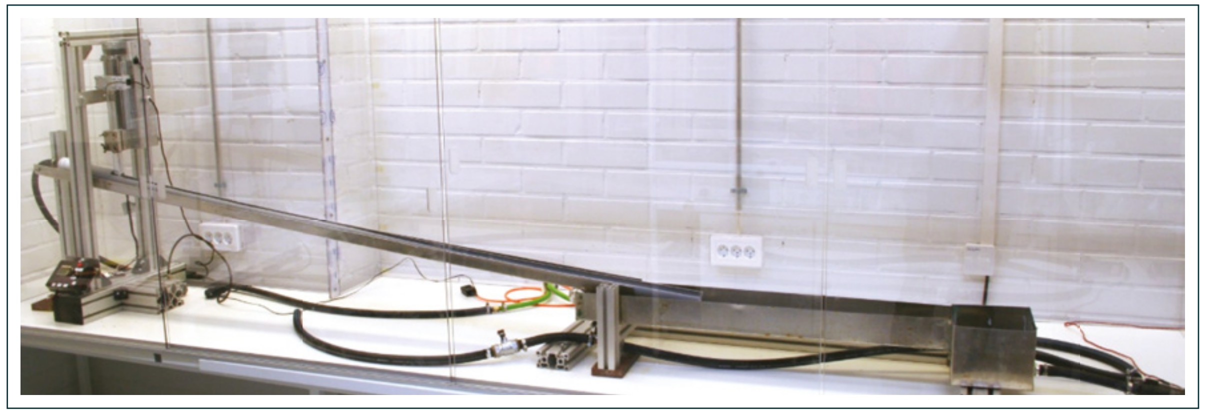
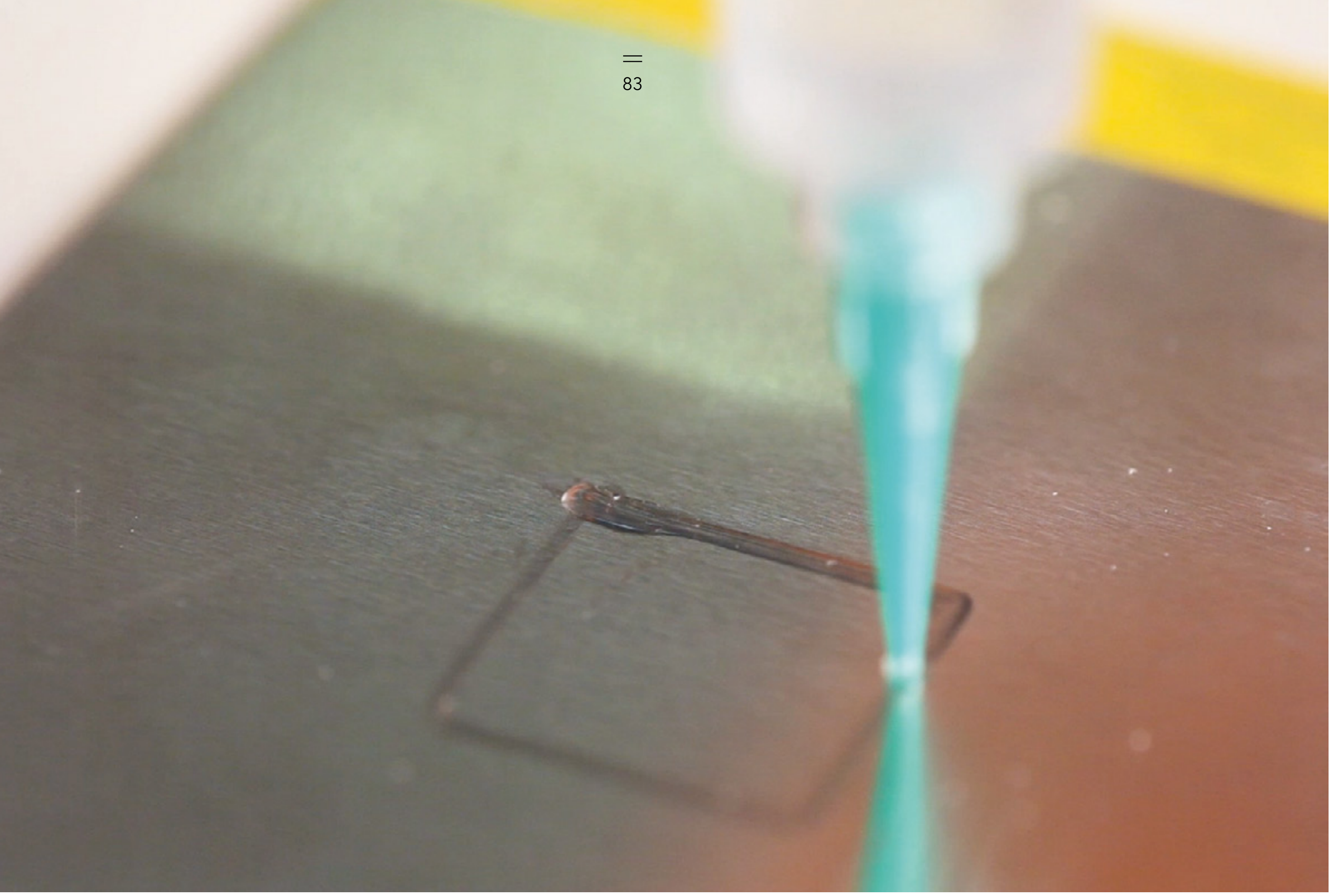


FIGURE 68 Prototype inclined channel spinning line. Photo: Ville Klar.

We constructed a modular prototype spinning line (shown in **Figure 68**), in which process-critical parameters could be measured and controlled. We studied the influence of various spinning parameters and were able to increase the load-bearing capacity and decrease the linear density of the yarn. By adjusting the angle of the channel and the flow rate of the ethanol we were able to continuously spin the yarn. The inclined channel spinning approach both reduced the linear density and increased the load-bearing capacity of the yarn. Linear densities decreased from 21–24 tex to 13–15 tex. Tenacities improved from the previously reported 5.3 ± 1.8 cN/tex to 7.5 ± 0.3 cN/tex.

Despite substantial increases in the production rates in several spinning approaches, the properties of the yarn remained low compared to, for example, regenerated cellulose fibres. The yarns had an irregular cross-sectional geometry, which led to variation in the tensile properties. This limited the use of the produced yarn and filament samples in the research of woven or knitted textile structures. Instead, the produced yarn was used for the research of non-wovens with different staple lengths See Non-woven textiles with foam-forming, page 41.

FIGURE 69 DES fibre yarn.



Machinery for 3D printing

Ville Klar, Pyry Kärki, Hannes Orelma,
Tiia-Maria Tenhunen, Petri Kuosmanen

FIGURE 70
Printing of non-thermoplastic cellulose materials with new machinery.

In the second phase of the DWoC project, a custom 3D-printing testing platform was developed. The goal was to develop an efficient way of testing a wide variety of different pastes, solutions and other liquids. One of the main requirements was to be able to extrude high-viscosity liquids, even through small orifices, in a controlled manner.

The cartesian motion was performed by a commercial inexpensive table-top CNC frame. Open-source electronics and firmware were used to translate the g-code into stepper motor movements. Most of the software toolchain in the 3D printer prototype was open source, which meant it was highly configurable, unlike most commercial alternatives.

The printer development focused on designing the extruder. The development work began by benchmarking various commercial solutions and testing different extrusion methods. Several 3D-printed prototypes were tested, and the most performant extruder design was a syringe pump. To further improve the syringe pump idea, we attached a load cell to the piston, which enabled us to monitor and control the extrusion pressures while printing. In addition, the printing could be performed at either a constant speed or a constant pressure mode. **Figure 71** shows the printer and extruder prototype.

The tested materials included

- Aqueous suspensions of various nano- and microfibrillar celluloses with different solids contents
- Different cellulose derivatives such as cellulose acetate in various solvents (e.g. acetone)
- Cellulose solutions (ionic liquid as solvent) of different substrates such as fabric and non-wovens (described in the next chapter)

We also developed methods for evaluating the drying related geometrical distortion of the 3D-printed structures. The first iteration of this evaluation method was based on a custom optical system based on photography and image recognition. The second iteration was based on the algorithmic analysis of point clouds from 3D scans.

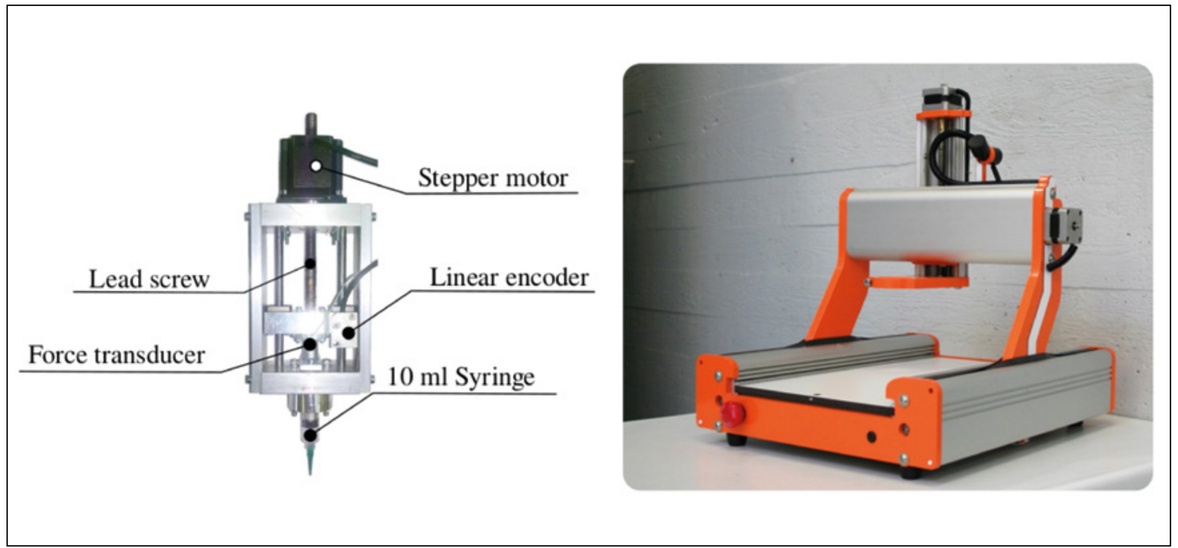


FIGURE 71 Syringe extruder prototype and 3D-printer frame. Photo by Ville Klar.

FIGURE 72 Extruder prototype for 3D printing non-thermoplastic cellulosic materials. Designed and constructed by Pyry Kärki and Ville Klar.

3D PRINTING OF CELLULOSIC MATERIALS

Material extrusion-based additive manufacturing, often termed three-dimensional (3D) printing, has risen to the status of a standard manufacturing technique in just a few decades. It enables toolless and patternless production of complex geometries. Furthermore, due to its digital nature, 3D printing can be used for local on-demand production as well as mass-customisation.

Many 3D-printing techniques rely on layer-wise shape production. Thermoformable materials such as metals and plastics are widely used. Non-thermoformable materials such as ceramics are also used in paste-based printing. We have focused our research on two printing technologies: **Direct Ink Writing** (**DIW**) and **Fused Deposition Modeling** (**FDM**).

