

# Cellulose goes digital

VTT's vision of digital  
cellulose-based industries



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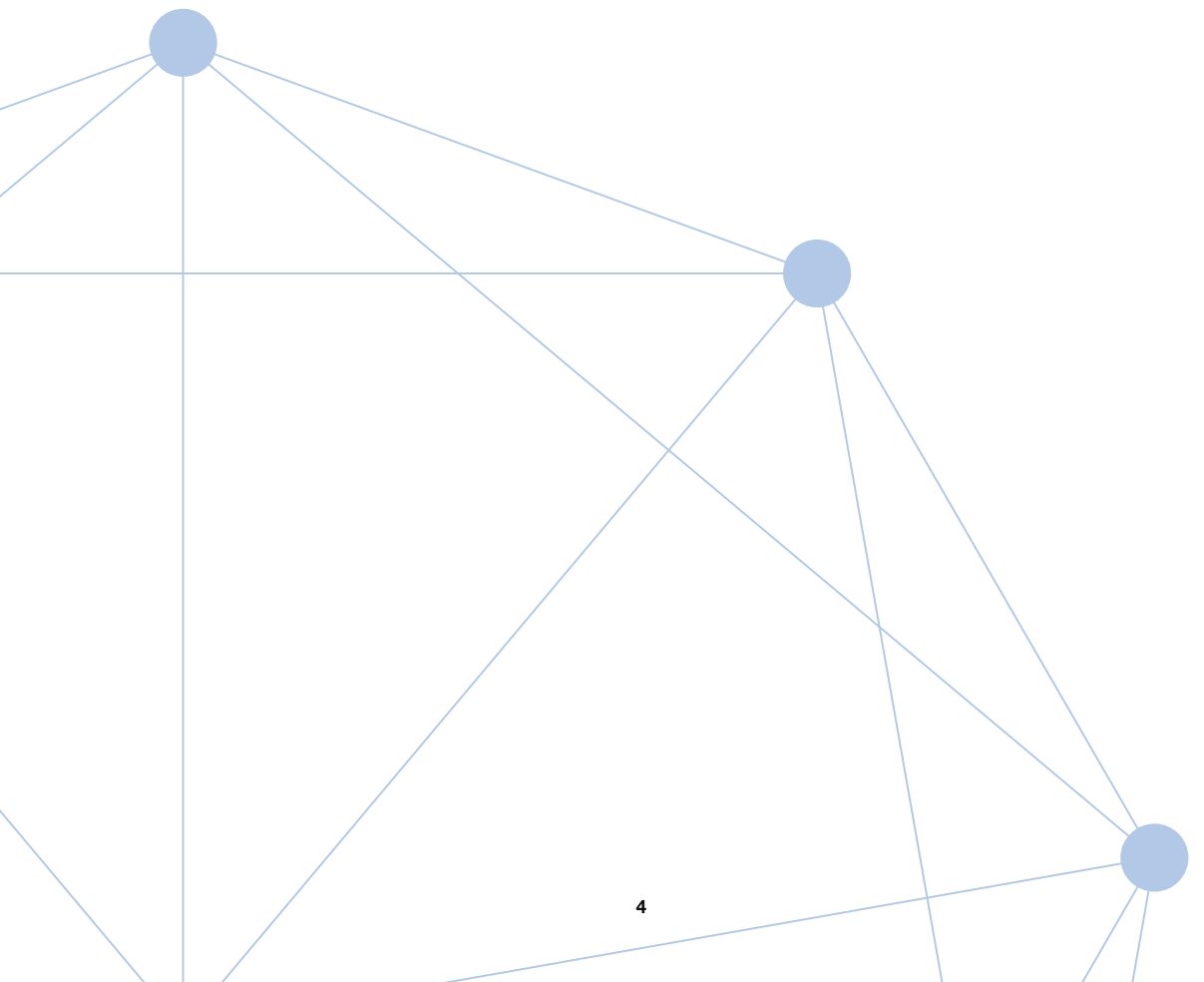
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# Preface

Cellulose is the multi-purpose material of the future. Beyond its contemporary uses, it has a new role as a versatile raw material, for example in composites, high-performance plastics, membranes, filters and foams.

Over the years, the forest-based industry has always adapted to the requirements of the time and found new paths for growth. In the 1990s digitalisation initiated a reorientation of the pulp and paper industry, and the decline in the demand for printing paper directed cellulose research towards different application areas. Recent advances in digital technologies and fabrication, recyclability and widening end-use opportunities are again making cellulose a topical theme. In the coming two decades, cellulose will scale in importance, and the industries that use cellulose will again be reoriented. Indeed, the turnaround has already started.

The preparation of this vision document was a part of VTT's strategy process. Our vision focuses on the next generation of the forest-based value chain, where multiproduct biorefineries will play a central role. The vision addresses the emerging technologies used to fractionate cellulosic raw material, future cellulose-based products and growth opportunities for the use of the renewable materials enabled by digitalisation of the cellulose industry.

During the process, we have combined information from several vision works of VTT and other institutes, industry, the EU and global organisations. VTT's strategy process has enabled us to see wider relations and development cycles in the related industries. The ideas of this vision have been tested with customers and other stakeholders, as well as in seminars and workshops internally. However, the whole vision is presented here for the first time.