In the DWoC project we believe that 3D printing with cellulose-based materials holds the potential to realise a truly sustainable and circular economy. The majority of current research efforts in the context of the 3D printing of cellulosic materials are in the biofabrication context, meaning, for example, tissue engineering and wound dressings. In the DWoC we set out to expand the possibilities of cellulose as a 3D-printing raw material.

Several different cellulose-based materials were successfully 3D printed using DIW or FDM technologies. The results are described in the following three sections. The research in the first three sections was conducted using DIW technology, and the fourth case was performed using FDM. The distinctive trait of DIW technology was that the solidification of the printed structures was not based on phase transition from molten to solid form, but rather on evaporation or the removal of a solvent or liquid phase. DIW technology is necessary for most cellulose-based materials, as they lack the necessary thermoformability for conventional 3D-printing techniques. The DWoC project used both a commercial printer (nScrypt) and a custom testing platform (described in the previous section). We tested a wide variety of different cellulose-based liquids and pastes. We also tested the use of a thermoformable filament in existing FDM 3D printers. The different printing trials are discussed in further detail in the following four sections.

FIGURE 73
3D/2D printed pattern on fabric changes its visual and elastic properties.

3D textiles by printing cellulose on cellulose

Tiia-Maria Tenhunen, Pirjo Kääriäinen, Marjaana Tanttu, Ilona Damski, Pauliina Varis, Kari Kammiovirta, Ville Klar

Several experimental garments have been 3D printed over recent years. In some cases, the material structure has been reminiscent of textiles, but the raw material has been plastic based and unsuitable for everyday use. Instead of printing the whole textile, an interesting option could be printing on textiles. The use of cellulose-based printing materials in fabric modifications could have high application potential because of the structural similarities between the cellulose fabric and the print. Moreover, these materials could be utilised to install functionalities on fabric surfaces as light or thermo-responsible materials. From a design point of view, affordable modifying or personalisation of textiles using 3D printing will make them available to the masses, and the use of personalisation will rapidly expand in the near future.

We tested the suitability of several cellulosic materials for 3D printing on fabrics. Textile applications that could use cellulose materials on cellulose-based fabrics would be environmentally friendlier, less allergy-causing, and easier to recycle. This approach to modifying and customising textiles using 3D printing

and bio-based materials could open up whole new application areas and design and service concepts.

3D printing of cellulosic materials on cellulosic fabrics was performed using a direct-write method by printing cellulose derivatives on woven and knitted cotton and woven viscose fabrics. The adhesion of the printed structures was evaluated via peeling and washability tests. The results indicated that although both the cellulose derivatives used – rigid cellulose acetate (CA) and flexible acetoxypropyl cellulose (APC) – had a positive attraction to the cellulose substrate, CA had a higher affinity and good adhesion properties, whereas the more branched molecular structure of APC was less firmly attached to cellulosic material.

The applicability of 3D printing cellulosic materials for textile modification and functionalisation was assessed through iterative prototyping. Visual effects and functional surface structures were demonstrated. The utilisation of 3D printing of cellulosic materials for surface tailoring of cellulosic textiles eliminates labour-intensive processing or external glues and may enable new, simple customisation processes with minimised material usage.

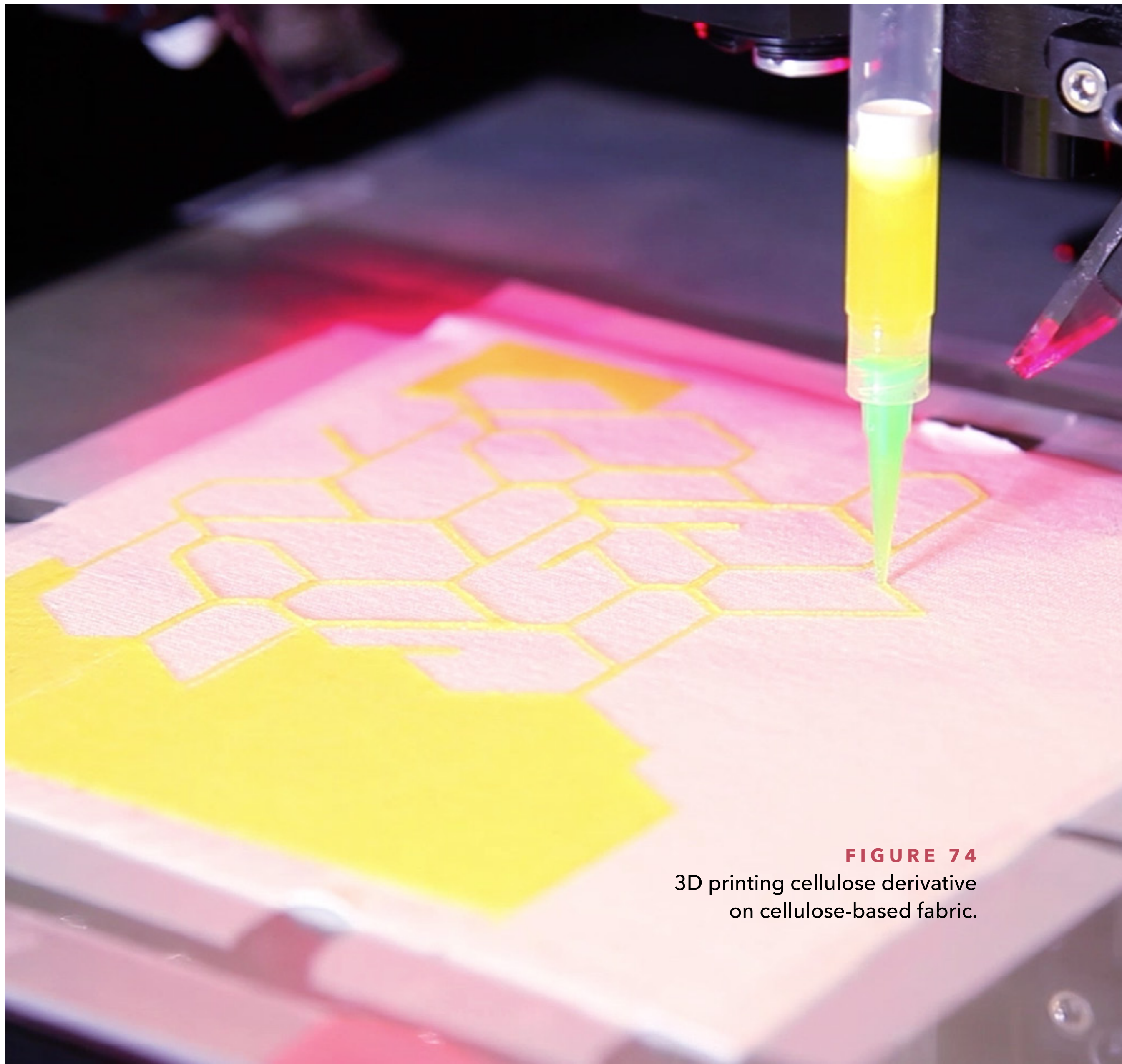
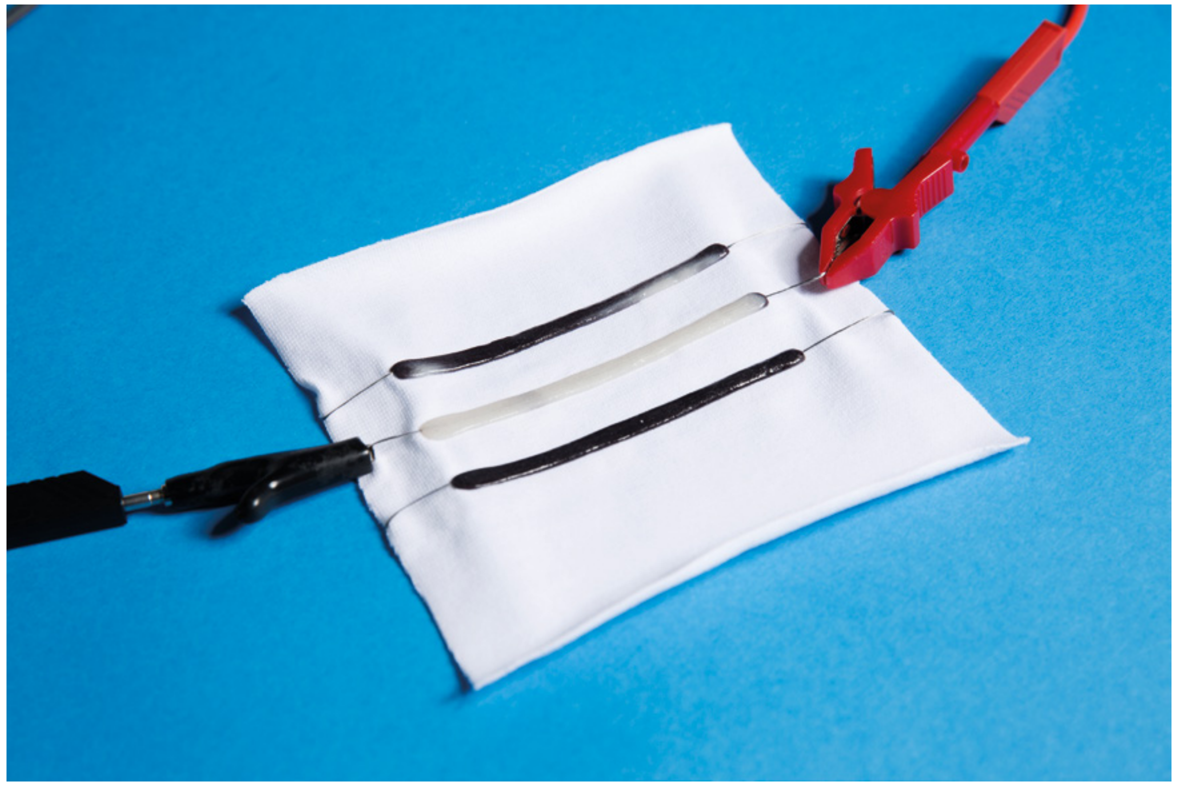


FIGURE 74
3D printing cellulose derivative on cellulose-based fabric.



FIGURES 75, 76 3D-printed textiles, functional prototypes. Designed by Pauliina Varis. Above: A thermoresponsive prototype utilising thermocromic powder mixed with APC solution. A conductive metal yarn is embedded into the print. When current passes through the wire, the produced heat changes the color of the printed tag on the fabric. Below: Printed seam material (coloured APC) replacing stitches in the pocket.