We believe that a new era is starting for bio-based materials and especially cellulose. Cellulose is the only large-scale material that is bio-based, recyclable, biodegradable and available for consumer goods.

We hope that this vision provides new insights into what the future cellulose-based material economy may look like, and what technical solutions it will be based on. There are two main paths towards the future: the new bio-based materials and their preparation, and the opportunities provided by digitalisation.

We invite all stakeholders and interested parties to join forces and to create a more sustainable world with cellulose.

In Espoo April 2018  
Project Team

# 1. The forest-based industries – disruptions followed by renewals

Over its 200-year history, the pulp and paper industry has adapted to constantly changing requirements and found new paths for growth. The development has not been a continuum of only one track, but rather an exploration of new complementary business models based on long traditions.

The first massive change in the industry was caused by petrochemical disruption in the early 1950s. The second tremendous change was led by digital disruption, which resulted in extensive reorientation of the pulp and paper industry. As an outcome, the worldwide demand for graphic papers for printing and writing started to gradually decline. The same trend is continuing, mainly due to accelerated developments in the digital society. This decreasing market is offset by the increasing demand for packaging paper, boards and tissue papers.

Recent advances in digital technologies and fabrication, recyclability and widening end-use opportunities are again making **cellulose** a topical theme. In the coming two decades, cellulose will scale in importance, and the industries that use cellulose will again be reoriented. Indeed, the turnaround has already started. Massive *digitalization* and the reorientation of the industry infrastructure are currently leading to a multiple-product era enabled by emerging modern **biorefineries** and *novel cellulose materials* (Figure 1).

The following chapters look at the global trends affecting the reorientation of the forest-based value chain, the role of digitalisation, and the reorientation of the industry infrastructure to serve the whole value chain better. Additionally, the paper takes a view on the agile fractionation processes, game-changing technologies and emerging cellulose-based materials.

Concern about the sufficiency of natural resources, as well as climate change, is starting to affect the forest-based value chain. Operational efficiency is one road to ensuring resource sufficiency. Modern kraft biorefineries are one example of high operational lignocellulose **fractionation** from both chemical and energy recovery perspectives. Forest-based raw materials can be partially replaced by other raw materials, such as agro-based cellulose, however, that may require alternative fractionation processes. Even though emerging modern kraft biorefineries are frugal in material use and utilise side streams, they will need to meet the future demands. For example, to an increasing extent they will need to become independent of fossil resources and to fully exploit the available carbon side streams. In future, this trend will be obvious both from the competitiveness perspective and sustainability point of view. Furthermore, in modern biorefinery concepts, all side streams will be taken into use more efficiently and energy recovery and utilisation will be optimised to maximise production capacities of all products.

## **Cellulose**

*A linear polymer with thousands of glucose units. The main component in wood (40-45%).*

## **Biorefinery**

*A facility that converts biomass to multiple products.*

## **Fractionation**

*Separation of cellulose and other major constituents from wood by various technologies.*

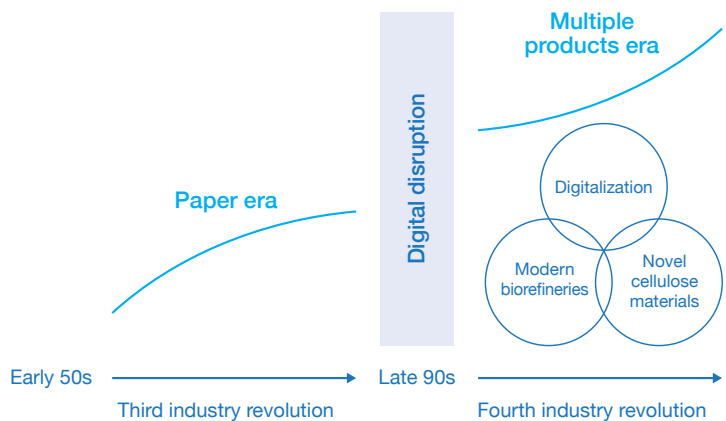
**Inherent properties of cellulose**

*Existing, innate properties e.g. good mechanical performance, hydrophilicity and hygroscopicity i.e. cellulose interacts strongly with water.*

Society is concerned about biosphere contamination (soil, sea, and atmosphere). At the same time, leading brands and consumers require sustainable differentiation in their products. This will diversify the structure of the industry and intensify the research and development towards value-added consumables. Production is becoming more demand-driven, agile and geographically distributed. The forest-based value chain is expected to continue to focus on packaging and to reorient itself towards textile and structural applications. Cellulose will be the composite and plastic material of the future.

The continuous growth of overall consumption will necessitate the creation of more value from the same limited raw material base. A range of special products will replace the production of bulk-market pulp. The future of the forest-based value chain is to become a provider of high-performance materials from renewable resources to make society more sustainable. At the same time, it provides society with a means to recycle used materials.

The on-going cellulose industry reorientations will have positive effects on companies' turnovers, even if there are limits to the raw material supply. The key is to define the areas where cellulose and its **inherent properties** provide a competitive edge. Though digitalisation caused the disruption in the forest industry at the end of 1990s, it can also serve as an enabler for a totally new operational and business structure for producing value-added services and products.



**Figure 1. Disruptions and developments in the forest-based industry.**



## 2. Change drivers in forest-based and cellulose value chains

### GLOBAL MEGATRENDS

The following on-going global changes and trends are laying the foundation for the industry's transformation.