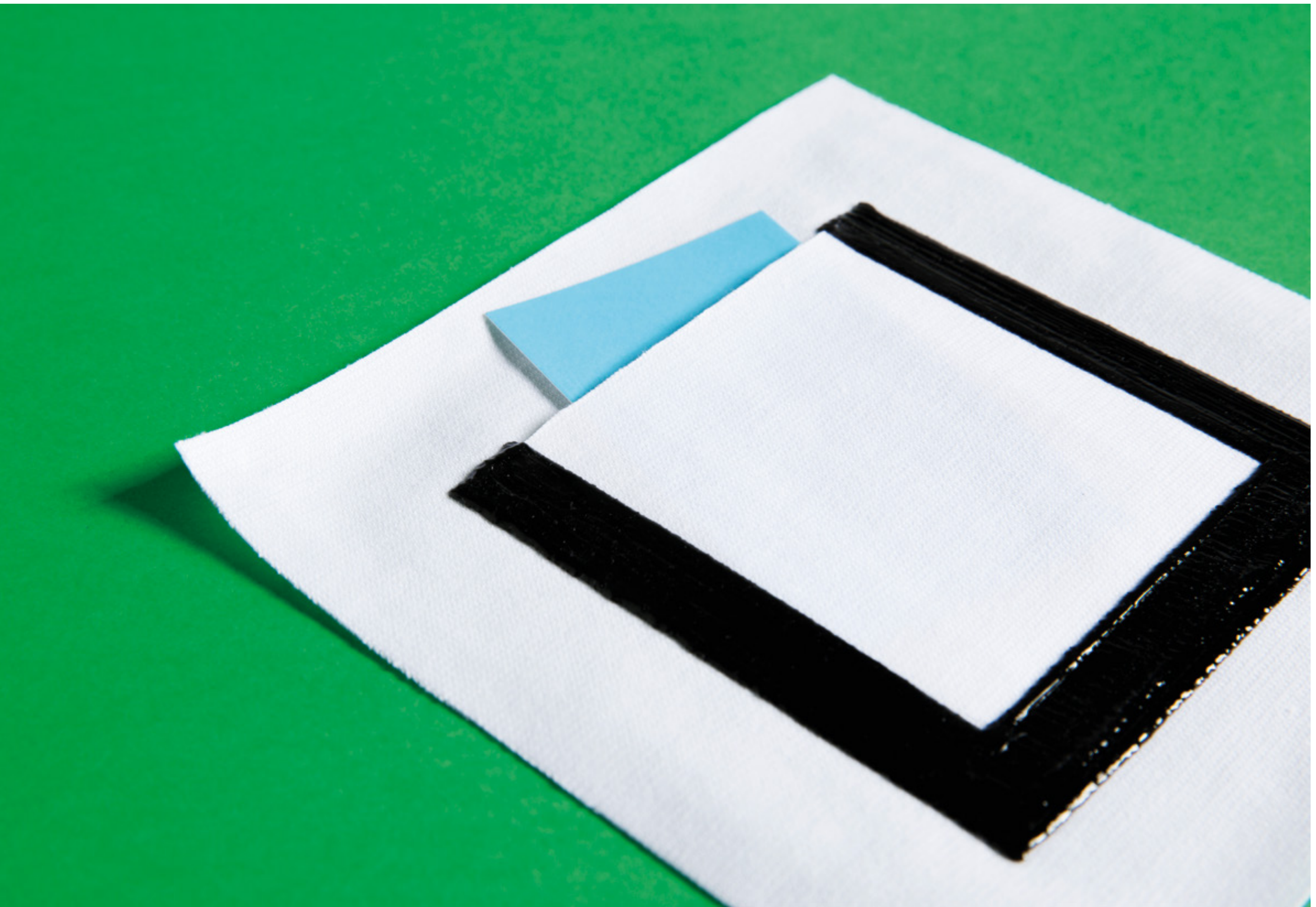


FIGURE 77 Structures printed using cellulose dissolved in ionic liquid could be used for smocking effects. Design by Pauliina Varis and Ilona Damski, 2016-2017

3D printing of pulp filaments

Steven Spoljaric,
Jukka Seppälä

We prepared monofilaments from enzymatically fibrillated pulp blended with crosslinked polymer and a lubricant. The incorporation of crosslinked polymer manipulated dope rheology, allowing successful spinning of filaments. We also incorporated strength, stiffness and a degree of water stability. The addition of a lubricant increased filament ductility and elongation, without compromising strength. Finally, we applied a thermoplastic cellulose-based coating to the filaments to enhance water stability and provide a smooth filament surface.

MATERIAL CHARACTERISTICS: The structures were tough and hard, yet delicate. Strength and robustness could be increased by applying more filament layers to the structure. The pure monofilaments were rough, but a smooth feel could be achieved by applying a cellulose-based coating. The coating also provides a degree of water stability.

TECHNICAL DATA: The dry tensile strength of the monofilament was 40 ± 6 MPa and elongation at break 1–5%. Wet tensile strength was 65 ± 4 MPa, and elongation 17± 2%. The reference values for dry cotton yarn were 625 ± 225 MPa and 3-8%, and for wet cotton yarn 590 ± 150 MPa and 9 ± 2%.

POTENTIAL APPLICATIONS: Non-woven structures can be utilised in various 3D and 2D applications, including interior decoration and décor products, furnishings, matts/coverings, and construction applications.

FIGURE 78
3D-printed lace from pulp filaments.

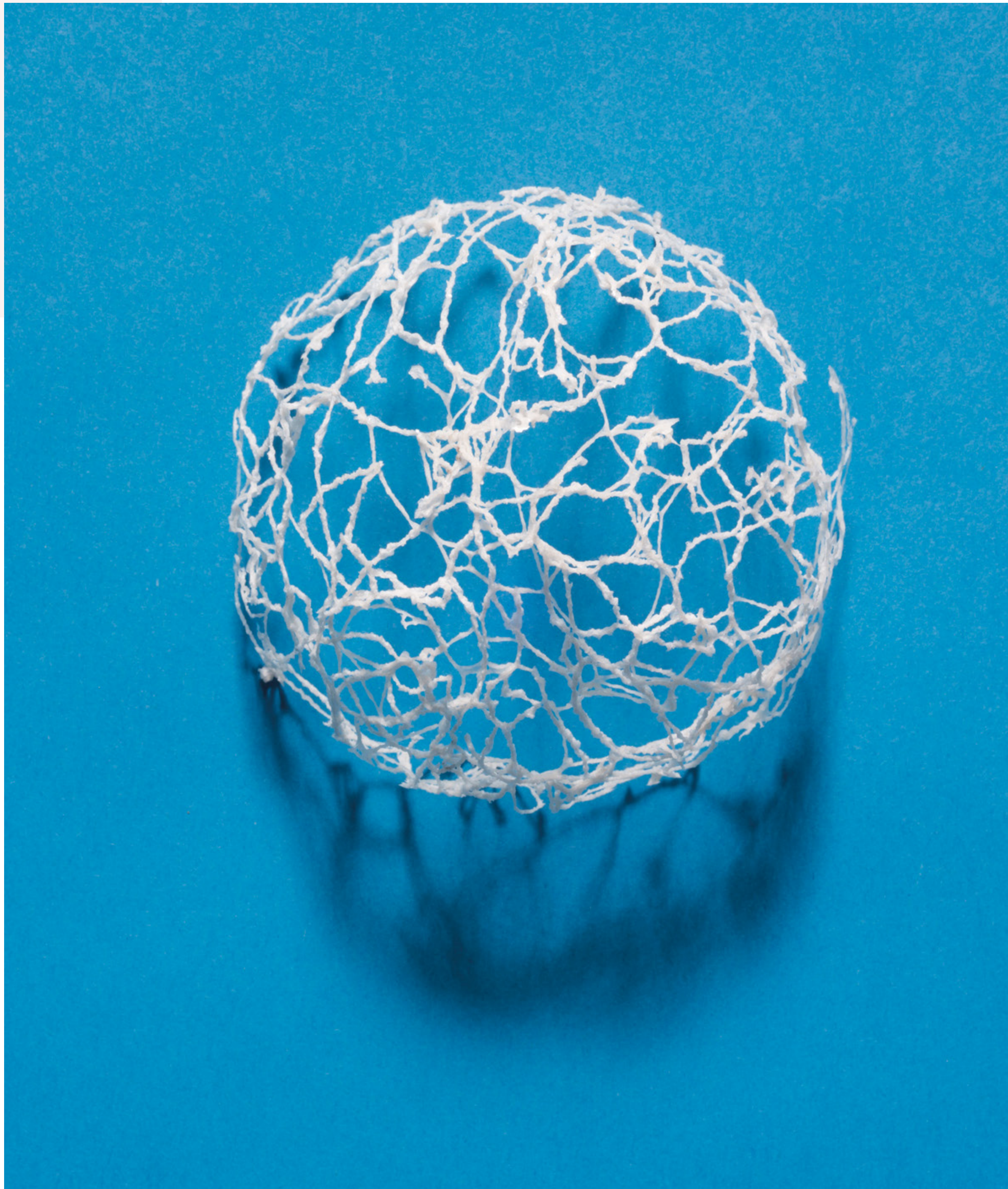


FIGURE 79 3D-printed cellulose objects.
Designed by Anastasia Ivanova, Ville Klar and Pyry Kärki

3D printing of solid objects

Ville Klar,
Pyry Kärki,
Hannes Orelma,
Jaakko Pere,
Tiia Tenhunen,
Anastasia Ivanova

We printed solid cellulose-based structures from both aqueous cellulose fibre suspensions and cellulose derivative solutions. We studied the influence of raw material parameters (such as solid content and concentration) and printing parameters (such as infill density and extruder diameter) on the geometrical and mechanical properties of the printed structures.

The main challenge with printing aqueous cellulose suspensions is that they are typically only processable (i.e. extrudable through small diameters) at low solid contents. The problem with low solid contents is that as the structures dry, they undergo significant deformation, as most of the volume is lost (evaporates) during solidification. Specialised drying methods such as freeze-drying have shown to be an effective way of preventing collapse and thus retaining the intended shape in the 3D prints. However, these techniques suffer from a significant drawback; the loss of mechanical strength.

Our aim was to control the drying deformation by printing at higher solid contents and concentrations, and using air drying with controlled temperature and humidity. A further objective was to quantify the drying deformation via 3D scanning in a more accurate way, to enable drying compensation. Drying compensation essentially means that with a known distortion, the reverse could be applied to the digital model, thus attenuating the geometrical distortion and improving shape fidelity.

MATERIAL CHARACTERISTICS: 3D -printed objects can be designed to have different characteristics. By using different slicing parameters (e.g. infill patterns and layer thicknesses), objects can be modified to suit different applications. Different materials can be incorporated into a single model using multiple extruders. Furthermore, cellulose-based materials can be printed on top of other materials, such as fabric.

POTENTIAL APPLICATIONS: 3D printing can be used to create complex three-dimensional objects. Properties can be tailor made to fit the specific applications. Different structures (e.g. composites) can also be prototyped using 3D printing. One promising area is prosthetics. Strong, biocompatible cellulose-based prosthetics can be printed to fit each individual perfectly. Optimising the printing process to achieve both good control of the geometry and high mechanical properties could broaden the application range to, for instance, packaging and architecture.

Utilising FDM technology - 3D printing of thermoplastic cellulose derivatives

Arto Salminen, Jukka Seppälä

Of the different 3D technologies, **Fused Deposition Modeling** (**FDM**) is the most common technique among household printers. 3D FDM printers use thermo-plastic polymers as raw material and the market is largely dominated by two plastics; ABS and PLA. To broaden the selection of renewable materials and investigate the suitability of cellulose-based raw materials in 3D printing, we studied the 3D FDM printing of thermoplastic cellulose derivatives.

FIGURE 80
First tests of 3D-printed thermoplastic cellulose derivative 2014.