#### Climate change

The rapid increase of carbon dioxide in the atmosphere as a consequence of human activity has resulted in climate change. This is the biggest threat of our time, and worldwide political efforts are being made to reduce carbon dioxide emissions in order to mitigate the effects of climate change. In 2015, the world agreed on the *Paris climate agreement*<sup>1</sup> (UNFCCC), which aims to keep the global temperature rise below 2 degrees Celsius above the pre-industrial level and to endeavour to limit the temperature increase even further to 1.5 degrees Celsius.

There is no clear view on all the consequences that will take place due to climate change. Nevertheless, extreme climate conditions will have an impact on sources of cellulose. Implications can be seen for instance, as strong winds levelling forests, droughts that minimises crop growth, or warm winters in the north that exacerbate conditions affecting winter timber production.

#### Globalisation

Large international companies will continue to dominate the world markets. Globalisation will continue, and individual governments will probably lack the power to control the companies. The potential rise of more protectionist policies in some countries may affect free trade and lead to various developments in different regions. However, the fastest growing economies seem to be increasing their influence on the global economy.

#### Increasing population and raw material demand

The world population is rapidly increasing. In 2017 the population reached 7.6 billion, and in the next 30 years, it will increase by 2 billion<sup>2</sup>. While population grows globally, the growth rate varies in different parts of the world. More resources are needed to support the growing population and this increasing demand for raw materials may affect the availability of arable land and fresh water. Therefore there is an increasing need to utilise non-food renewable raw materials that do not interfere with food production as a food supply crisis could lead, for example, to conflicts and result in mass movements.

## *Consumption of wood pulp will increase by 2025*

Until 2025 a worldwide annual growth of 2.5%, driven by Asian countries and particularly China, in pulp demand is expected<sup>3</sup>. This demand is caused by the increased need for tissue paper and packaging boards. The overall production of printing papers has seen a minute increase but will eventually head downwards, as has already happened in North America, Western Europe, and Japan. Overall, the consumption of pulp is forecast to increase by over 60 million tonnes by 2025<sup>3</sup>. This will increase the need for new pulp production capacity, especially since there is simultaneous pressure to shut down out-dated mills that utilise environmentally harmful technologies.

### **Increasing consumption through demographic changes**

Consumption is unavoidably increasing also due to global demographic changes. Improving living standards and continuing economic growth lead to increased consumption and demand for premium-quality supplies. The growth is increasingly generated in developing and emerging economies, not only in developed countries. This increases the demand for housing, interior products and furniture, as well as other luxury items, such as fashion clothing and home appliances. This growing global market has a marked influence on the consumption of packaging and transportation.

### **Environmental degradation vs. use of sustainable resources**

A degrading local environment will force people to examine their consumption behaviour. The discussion has lately focused on several environmental problems that are caused by synthetic materials. Plastic waste in oceans and micro-plastics in food and drinking water are worrying developments. Non-governmental organizations (NGOs), scientific communities and many other independent funds and pioneering companies have raised public awareness of these issues.

The risks of overconsumption have been recognised especially in the western world, where there is a strong focus on material recycling. For example, more than a decade ago the EU adopted a strategy for the prevention and recycling of waste<sup>4</sup>. As part of this development, landfilling of organic waste has been restricted by legislation. Gradually other nations have started to adopt material reuse practices. The EU also recently launched the first strategy for plastics in a circular economy that includes targets for plastic waste recycling<sup>5</sup>. This strategy will boost the demand for recyclable materials made of renewable and biodegradable raw materials.

### **Sustainability as a global norm**

Sustainability is becoming the new normal. The key question is when will the fast-developing markets be ready to adopt sustainable production and consumption standards. China, as an example, has a dedicated focus on the

*What if the rapid growth of sustainable raw-material demand is fully satisfied with pulp from wood and annual plants?*

environment in their current five-year plan. The sustainability requirements set by western brands are already influencing Asian production practices in the Far East.

The engine of economic growth has shifted to the Far East, where demographic changes and rising living standards act as market drivers. A real global turnaround and reorientation of production volumes requires the adoption of sustainable new solutions in fast-growing and mature markets alike.

## INDUSTRY TRANSITION TOWARDS UTILISATION OF RENEWABLE RESOURCES

The decreasing interest in utilising the remaining fossil resources, and the adverse effects of greenhouse gases and climate change, have together motivated the search for an economic structure that is aligned with the biosphere and the services thereof.

The inevitable transition from linear consumption of non-renewable resources towards circular consumption models of renewable alternatives has already started (Figure 2). In the biogenic carbon cycle, forestry has a central role. Renewable resources and especially lignocelluloses are key enablers of resource abundance.

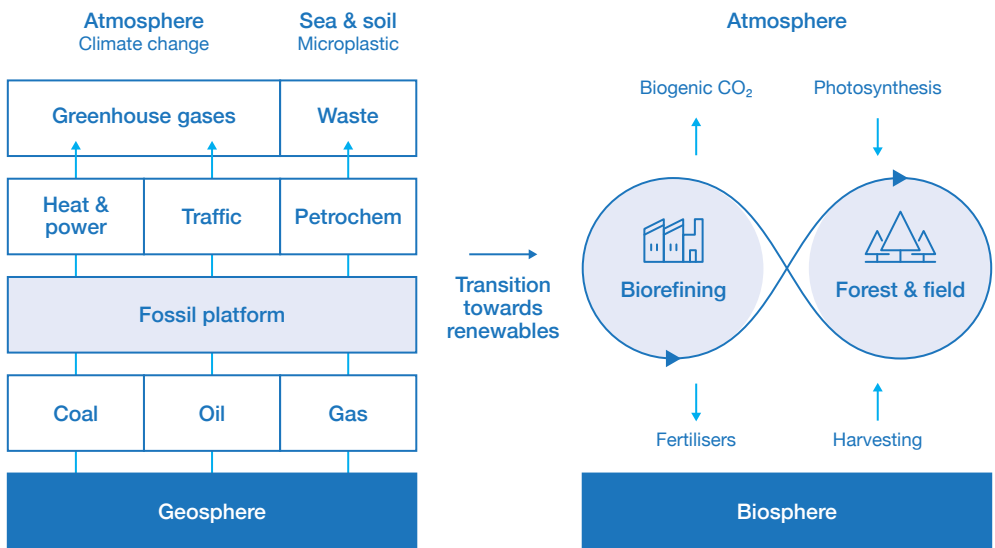


Figure 2. The transition from fossil carbon cycle to the biogenic carbon cycle.

*To make cellulose sufficiently available, the industry structure needs to change*

Today's industries desire affordable and sustainable raw materials. The choice of materials is strongly dependent on their availability but there are also other factors that direct the choices, such as the carbon emission directives. On the other side, consumers are concerned about the contamination of soil, oceans and the atmosphere that affect both nature's and humanity's ability to survive. The forest-based value chain can provide society with environmentally friendly cellulose-based products that have a limited impact on food production and the competition for farmland.

The raw-material reserve becomes sufficient when it fulfills the requirements of converters, consumers and society as a whole on the amount and type of raw materials. To achieve this goal, there will be demand for a pronounced cellulose-based offering in the future. The industry already has a worldwide potential capacity and infrastructure for rapid scale-up, but still, breakthrough business models and pioneering products and services are needed.

New, even unexpected, alliances between industries are needed to make biorefinery intermediates, including special and modified celluloses, available for a wider variety of products. Technical knowledge and customer intelligence will increase to an entirely new level and after these changes, the operations of the industry will never be the same again.

# 3. Vision – digitalisation reorients cellulose-based industries towards customer-centric business

## **Artificial Intelligence (AI)**

*Intelligence demonstrated by machines, simulation of human intelligence processes by machines, especially computer systems.*

## **The Internet of Things (IoT)**

*The IoT is a system of inter-related computing devices, mechanical and digital machines, objects, animals or people that are provided with unique identifiers and the ability to transfer data over a network without requiring human-to-human or human-to-computer interaction.*

Cellulose has inherent properties that make it an interesting material for various applications. In the future, forest-based value chains will take full advantage of this fascinating material and make it available for novel value-added applications. The new ecosystems will be highly virtualised, enabling holistic optimisation and automation of processes throughout product life cycles. Complexity will be mastered with, for example, modelling, simulation and optimisation, data analytics and exploitation of **artificial intelligence (AI)**. Information will be collected, processed and exchanged continuously from harvest, use, reuse and recycling of cellulosic materials.

**Digitally assisted business ecosystems between industries will develop value-added cellulose products and revolutionise bio-based material markets.**

The vision entails three major concurrent developments. Firstly the chemical processes for separating cellulose from wood will develop further, and novel technologies for dissolving pulp will emerge (part A. in Figure 3). Secondly, a rich ecosystem of new products made from cellulose raw material will be brought to life with networked, design-driven approaches, and a value-adding consumer market will emerge (part B. in Figure 3). The third development is the adoption of digital technologies in the forest-based value chain.

Digital technologies and digitalisation are continuously progressing beyond the mere instrumentation and automation of production processes. The internet has become a backbone for many kinds of global and local process and business management functions, both in open and confidential applications. The internet offers services for integration, interoperability and remote operation as so-called cloud services.

The open, cloud-based **Internet-of-Things (IoT)** platform connects machines and physical infrastructure to the digital world and provides powerful industrial applications and digital services to help operate production plants. Distributed manufacturing requires novel process control solutions, when the same production can take place in several locations simultaneously or is continued in a remote place, even by different operators. Intelligent systems are also penetrating tasks closer to the user interface, such as demand prediction and design processes.

Data, especially so-called big data, has become an asset for many kinds of situational awareness, predictive analytics, deep learning, wide optimisation

and general new AI applications. Virtualisation based on modelling and simulation techniques offers versatile opportunities for both factory design and operative factory management.

The adoption of digital technologies will speed-up the above-mentioned developments and disrupt the whole value chain from forest, through pulp processing, to novel products and consumer experiences. Digital transformation necessitates efficient data and information management and processing in a *cloud of clouds*, where information about resources, products, productions, logistics and consumers will be merged (Figure 3).

The resource cloud contains information on available forestry and wood reserves and pulps as well as cellulose intermediate products made of them. For example, clouds enable us to track the history of the raw material. The logistics cloud is essential for controlling the inventory of virgin and recycled pulps, as well as different intermediate products and by-products. Finally, the product cloud combines information about consumer habits, product offerings and perceptions of quality. Merging all these aspects in the cloud of clouds enables end-to-end visibility of the value chain: an overview of resource availability, optimisation of the complex production processes and supply chains, and insight into customers' future needs.