MATERIAL CHARACTERISTICS: We selected a thermoplastic cellulose derivative with a low processing temperature for the 3D printing trials. The pure cellulose derivative performed poorly during 3D printing due to insufficient layer adhesion. The performance of the material was improved through plasticisation, which reduced the melt viscosity and lower glass transition temperature. Plasticisation improved the layer adhesion and overall performance during 3D FDM printing, thus enabling 3D structures from the thermoplastic cellulose derivative.

POTENTIAL APPLICATIONS: The flexibility of 3D FDM technology enables the manufacture of a variety of small volume products that are tailored and customised for individual needs. 3D FDM technology is mainly used to manufacture three-dimensional objects, and potential applications could be decor items and utensils.

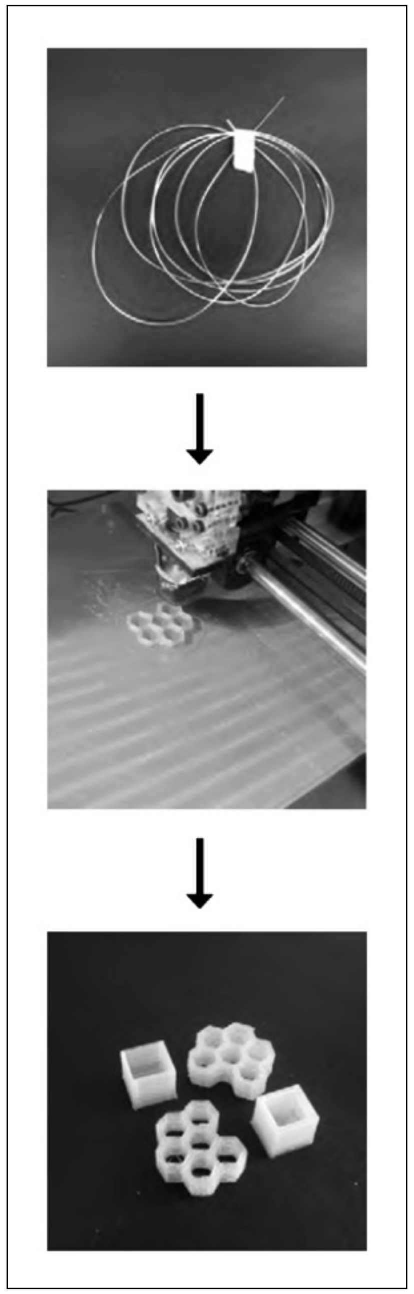


FIGURE 81
Cellulose-based 3D structures using FDM technology and thermoplastic cellulose derivative.

TOWARDS READY-MADE CONCEPTS: CIRCULAR KNITTED PULP FILAMENT

FIGURE 82
Proof of concept research: Pulp-based filament was circular knitted directly from paste to product (white loops in the red textile).

Ali Harlin, Steven Spoljaric, Ville Klar, Arja Puolakka

One objective of the second phase of the DWoC project was to create a concept for combined fibre yarn spinning and textile production. More precisely, the aim was to integrate the spinning (yarn formation) phase directly into a textile, composite or non-woven production process. Combining the spinning process and a manufacturing process would significantly shorten the production process. Consequently, the costs, lead times and environmental impacts of production can be reduced. As an example, in the context of knitting, yarn bobbins could be replaced by spinnerets, directly outputting yarn. This idea is illustrated in Figure 83.

Even though a combined process could drastically shorten the path from fibre yarn to usable structures, this was a challenging undertaking. The most significant hurdle was related to choosing to use the filaments and fibre yarn that were still under development. These spinning approaches were ill-suited to a combined approach, as the development of strength in the incipient was very slow. A melt or solvent spinning technique might have been a better choice for a combined process.

We are proud to report that the combined process was successfully demonstrated with the dry-spun filaments (described in 3D-printing of pulp filaments) coupled with a circular knitting machine. Several loops were knitted using a conventional circular knitting machine. The developed concept is a giant leap forward in complete textile manufacturing. The systematic testing and optimisation of the concept remained limited due to time constraints, and thus need further research in future projects.

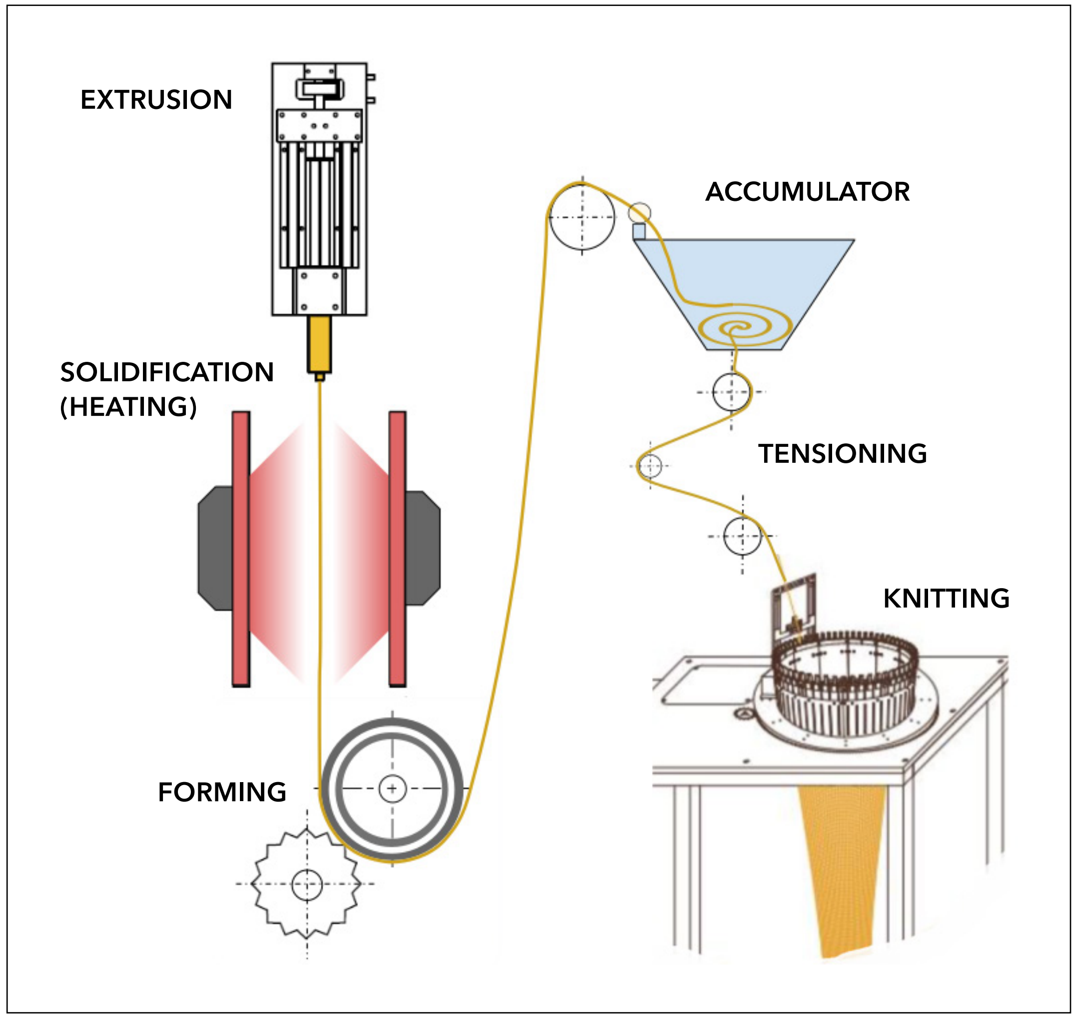


FIGURE 83 Illustration of a combined spinning and knitting process.

CREATING A NEW CELLULOSE ECOSYSTEM

Greg O'Shea, Ainomaija Haarla,
Henri Hakala, Teemu Kautonen,
Steffen Farny, Seppo Luoto, Kirsi Kataja

'Ecosystem' is one of the buzzwords of our time. We have identified the existence of at least the following ecosystems: a business ecosystem, an innovation ecosystem, an industrial ecosystem and an entrepreneurial ecosystem. At the core of the concept is co-evolution, which occurs between companies and other actors in a business ecosystem in the same way as between organisms in a natural ecosystem. Entrepreneurial ecosystems are formed by a diverse set of interdependent actors and are characterised by 'high rates of entrepreneurship in a local region' (Spiegel, 2017) and 'rapid job rotation, GDP growth, and long-term productivity' (Isenberg, 2010). This clearly involves a major challenge requiring a conducive culture and enabling policies and leadership, availability of appropriate finances, quality human capital, venture-friendly markets for products, and a large range of institutional support (Isenberg, 2010). Context is also important because each ecosystem emerges under a unique set of conditions and circumstances. At the beginning of the DWoC project, we had only a goal – to add value to the raw materials of wood through design – but along the way, an emerging community of interested, curious and, in various ways, capable people, was born. It was a self-organising system.

The business research of the DWoC project elaborated on the development of phases, and identified the roles of the key actors in creating a **Cellulose Entrepreneurship Ecosystem** (**CEE**)

in Finland. The CEE underwent several phases during its development. In the beginning, we had a **Community of Dreams**, in which awareness and interaction between like-minded actors began to take place, both virtually and physically. This was followed by the transition to a **Community of Commitment**, in which a meaning was created, and then a move to a scientific research-focused **Community of Inquiry**. Finally this led to a go-to-market focused **Community of Commerce**, which enabled us to find many gaps still needing to be filled: branding and marketing; certifications for materials; sufficient raw materials for pilots; risk-taking, capable entrepreneurs; and business initiatives that require many phases and patient investors.

We increased our understanding of opportunity recognition, development and exploitation, and therefore value-creation in the ecosystem(s) around cellulose-derived design products, through literature reviews, theory-based research and interviews with large stakeholder groups. We also researched actors' roles and legitimacy development in these value systems.

REFERENCES

Spigel, B. 2017. The relational organization of entrepreneurial ecosystems. *Entrepreneurship Theory and Practice*, 41(1), 49-72.

Isenberg, D.J. 2010. The big idea: How to start an entrepreneurial revolution. *Harvard Business Review*, 88 (6), 40-50.

FIGURE 84 Business research content and outcomes.