**Mini-mill**

*Small-scale conversion unit.*

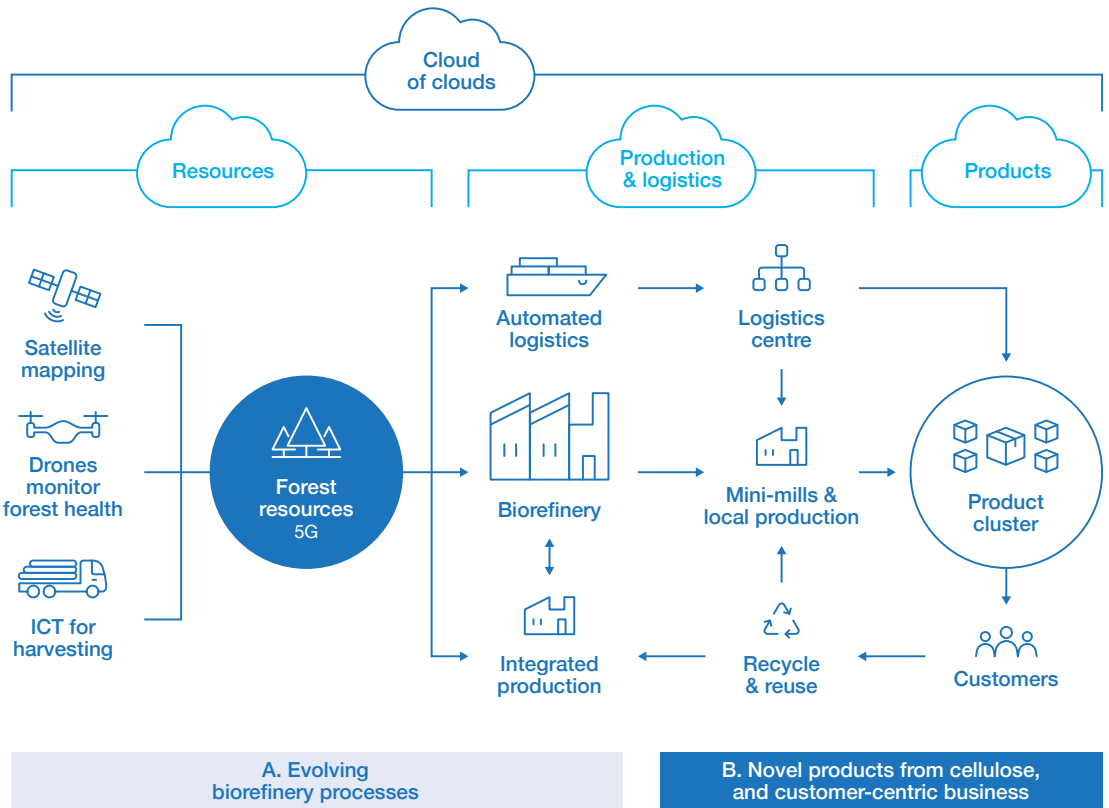


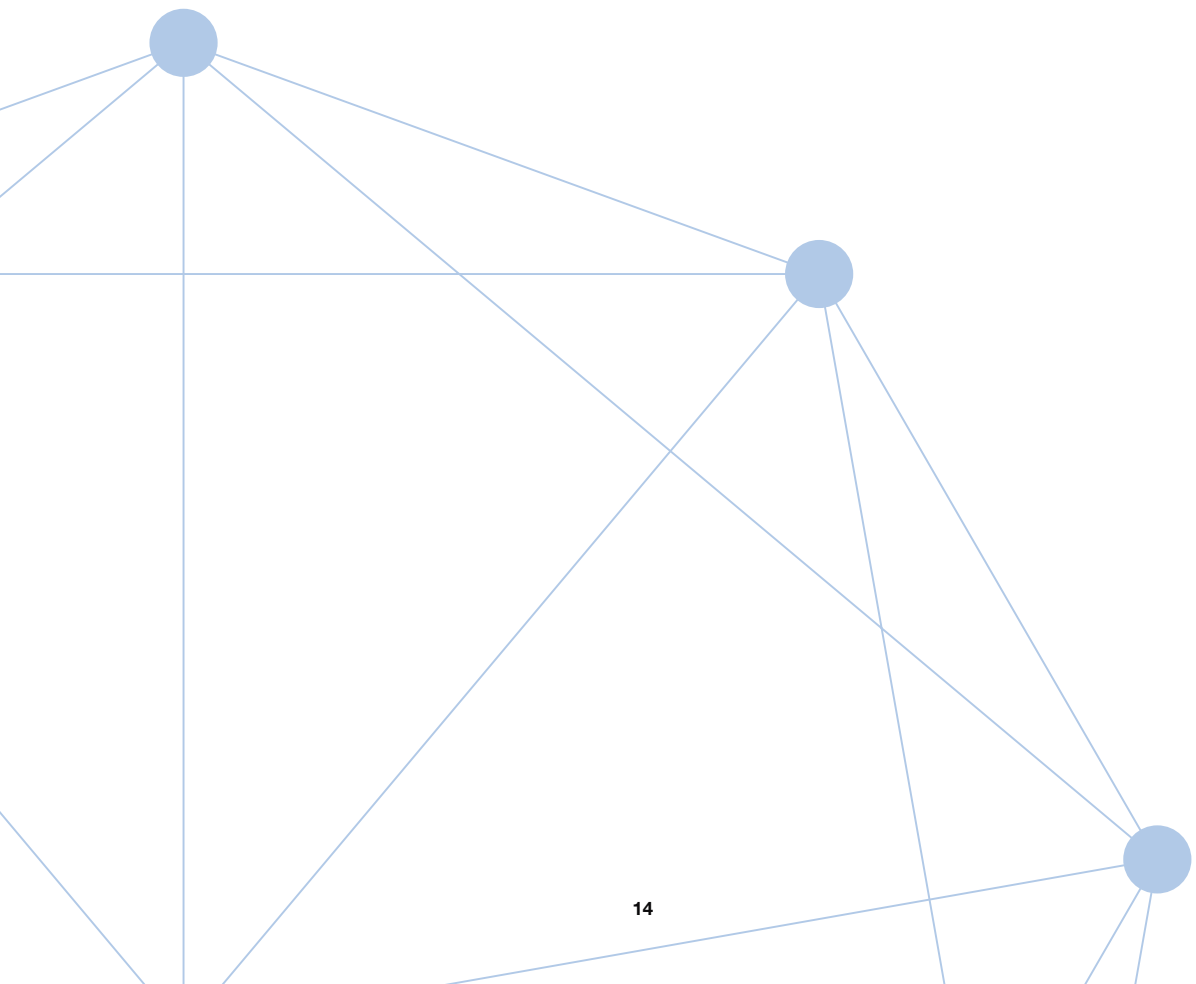
Figure 3. The central role of digital technologies in future cellulose-based industries.