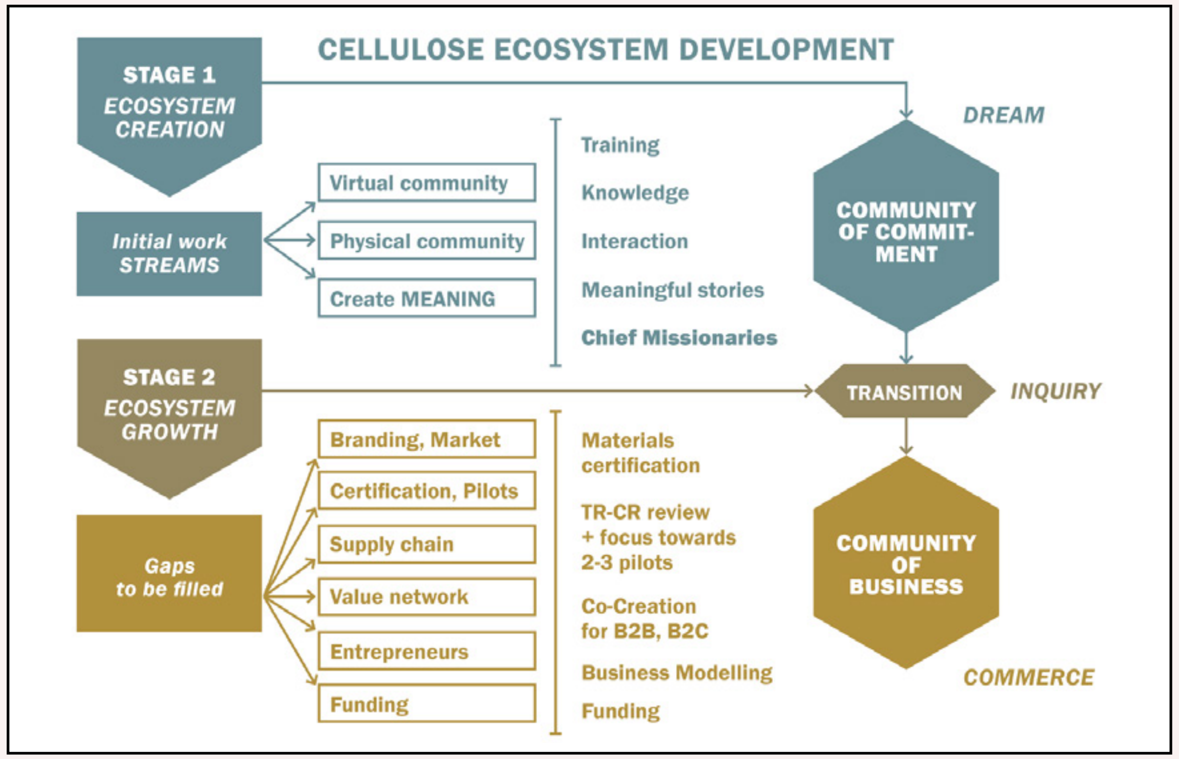


FIGURE 85 Our ecosystem development stages and identified gaps. We are now in Stage 2; moving from community of inquiry to community of commerce.

The main outcome of the business research and activities:

01 The development of the Cellulose community was catalysed by visits, interviews, information sharing, and workshops with tens of companies, both large and small/medium sized. The focus was on building awareness, interaction and commitment, and par-ticularly on capitalising on the **www.CelluloseFromFinland.fi** plat-form (a virtual community). Distinctive model-narratives for innovation, business, and entrepreneurial ecosystems all stress the importance of the forms of interaction within the ecosystem.

02 We conducted Market/User understanding interviews, and identified the highest potential product categories: special packaging solutions, interior wall structures and dividers, acoustic elements, business gifts, toys, and all kinds of applications replacing mdf board. In addition, we clarified in our survey which of our materials interest users the most, user willingness to pay for the materials, and areas requiring development.

03 The role of environmental friendliness - a key advantage of cellulose-based products - as a factor in Finnish manufacturing SMEs' decisions to switch to new input materials was examined through a large survey. The results showed that a firm is more likely to adopt a new material if it is substantially more environmentally friendly than their current material. Sustainability is a significant, robust predictor of the willingness to switch input materials; even if we control for many different strategic parameters. This bodes well for bio-based materials!

04 We identified the gaps to be filled in the value network. Policy-makers have primarily supported the creation of knowledge ecosystems, assuming that these ecosystems will automatically trigger the development of business ecosystems. In the case of biomaterial businesses, this development has not been realised as efficiently as we would have hoped. Other actions are needed. Most importantly, we are facing a funding gap and need urgent action. We need raw material producers to provide for the entrepreneurs starting production of new cellulose-based products. The problem, however, is: Who starts producing raw material when there is not yet a market for it? And who can begin a business based on a raw material that has not been yet produced? We need funds for upscaling research, and pilot mac-hinery for new material production.

FIGURE 86 Dyeing research of pulp. See page 58.

05 Our Cellulose Entrepreneurship Ecosystem underwent several phases of development, a series of emergent forms or phases of a community transition, and eventually became the entrepreneurial ecosystem. We created guidelines for further developing the new cellulose ecosystem. Despite the self-organising characteristics of these ecosystems, we stress that it is important to view sustainable ecosystems as something that can be catalysed, created and led. We propose that the ecosystems approach should embrace a more diverse understanding of leadership than it currently does. Actors play key roles in critical processes that cause phase transitions. To successfully develop community-based ecosystems, leaders will need to manage new operating models and learn new ways of collaborating and of creating and capturing value, as well as find a process for co-creation that encompasses various actors. Opportunities are generated within the Community of inquiry through the three main process elements of co-intuiting, co-interpreting and co-integrating work to produce new venture ideas and opportunity confidence. A strong, shared intention is a powerful enabler for keeping such a Community of inquiry together.

06 We described key roles in the phase transitions in the ecosystem, see **Figure 88.** The role of promoters was investigated using a case study within a large collaboration or ecosystem in the Finnish bioeconomy. Through the identification of key promoter roles, the policy-maker (leader, funding body) may be better informed to build ecosystems and recruit people for specific roles. In addition, people working within the ecosystem can better identify their own key role in the catalysation of emergence.

07 We identified two main pathways to commercialising new cellulose-based design product inventions: **Technology Transfer** would involve partnering with large organisations in the cellulose ecosystem as part of a joint venture or some form of consortium. The other pathway is to **Pilot technologies towards start-ups or spin-offs**.

08 We estimated the technology readiness level (TRL) and commercial readiness level (CRL) of the technologies and concepts developed in the project. We also created an IPR map to visualise commercialisation possibilities.

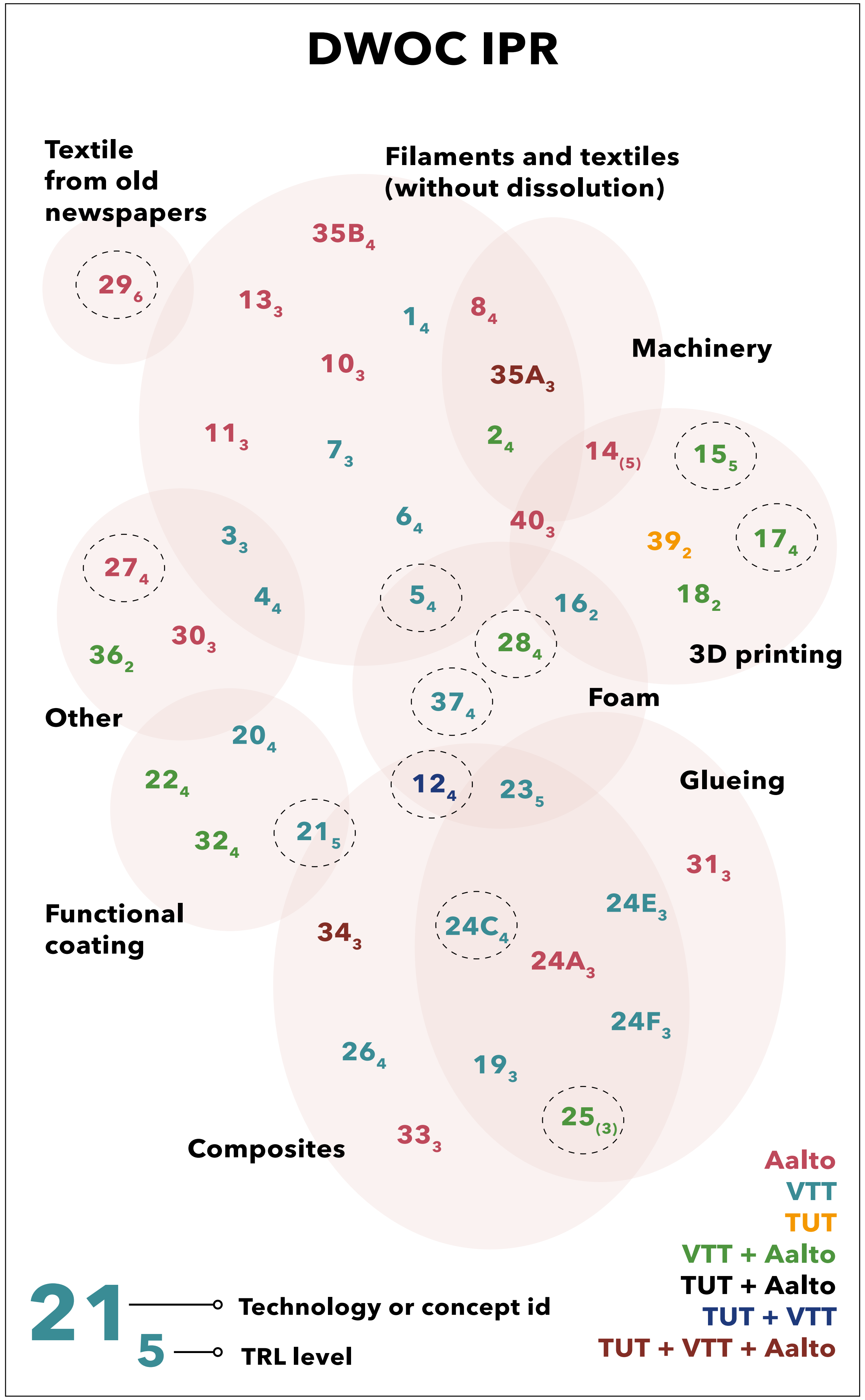
09 We collaborated with students from three **Aalto University Capstone** courses. The students made business models for some possible future products, based on the technologies and concepts developed in this project. The first Capstone project looked at the uses and go-to-market possibilities for cellulosic non-woven fibre materials and found a possible competitive niche use for the material in the form of mulch. The second Capstone project recommended possible go-to-market steps for nanocellulosic tubes, and a pathway for their use as kayak paddles. The third project looked at the go-to-market possibilities of casted wood and its use as furniture.

10 We began activities to strengthen awareness and emotional commitment to new cellulose ecosystems via the creation of meaningful narratives and by finding a 'champion' figure to tell these narratives. We participated in the writing of a leaflet/book called 'Wood-based Bioeconomy: Solutions for Global Challenges' edited by TEM, to be utilised in their international activities. This leaflet tells the story of **Spinnova**.

FIGURE 87
The final main results of the project were presented in the seminari Designing cellulose for the future III, 9.1.2018, Finlandia Hall, Helsinki

FIGURE 88 : Key roles and role descriptions in the phase transitions.