*Digitalisation has untapped potential from forest to consumer products*

In the future, next generation biorefineries will combine high throughput fractionation of cellulosic raw materials with the production of speciality products. Smaller processing units will also draw benefits from energy, water and chemical integration with the main biorefinery. These forest-based biorefineries will boost the economy from the middle of the 2020s to 2030 and even beyond. The forest-based biorefinery produces added-value products in an intelligently optimised manner, which will mitigate the volatility of product prices and hence increase the net profitability of the plant to a new level.

At the consumer end of value networks, unique product concepts will be generated by innovative design that applies basic manufacturing technologies to convert cellulose fibres to materials and products. This enables the emergence of new industrial stakeholders. Production units will be smaller in size and operate closer to the end customers. This will create totally new industrial ecosystems by combining high technology, product design and business.

Digitalisation is changing the way industries function from supply chains to customer experiences, particularly in the processing and manufacturing sectors. The renewal becomes possible if industries are prepared to explore and unleash global opportunities for value creation through, for example, advances in automation, big data, machine learning, AI and IoT.



## CUSTOMER-SPECIFIC MANUFACTURING

The next generation of added-value production is lean, agile and customer oriented, while the degree of processing becomes higher and the delivery chain shorter. The focus will shift from process optimisation and maintenance to co-design of customised products and services, and customer-driven commerce based on up-to-date information.

A larger share of products will be produced close to the customers and delivered without intermediary warehouses. In customer-driven product segments product lifetime will be shortened from decades to years or even months. Customer-specific adaptations may happen in weeks or days, and the number of products will increase from hundreds to hundreds of thousands of variants, which will pose high requirements on production systems and supply networks. Automation needs to be exploited at all steps, from product design to production, service and customer interaction. Also, the demand for product-related technical services and intelligent customer interfaces will increase.

Cloud computing will control and manage the distributed production networks. We are already in the first stages of creating cloud-based management systems of customer interfaces and demand-prediction. The next step will be to create intelligent systems that enable proactive design and management of production as a part of logistics. Finally, design, production, and supply are fully integrated and based on known customer and market needs, which leads to minimum waste.

The basic requirement for capacity optimisation is the availability of transparent and reliable digital data over the supply chain. The next step will be to share the production resources to a greater degree, which will eventually lead to multi-product ecosystems, where networks of actors can produce multiple new products. The networks are agilely configured according to customer demand and logistical needs while taking into account available resources from raw-materials to production capacity.

When products are highly customised and specialised, and product series small, production with smaller production units becomes feasible. In contrast to bulk on-demand production, smaller units can form efficient and agile networks that benefit from each other. Process control of a network of small units can be implemented as a service, where a central unit provides automation to the distributed, relatively simple, or even mobile, production stations.



# 4. Digitalisation – the path to industry revolution

## DIGITALISATION IN THE CELLULOSE-BASED INDUSTRIES

The pulp and paper industry, like any process industry, has a long tradition in applying process control solutions and automation. The first fully automated and instrumented production lines appeared in the 1980s, and gradually the whole production process was taken under computer control.

Over the following decades, and with several new technology generations, control technologies and remote operations considerably improved the efficiency of **pulping** and paper making processes. Contemporary digital solutions, IoT and automation have been enhancing production, maintenance and logistics processes. It has become possible to operate ever-larger production plants with increasing production volumes and improved product quality, with fewer personnel.

However, data collected in the production processes, services and operations have not been linked with other existing systems, making it difficult to benefit from all the collected data. AI is a promising new aid to improving the efficiency of operations in raw material purchasing, harvesting, logistics and manufacturing. It opens up possibilities to exploit, for instance, data of vast contents and modelling of customer service that enables proactive planning of activities.

As an example, through AI it is possible to extract the essential product features for each customer. Further, AI can define optimal raw material combinations, compensate the quality variations in raw materials, and control the complicated multivariate manufacturing processes. In the future, the focus will be increasingly on the processes that improve the value-gain of products. The more complicated and advanced the products should be, the more information intensive they also become. There is a tendency to specialise in new or niche end products, and the production is becoming more demand-driven, agile, and geographically distributed. Outsourcing of auxiliary business functions such as condition monitoring and maintenance is gaining popularity, leading to highly interconnected businesses. There are many opportunities for energy, waste, material and recycling optimisation over the value chains and across company boundaries. Such advantages are only realised by having significantly more extensive digitalisation and AI in place.

The EU's industrial policy now aims at building a digital single market for European industries. To achieve this, industrial applications need a so-called industrial internet, a much more capable internet compared to the traditional one. Its form and functionality are now being developed under the title *Industry 4.0*. Industry 4.0 is expected to contain all the elements that are needed to realise the heavy software and automation-managed systems. The global

### **Pulping**

*Separation of fibres by mechanical, chemical or chemi-mechanical means.*

## *Digitalisation will lead to a rebirth of all industries*

solutions are distributed and flexible businesses, across value chains, across company and geographical borders, from process to business function levels. When entering an era of novel bio or fibre-based products, much relies on the digitalisation capacity of new processes and business models.

Digitalisation is expected to offer numerous benefits for pulp and paper plants and biorefineries, such as:

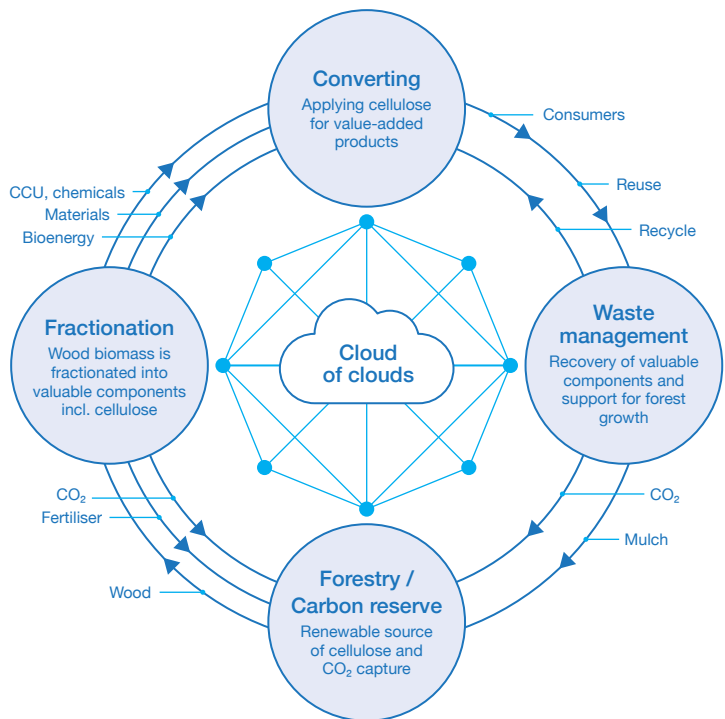
- Improved raw material logistics as a whole, through detailed forestry inventories and digitalised wood procurement.
- The ability to choose the best feedstock for each process by improved handling of raw material flows and access to specific wood fractions.
- Improved control of integrated processes, and increasing remote operation or low-manpower operations. Prediction of inventories and material balances in all situations will improve. Predictive maintenance and planning will reduce downtimes to a minimum.
- Synergistically joined process design and process operation in the digital systems.
- Easier production planning. Combining production runs of different lengths will become easier, and production of speciality grades can benefit from, for example, energy integration.
- Improved total control of distributed manufacturing.
- Increased possibilities to serve customers with flexible online services.

Top business management is starting to see innovation and development as the focal points of their companies' digital solutions, instead of process efficiency and productivity increase. For example, 96 per cent of the Finnish industry respondents recognised digital possibilities in their strategy, and up to 80 per cent considered real-time planning and data-based decisions to be top priorities<sup>6</sup>. Business opportunities can be found through data utilisation, process automation, robotisation, and new products and services. Utilisation of digital solutions for innovation and new business creation is gradually rising to the same level of importance as other business drivers.

However, the role of digital solutions in business creation is not easy to prove, probably because the value of their outcomes measured by traditional key performance indicators, such as profit or customer satisfaction, is unclear. Nevertheless, Industry 4.0 will considerably improve the scores of the organisations by 2030. As an example, it has been forecast that productivity will increase moderately by 3% to 5%, but time-to-market will shorten by 20% to 50%, maintenance costs will decrease by 10% to 40%, and total machine downtime will fall by 30% to 50%<sup>7</sup>.

## CLOUD TECHNOLOGY BOOSTS MATERIAL CIRCULATION

The paper industry has long experience in collecting and recycling fibres into new paper and board products, and novel digital technologies make it possible to develop a whole new concept from this starting point. The idea is to create an inventory of the biogenic carbon reserve, i.e., an inventory of all the forms and transactions that the cellulosic materials experience. The industry can then provide and recover cellulose and optimise its use. Figure 4 depicts a future circulation scenario of cellulose-based materials and data exploitation for building a frugal and resilient system for resource utilisation.