PHASE	KEY ROLES	DESCRIPTION
DREAM	Visionary	A driving, future-oriented role imagines and clarifies new entrepreneurial opportunities and large-scale institutional change to address future opportunities.
	Resource explorer	Collects and organises existing resources and networks; influences external actors; helps in the process of recombining existing practices, technologies, and institutions as a resource.
	Diplomat	Shows political awareness in understanding the interests of the other actors in the expanding community, helps frame the dream agenda to appeal to the interests and identities of actors outside the initial community, and liaises closely with the funding body and local and national government.
	Missionary	Helps create and then convey meaning and meaningful stories about the importance of the entrepreneurial ecosystem vision, and about the need for actors and others to make institutional changes and take actions that can help promote such a change.
INQUIRY	Conductor	Nurtures membership by building on everyday conversations, creates agreement on how to ensure transparency in decision-making processes, helps the structuring needed for effective self-organising.
	Interpreter	Keeps the diverse, multidiscipline group together, mediates the dialogue between the domains of expertise, facilitates an open communication process.
	Sense-helper	Creates and presents frameworks to help with the mutual and individual sensemaking processes that are needed to give individuals within the community some clarity of direction in the medium to longer term.
	Boundary crosser	Takes the mundane from one discipline across a boundary into their own discipline; recognises, gathers, interprets, and disseminates relevant information across boundaries to create ideas for new opportunities.
COMMERCE	Co-creator	Facilitates, helps articulate and support emerging understandings and the opportunity ideas of the partners and of the group-level collaboration needed as a basis for joint action, and facilitates an open, equal approach to innovation.
	Architect	Leads the construction process of an industrial infrastructure for commercialisation, implements through negotiation and persuasion, and helps design critical institutional arrangements such as clarity regarding property rights, materials and certification, supply chain construction and future financing arrangements.
	Bridger	Possesses joint venture and partnering expertise to lead collaboration with larger partners, SMEs or possible in-house start-ups or spin-offs that evolve from pilots; creates and supports activities that enhance the entrepreneurial environment – for example, lobbying government and establishing organisations that support entrepreneurial activity.
	Mentor	Provides director-level experience through positions on the boards of start-ups or spin-offs. Acts as a teacher and judge in new student start-up competitions.



01 Pulp fibre yarn using DES as a medium

Pulp fibre yarn is manufactured using the deep eutectic solvent (DES) system as a medium. This eutectic mixture can disperse pulp fibres and dissolve the crosslinking polymer, with no dissolution of cellulose. DES is washed away from the spun yarn by ethanol. This method could enable the production of wood-based textiles without the use of harsh chemicals or excessive consumption of water, bringing new options to the textile industry. See also Spinning pulp fibres with deep eutectic solvents (DES fibre yarn), page 34 and Dry-jet wet spinning of DES (Deep Eutectic Solvent)-treated pulp, page 81. Patented. ▹ Contact information kirsi.kataja@vtt.fi

02 Method for producing wood-based yarn filaments

This method is based on the method introduced in Item 1: 'Pulp fibre yarn using DES as medium'. It enables the production of more fibre yarn filaments in the same time span as is currently possible. The solvent can also be circulated and used again during the production process. Furthermore, the present invention reduces the investment costs and the production time, and enables easier upscaling of the process. See also Spinning pulp fibres with deep eutectic solvents (DES fibre yarn), page 34 and Dry-jet wet spinning of DES (Deep Eutectic Solvent)-treated pulp, page 81. Patent application filed. ▹ Contact information kirsi.kataja@vtt.fi

03 Water-absorbent application of pulp yarn (DES)

The fibre yarn, prepared using the wet-spinning approach and a deep eutectic solvent as a spinning medium, absorbs 500% water from its own weight. The filament has a porous inner structure, but is still fully water resistant. The dry tensile strength of the fibre yarn is approximately 130 MPa, with an elongation of 17%. See also Spinning pulp fibres with deep eutectic solvents (DES fibre yarn), page 34 and Dry-jet wet spinning of DES (Deep Eutectic Solvent)-treated pulp, page 81. DES yarn production has been patented. The water absorption results have been published. ▹ Contact information kirsi.kataja@vtt.fi

04 Hormone capturing - application of pulp yarn

A strategy was developed to produce a wood fibre-based yarn to be used as a platform for human and veterinary pharmaceutical hormone capture from wastewater. The concept was tested successfully using synthetic estrogen hormone capture from water. The pulp yarns were prepared by spinning with the DES medium, and were crosslinked. Despite their high porosity and water absorption capacity, the spun fibre yarns displayed high wet strength. See also Spinning pulp fibres with deep eutectic solvents (DES fibre yarn), page 34 and Dry-jet wet spinning of DES (Deep Eutectic Solvent)-treated pulp, page 81. Published. ▹ Contact information kirsi.kataja@vtt.fi

05 Novel cellulose fibre-based non-wovens by foam forming

This includes ultra-thin, layered or very thick non-wovens. The non-woven properties are controlled by fibre entanglement, and functional fibres can be embedded. Possible applications include technical textiles, commodity products, composite applications, and interior decoration. Density, 150–300 kg/m3; high extensibility; strength, 0.2–2.8 Mpa. See also Non-woven textiles by foam forming, page 41 and All-cellulose shoe: Novel wood-based materials in footwear, page 53. ▹ Contact information kirsi.kataja@vtt.fi

06 Dry-spinning of CNF filaments on a non-adhesive surface

Patent application filed, sold to company. ▹ Contact information kirsi.kataja@vtt.fi

07 Improving mechanical performance of cellulose (yarn) by partial dissolution with NMMO

A generic method to combine pulp or CNF structure components. It produces enhanced mechanical properties. See also Improving the wet strength of fibre filaments using partial dissolution with NMMO, page 38. Published for CNF film. ▹ Contact information kirsi.kataja@vtt.fi

08 Coaxial spinning of CNF filaments

Nanocellulose demonstrates its full strength when effectively oriented inside a material. This orientation can be achieved by wet-spinning nanocellulose into filaments. Filament properties are controlled by the processing: (1) Nozzle size, water content in nanocellulose, winding speed ➔ filament thickness (2) Batch spinning of 5–50 cm filaments ➔ strong and stiff filaments, slow process (3) Continuous spinning of up to 2 km/h ➔ brittle filaments, scalable process (4) Water-repellent additive or coating ➔ stability in water. Nanocellulose filaments can be used as a reinforcement in composite materials in which the combination of strength and lightweight is important (e.g., materials for transportation). See also Coaxial wet spinning with a CNF core, page 80. ▹ Contact information: pirjo.kaariainen@aalto.fi

09 Composite filament

Microfibrillated cellulose-based composite filament, water stable. No additional water removal after crosslinking. See also IPR 35B and Filaments from enzymatically fibrillated pulp, page 37. ▹ Contact information: pirjo.kaariainen@aalto.fi

10 Hydrophobic CNF filaments

▹ Contact information: pirjo.kaariainen@aalto.fi

11 Conductive filaments

No detailed information will be given concerning production process. ▹ Contact information: pirjo.kaariainen@aalto.fi

12 Conductive (heating) cellulose-based composite material for living spaces

We developed a method to produce a conductive (heating) cellulose-based non-woven textile or thick 3D-shaped element. The structure is produced using a minimum amount of materials and chemicals, and minimum processing steps. In the developed process, sonication is used to homogenise the dispersion of carbon nanotubes (CNTs) and nanocellulose. The dispersion is mixed with matrix fibres (e.g. cellulose pulp and viscose staple fibres) using foam-forming. See also Conductive (heating) non-woven textiles and 3D elements, page 65. Patent application filed. ▹ Contact information mikko.kanerva@tut.fi, kirsi.kataja@vtt.fi

13 Preparation of photoreactive nanocellulosic materials via benzophenone grafting

This is a strategy for grafting benzophenone (BP) onto highly hydrophilic, TEMPO-oxidised cellulose nanofibrils (TOCNF). The developed method may be easily adapted for further grafting of other functional groups onto CNF fibrils. The UV-induced crosslinking of BP-TOCNF makes films strong in even humid or wet conditions. Useful in applications that require increased wet strength and resistance against light induced ageing. See also Towards water-stable and functional cellulosic filaments, page 30. Results have been published. ▹ Contact information: pirjo.kaariainen@aalto.fi

14 3D printer for cellulose materials

We developed a 3D-printer prototype to explore various cellulosic materials in additive manufacturing. Various paste extruders were developed, tested and compared to commercially available paste extruders. A closed-loop control syringe pump design was shown to be most functional and was used to print various cellulose solutions and suspensions. See also Machinery for 3D printing, page 83. No IPR to patent. ▹ Contact information: pirjo.kaariainen@aalto.fi

15 High dry content nanocellulose paste for 3D printing and adjusting print parameters

(1) We developed nanocellulose paste material with solid contents above 15-w%, and achieved better control of the drying deformation. (2) We adjusted printing parameters to minimise the drying deformation. (3) We tested air drying with controlled temperature and humidity. (4) We developed a method for quantifying the drying deformation via 3D scanning in a more accurate way, to enable drying compensation. (5) We researched the relation between solid content and tensile properties. See also 3D printing of cellulosic materials, page 86. ▹ Contact information: kirsi.kataja@vtt.fi, pirjo.kaariainen@aalto.fi

16 Ultra light, cellulose-based 3D printing material

See also 3D printing of cellulosic materials, page 86 ▹ Contact information: kirsi.kataja@vtt.fi

17 Customising textiles through 3D printing - smocking

The shrinking characteristics of cellulose dissolved into ionic liquid can be utilised in textile design for smocking structures. See also 3D textiles by printing cellulose on cellulose page, 87. Results have been published. ▹ Contact information: pirjo.kaariainen@aalto.fi and kirsi.kataja@vtt.fi.

18 Customising textiles with 3D printing – functional effects

We developed a new all-cellulose approach for modifying and functionalising textiles: The use of 3D printing and two acetylated cellulose derivatives on cellulosic fabrics. We generated prototypes using a design-driven approach, and demonstrated visual effects and functional surface structures. See also 3D textiles by printing cellulose on cellulose, page 87. Results have been published. ▹ Contact information: pirjo.kaariainen@aalto.fi and kirsi.kataja@vtt.fi.

19 Composites from nanocellulose powder and commercial cellulose derivative

▹ Contact information: kirsi.kataja@vtt.fi

20 Preparation of HefCel for spray application

*HefCel = High-Consistency Enzymatic Fibrillation of Cellulose. See also Glueing with nanocellulose and Cellulose nanofibril-based coating as fire retardant, page 68. No detailed information will be given. HefCel technology is developed and patented at VTT. ▹ Contact information: kirsi.kataja@vtt.fi

21 Fire retardancy – new functional properties using nanocellulose

We developed a material combination of microfibrillated cellulose (HefCel) and inorganic nanoscale pigments, which acts as fire retardant on wood surfaces. A surface layer with a thickness less than 100 microns is capable of protecting wood from ignition during flame exposure of 180 seconds, which is a very good result. The material is easy to apply to wood and is safe for the environment, unlike traditional fire retardants. See also Cellulose nanofibril-based coating as fire retardant, page 68. Patent application filed. ▹ Contact information: kirsi.kataja@vtt.fi

22 Nanocellulose paint

This is a novel nanocellulose technology (HefCel = High-Consistency Enzymatic Fibrillation of Cellulose), adopted to produce material with a 10% consistency, dyed and sprayed on wooden surfaces to provide coverage and act as water soluble paint. See also Cellulose nanofibril coating as paint, page 73. Published. ▹ Contact information: kirsi.kataja@vtt.fi

23 Nanocellulose (HefCel) as glue

All-cellulose structures, such as soft/hard, soft/film, hard/film cellulose structures, can be excellently glued with enzymatically fibrillated nanocellulose (HefCel*). *HefCel = High-Consistency Enzymatic Fibrillation of Cellulose. See also Glueing with nanocellulose, page 68. HefCel technology is developed and patented at VTT. ▹ Contact information: kirsi.kataja@vtt.fi

24A All-cellulose sandwich structures – Nanocellulose -based sheets and corrugated sheet structures

Light, strong and stiff all-cellulose structures with several layers (nanocellulose-based sheets and corrugated sheets) can be produced using this method. No detailed information will be given concerning production process. ▹ Contact information: pirjo.kaariainen@aalto.fi

24C All-cellulose sandwich structures - Laminated cellulose structures

We developed a method for producing novel, hard and solid block structures, combining nanocellulose and cellulose. The method was demonstrated by creating interior architecture design elements. The strength properties surpass those of the reference materials softwood plywood and medium-density fibreboard (mdf). The surface of the structure can be finished using patterns, pictures or 3D forms. The developed structure is bio-based and bio-degradable. Economy: competitive raw material price, simple production process. See also Glueing with nanocellulose, page 68 and Laminated structures for interior architecture, page 70. Patent application filed. ▹ Contact information: kirsi.kataja@vtt.fi

24E Layered, transparent CNF -composite film structures

▹ Contact information: kirsi.kataja@vtt.fi

25 Designed structures using sawdust/wood flour etc. and CNF

Nanocellulose and wood dust or coarse sawdust are mixed and casted in designed moulds, resulting in hard predetermined shapes, after the water has evaporated. These cast pieces are reproducible as the moulds can be reused. No machining is necessary. The completely wood-based material combination has a low environmental impact and is recyclable. See also Casted wood, page 76. ▹ Contact information: pirjo.kaariainen@aalto.fi

26 Nanocellulose treatment of non-wovens

See also Non-woven textiles by foam forming, page 41 and All-cellulose shoe: Novel wood-based materials in footwear, page 53. ▹ Contact information: kirsi.kataja@vtt.fi

27 Different kind of casted nanocellulosic structures/nanocellulose tubes

Nanocellulose can be processed into extremely light, strong tubular structures by using moulding technology. With a material thickness of less than 1 mm, it is strong enough for many load bearing applications. See also Exploring the formability of nanocellulose for solid structures, page 47. ▹ Contact information: pirjo.kaariainen@aalto.fi

28 Acoustic panels with foam and mould technology

Foamed pulp is used to produce acoustic and insulating panels. The material's density, stiffness, permeability, heat insulation, and acoustic properties can be tailored. The form of the panels can be customised on multiple scales and the mouldability of the material enables tailored solutions. Multiple colour variants can be produced by mixing pulp from just a few different colour batches. All-cellulose panels are easy to recycle after use. The foam-forming process is simple and requires a relatively light infrastructure. See also 3D forms and surface structures from foam forming, page 57. Published. ▹ Contact information: pirjo.kaariainen@aalto.fi, kirsi.kataja@vtt.fi

29 Textiles from old newspapers

We spun Ioncell newsprint fibres from a deinked newsprint/(DBNH)OAc dope using a dry-jet wet spinning method. The fibres were cut into 40 mm-long staples before washing. The yarns were spun from a 50:50 blend of Ioncell newsprint fibres and commercial viscose fibres. They were knitted into textiles. See also How to wear old newspaper -Fabrics from waste cellulose, page 44. Patent application filed. ▹ Contact information: pirjo.kaariainen@aalto.fi

30 Dyeing of (nano)cellulose

We successfully used the simple and cost-effective cold pad-batch dyeing method for dyeing nanocellulose and pulp with reactive dyes. We created a colour palette. An amount as low as 5% of dyed nanocellulose mixed with 99% native non-dyed nanocellulose gave the product a beautiful colour. See also 3D forms and surface structures from foam forming, page 57. ▹ Contact information: pirjo.kaariainen@aalto.fi

31 Confidential

32 Coating of wood veneer with cellulose nanofibrils.

Nanocellulose treatment of veneer in the gluing process enhances plywood strength. Patent application filed. ▹ Contact information: pirjo.kaariainen@aalto.fi, and kirsi.kataja@vtt.fi

33 Knit-reinforced cellulose structures

Nanocellulose structure reinforced with knitted cellulosic yarn. The demo cases were a stool and a bike. We developed a method for further reinforcing nanocellulose layers in cast tubes with the Ioncell-F filament knit on a mandrel. See also IPR id 27 and Exploring the formability of nanocellulose for solid structures, page 47 ▹ Contact information: pirjo.kaariainen@aalto.fi

34 Yarn filament/fabric reinforced composites

▹ Contact information: pirjo.kaariainen@aalto.fi, and sanna.siljander@tut.fi

35A Ready-made textile-like structure - Machinery

Combined processes: spinning of the filament and production of a textile-like product in one process. Proof of concepts – prototypes: (1) Combined knitting, (2) Combined planar, (3) Combined non-woven. See also Towards ready-made concepts: Circular knitted pulp filament, page 97. ▹ Contact information: pirjo.kaariainen@aalto.fi, and kirsi.kataja@vtt.fi

35B Ready-made textile-like structure - Material

(1) Microfibrillated cellulose-based composite filament (water stable). (2) No additional water removal after crosslinking. (3) Material can be spun into filament and knitted into a product in one process, see IPR ids 09 and 35A, See also Towards ready-made concepts: Circular knitted pulp filament, page 97. ▹ Contact information: pirjo.kaariainen@aalto.fi

36 Design Concept: Personal(ised) Assistive Products - Case: Orthoses

We have developed the orthoses concept, but have not yet demonstrated it. In this concept, cellulose-based materials offer valuable properties for orthoses, which may increase their usability, effectiveness, and recyclability. ▹ Contact information: pirjo.kaariainen@aalto.fi

37 Foam-formed pulp board (resembling plasterboard)

This board is produced from pulp by foam forming and pressing. Foam forming enables the production of a vast variety of fibre-based materials. The material of these boards contains only pulp and a small amount of additives (such as a foaming additive). The density profile of these foam-formed pulp boards (resembling plaster board) can be adjusted. Board surface can be designed – printed or patterned. See also Foam-formed interior elements, page 62. ▹ Contact information: kirsi.kataja@vtt.fi

39 Gradient printing 3D → 4D

▹ Contact information sanna.siljander@tut.fi

40 2D and 3D non-woven structures prepared from cellulose-based composite monofilament

See IPR ids 35B and 09. Material: microfibrillated cellulose-based composite filament (water stable). Monofilaments retain their shape and form without shrinking or cracking whilst drying. See also 3D-printing of pulp filaments, page 91. Not published in detail. ▹ Contact information: pirjo.kaariainen@aalto.fi

CONCLUSIONS

FIGURE 89
Foamed pulp.

LESSONS LEARNED

*Kirsi Kataja, Pirjo Kääriäinen,
Ainomaija Haarla, Tiina Härkäsalmi,
Carlos Peralta*

Learning process

The DWoC project has been a learning experience beyond comparison for all parties involved. The engineers learnt from the designers that, for example, it is not only functionality that matters but also perceptual characteristics such as haptic properties, aesthetics and symbolic experiences. Furthermore, the issue is not only fine-tuning a solution to the final end, but also experimentation, that is, iterative prototyping and taking quick corrective actions. Design provides tools for communicating scientific processes and results through, for example, visualisation, videos and exhibitions. Design tools can also be used for future scenario building. From their perspective, the designers in turn gained a deep understanding of materials and learned from material scientists and engineers about the potential of various materials and how they can be functionalised, processed and recycled. The intense collaboration also provided designers with access to the newest research information and tangible material samples even during the early phases of development.

FIGURE 90 Nanocellulose film dyed with curcuma, see also Testing natural dyes for cellulosic materials, page 67.

II Collaboration

Multidisciplinary collaboration is always a challenge. Each discipline has its own traditions, working culture and research methods, which means that working together is not necessarily easy. To work effectively together, we need a common language which requires mutual understanding, a common purpose, mutual trust and mutual respect. This takes time and a great deal of effort. In the DWoC, a cultural feature that smoothed our path was the absence of a hierarchical structure in the collaboration. We identified the following benefit from working together in a multidisciplinary team: we can better solve complex problems and foster creativity and impact, and cater for larger audiences.

III The role of Design

The DWoC design team provided new approaches to technology development and ideas for material applications, enhanced and accelerated material development through iterative hands-on prototyping, and handled communication.

Based on our experiences, the meaning and the role of design, designers and design researchers needs to be profoundly discussed already during the preparation phase of the project plan. Design as a term is as broad as engineering, and the designers, who are engineers or scientists, have varying skills and specialisations. We recommend involving design professionals already in the project planning phase to help define the best possible set of design skills for the specific project. For example: does the project need a facilitator for co-creation workshops, does it require skills in advanced prototyping or moulding techniques, or are infographics and visual communication the main need? And what kind of design expertise is required: knowledge of textiles, architecture, digital design, or something else?

FIGURE 91
Lightweight, durable structure of nanocellulose and pulp by Tiina Härkäsalmi.

IV Technology development

Several spinning approaches were successfully demonstrated on a small scale in the first phase of the project. The work plan of the second phase of the project underestimated the challenges and work required in upscaling these processes, which meant that insufficient resources were allocated to this task. This caused problems in the planned research work to develop yarn structures and further multiaxial structures for textiles and composites. We had an alternative plan to avoid the lack of cellulose I filament yarn, but this plan did not work either. This caused confusion in project collaboration dynamics and hindered the work, until a new focus was found.

The lesson learned is that project management should constantly create alternative plans, as soon as delays are observed. In this kind of strategic openings, it must be possible to adapt even the most important aims through agile management decisions.

V Human resources

The special nature of the DWoC project caused problems in managing human resources. The project proceeded and focused on certain topics which we could not have anticipated when planning the project and resources. As certain new research priorities arose, so did the need for research specialists in these new topics. However, it was not possible to recruit new researchers for the project. This problem could perhaps be solved if part of the resources were not fixed at too early a stage of the project.

The lack of continuity in some human resources also caused great challenges, making managing and planning more difficult than expected. The project plan was partially based on the unique know-how of the key persons, and losing some of these raised challenges. Management needs to make radical, agile decisions to change some of the targets. In hindsight it would have been advantageous to have a more strategic approach to community creation, both internally and externally. Ideally, a shared team space with a 'hub' organisation should have been set up at an early stage. When preparing for a multidisciplinary research project, it is important to carefully consider how to organise collaboration in practice, and how to create an optimal team with a balanced set of skills for the specific purpose.

VI IPR

Intellectual Property Rights (IPR) issues challenged collaboration. Patents, utility models and copyrights are very different types of IP. It became obvious that the design researchers' understanding of the nature of patenting was not sufficiently deep, and the technology researchers did not understand the utility models or copyright without additional training and several meetings with IP professionals. Unnecessary distrust occasionally arose.

We learned that in future collaboration projects with design and technology researchers, it is vital that IP training is given at the very beginning of the project. In addition, very strict internal rules are needed to ensure information and discussion in advance, before making invention disclosures and patenting activities.

VII Managerial actions

To avoid the silo effect, the distribution of the project into work packages must be planned very thoroughly. In addition to this structural guidance, good collaboration between researchers from different disciplines must be ensured through many managerial actions; openness and trust are essential for accelerating the creation of ideas. Nonetheless, the personal characteristics of project members have an important effect on collaboration.

FIGURE 92
Experiments of reactive-dyed pulp by Tiina Härkäsalmi.

FIGURE 93 Amazing cellulose - from thin, transparent sheets to thick, durable panels.

TECHNOLOGY HIGHLIGHTS

The main technological concepts proven in the project were all-cellulosic composites, cellulose coatings, nanocellulose prototypes, and ready-manufactured products. All-cellulose materials solved the major challenges of recycling and microplastic contamination. Nanocellulose coating provided not only aesthetically pleasant surfaces, but also breathability and fire protection. The project also demonstrated efficient technologies that enable production directly from cellulose fibre dispersions or fibre-based pastes to final products such as functional mouldings or knitted cloth.

We demonstrated and up-scaled several methods for preparing cellulosic filaments with native cellulose I crystalline structures. Both pulp-based filaments and nanocellulose-based filaments were developed. We also developed new process machinery and approaches at the same time as spinning raw materials. Already during the first phase of the project, after excellent research results, a **VTT** spin-off company – **Spinnova** – began operations in January 2015, and has since further developed one of these methods.

One intended objective of the DWoC project was to create a concept for combined fibre yarn spinning and textile production. More precisely, the aim was to integrate the spinning (yarn formation) phase directly into a textile, composite or non-woven production process. We believed that combining the spinning process with a manufacturing process would significantly shorten the production chain.

We are extremely proud to report that the combined process was successfully demonstrated by dry-spun pulp-based composite filaments, coupled with a conventional circular knitting machine. Several loops were knitted. The developed concept is a giant leap forward towards complete textile manufacturing.

We developed several simple technologies for producing cellulose mono-material structures or all-cellulose composites with good strength properties. The concept of all-cellulose composites is not new; earlier prototypes have been commonly prepared using cellulose solvents or other chemicals to fuse components together. But reactive binding agents may be unfavourable to the environment and ruin the possibilities of recycling. Our routes are more feasible, and we achieved sufficient adhesion using water and cellulose itself as a binder. These technologies enable the emergence of new sustainable business concepts and help accelerate the transformation of the current large-scale forest industry into a dynamic ecosystem for the bioeconomy, which contains both large and small-scale businesses.

FIGURE 94 Spinning research.

> **‘The DWoC project has created a globally unique cellulose knowledge platform that benefits from a cross-disciplinary approach. Many of the innovative material concepts developed will create new business in the near future.’**
>
> *Christine Hagström-Näsi, Chairman of the DWoC Board*

DESIGNING CELLULOSE FOR THE FUTURE: NEXT STEPS

The developed concepts indicated a wide variety of novel and innovative applications. It is essential that industrial manufacturing can be demonstrated, and that the characteristic benefits of cellulose, such as safety in use, recyclability and biodegradability, can be connected to these novel products. Several platforms for possible future products were developed, and open-minded business development and material innovations need to find companies committed to scale-up, which is still a topic of risk financing. This involves not only the concept of mass production, but also personalised products and materials, as a service providing novel opportunities for breakthroughs.

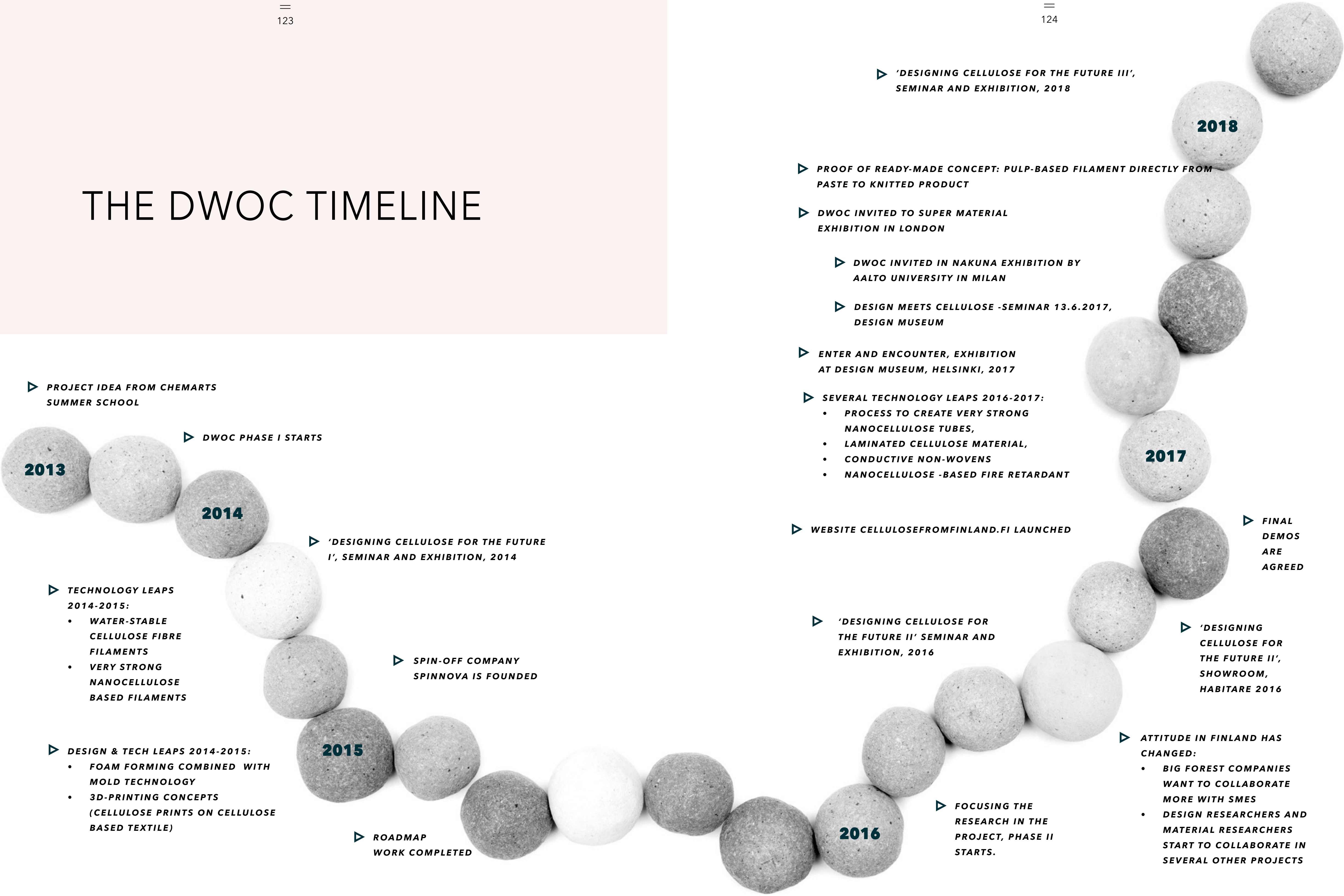
Multidisciplinary collaboration may be one of the key enablers in material research projects in the future. Designers play a vital role as interpreters between disciplines and as enablers of the humanisation of technology. Our findings show that design has three key roles in materials research. Firstly, designers can help scientists orientate their research at the very early stage by exploring potential future application sectors. Designers can even help scientists challenge themselves and raise the target level of their work through placing the innovation potential into future scenarios. Secondly, through

hands-on experimentation and iterative prototyping cycles, designers might speed up scientific research or suggest totally new opportunities. This is because, as designers are trained in reframing ideas, they can imagine problems and identify opportunities to see whether or not something is necessary. The third key task is communication: how to present the process and results to different kinds of audiences in an interesting way.

To conclude, the DWoC has been an important platform not only for cellulose-based material research and innovations, but also for testing new methods of collaboration and of nurturing the new ecosystem. This transformation still requires an amalgamation of designers, material scientists, engineers and business professionals. The potential of cellulose (and other wood-based materials) needs to be communicated further, and design entrepreneurs should become promoters of new materials. The coherent integration of technology into business concepts and continuous dialogue within the business ecosystem should continue in all possible ways in the future.

FIGURE 95
Casted wood, see page 76.

THE DWOC TIMELINE



- PROJECT IDEA FROM CHEMARTS SUMMER SCHOOL
- DWOC PHASE I STARTS
- 'DESIGNING CELLULOSE FOR THE FUTURE I', SEMINAR AND EXHIBITION, 2014
- TECHNOLOGY LEAPS 2014-2015:
  - WATER-STABLE CELLULOSE FIBRE FILAMENTS
  - VERY STRONG NANOCELLULOSE BASED FILAMENTS
- SPIN-OFF COMPANY SPINNOVA IS FOUNDED
- DESIGN & TECH LEAPS 2014-2015:
  - FOAM FORMING COMBINED WITH MOLD TECHNOLOGY
  - 3D-PRINTING CONCEPTS (CELLULOSE PRINTS ON CELLULOSE BASED TEXTILE)
- ROADMAP WORK COMPLETED
- FOCUSING THE RESEARCH IN THE PROJECT, PHASE II STARTS.
- 'DESIGNING CELLULOSE FOR THE FUTURE II' SEMINAR AND EXHIBITION, 2016
- ATTITUDE IN FINLAND HAS CHANGED:
  - BIG FOREST COMPANIES WANT TO COLLABORATE MORE WITH SMES
  - DESIGN RESEARCHERS AND MATERIAL RESEARCHERS START TO COLLABORATE IN SEVERAL OTHER PROJECTS
- 'DESIGNING CELLULOSE FOR THE FUTURE II', SHOWROOM, HABITARE 2016
- FINAL DEMOS ARE AGREED
- WEBSITE CELLULOSEFROMFINLAND.FI LAUNCHED
- SEVERAL TECHNOLOGY LEAPS 2016-2017:
  - PROCESS TO CREATE VERY STRONG NANOCELLULOSE TUBES,
  - LAMINATED CELLULOSE MATERIAL,
  - CONDUCTIVE NON-WOVENS
  - NANOCELLULOSE -BASED FIRE RETARDANT
- ENTER AND ENCOUNTER, EXHIBITION AT DESIGN MUSEUM, HELSINKI, 2017
- DESIGN MEETS CELLULOSE -SEMINAR 13.6.2017, DESIGN MUSEUM
- DWOC INVITED IN NAKUNA EXHIBITION BY AALTO UNIVERSITY IN MILAN
- DWOC INVITED TO SUPER MATERIAL EXHIBITION IN LONDON
- PROOF OF READY-MADE CONCEPT: PULP-BASED FILAMENT DIRECTLY FROM PASTE TO KNITTED PRODUCT
- 'DESIGNING CELLULOSE FOR THE FUTURE III', SEMINAR AND EXHIBITION, 2018


November 2014

November 2014

August 2016


August 2016

May 2016

March 2017

May 2016

January 2018

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Method for producing wood-based yarn filaments; 20175927; Inventors **Orelma Hannes, Harlin Ali, Rautkoski Hille, VTT, Ville Klar, Aalto.** Filed 20.10.2017

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FIGURE 96
Printed finishing material (dyed cellulose derivative) for a pocket, designed by Pauliina Varis

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CELLULOSE
- the next super material

The Design Driven Value Chains in the World of Cellulose (DWoC) project has challenged the traditional way of using wood cellulose and explored possible new and innovative applications and business opportunities for this amazing material. It has been a platform to test how co-operation between designers, material engineers and business researchers can work in practice, and what kind of outcome can be expected.

The DWoC project has been a great training exercise and valuable learning experience for all the participants. We catalysed in many ways the development of the new Cellulose community, with the goal of making Finland the source of value-added cellulosic products and business concepts.

Through this publication we would like to share our five-year long experimental journey with you and proudly present the main results of this unique collaboration project.

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