*Cellulose-based materials will play a crucial role in entering a post-plastic world*

**Figure 4. Digital technologies enable a controlled circulation of cellulose-based materials.**

Most of the produced materials cannot be recycled due to their complexity, and therefore they end up in energy use, when the goal is to keep materials in the loops for as long as possible. Material circulation is an essential part of the material management and frugal use of natural resources. The material and product design process are crucial for ensuring their efficient circulation. From the perspective of circularity, mono-materials are easier to recycle than multi-materials. Cellulose as a material is a robust alternative for replacing materials which cannot be recycled, furthermore as a renewable resource, cellulose-based materials have less environmental impact compared to, for example, fossil-based materials.

One of the greatest features of cellulose materials is that they can be recycled into high-value materials like textile fibres. Cellulose retains its value and can be used several (from three to seven) times in various forms and different loops without reducing the value of the material. Many other materials end up in secondary materials after a recycling process, resulting in a value loss.

### **Blockchain**

*A blockchain is a continuously growing list of records, called blocks, which are linked and secured using cryptography.*

**Blockchain** type of technologies and AI play an essential role in operating circulations of cellulose-based materials from forests to the consumer, and again back to consumer use through deliberately designed material converting processes and recycling activities that restore materials back into use.

As depicted in Figure 4, forests are a renewable source of cellulose and act as a valuable *carbon reserve*. Sustainable use of forests is crucial for preserving natural resources and ensuring balanced availability of resources from the economic and wellbeing perspective. Wood *fractionation* results in different substances and materials, and some parts are used for bioenergy. Ashes from bioenergy production can be applied as fertiliser to enhance forest growth. In future, carbon capture and utilisation (**CCU**) will ensure the return of carbon into use.

### **CCU**

*Carbon capture and utilisation refers to the use of pure CO<sub>2</sub> or CO<sub>2</sub>-containing gas mixtures as a feedstock to produce fuels, chemicals and materials.*

In the *converting* stage, cellulose is applied to value-added products that end up in consumer use. Depending on product and material form, a certain amount of the materials and products are in cascade use as long as possible. At the end of life, a certain amount of these materials and products are recycled back into the converting phase, where materials are used as any eligible material resource replacing primary materials.

Through *waste management*, valuable components and materials are recovered for recycling, and so support the sustainable growth of forestry. The more materials that are returned into loops, the less need there is to get primary resources direct from forests. Materials that cannot be used for recycling are utilised for mulch in forestry. Forests again act as a carbon reserve for emissions that are caused by waste management activities. Therefore the sustainable use of forests is a backbone for ensuring a stable business and for mitigating climate change.

## CELLULOSE-BASED MATERIALS AS A SERVICE

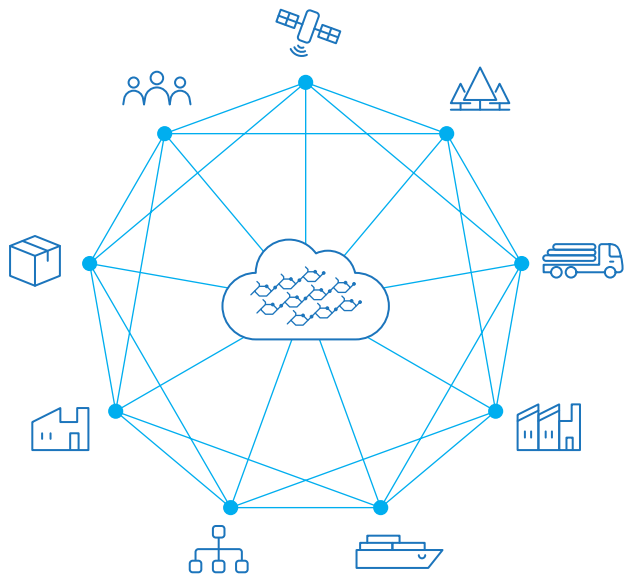
By mastering an intelligent material circulation, cellulose can become a service. In the future, as one form of owning, materials will be owned fully or partially by material producers, who will master the production, modification and recycling of the material. Shared ownership of raw materials will also become possible. Materials will be used, for example, by leasing them. In the material leasing concept, the customer pays for the material use and quality losses during the utilisation phase. All of the transactions between the service providers and customers are recorded in a blockchain type of technology.

Digital transformation necessitates efficient data and information management and processing in a cloud of clouds (Figure 5), where information about resources, products, productions, logistics and consumers are linked. The data accumulating from these stages is exchanged through blockchain types of technology. Thus, all stakeholders can rely on data authenticity, as no record is ever removed without an agreement of all the stakeholders involved. The secure exchange of data is a necessity in the new generation of digitalisation. If not solved properly, cybersecurity issues may become

showstoppers. Networked businesses also bring along hesitations about trust: How can companies in an open-like digital environment trust each other in a constructive way?

Blockchains are an example of evolutionary technologies that help to solve challenges such as a lack of trust. Gathering data from all material circulation phases is an essential part of building a resilient system that designs its operations based on information exchange, and optimises its activities based on deliberate computations. This, in turn, results in the effective and wasteless use of resources, meeting the demand more precisely.

Collecting data about a material's service life makes the optimisation of material usage, reuse and recycling possible. Accurate computations in the system can be based on known concepts, such as Material Input Per unit of Service (MIPS). MIPS can be used as a measure of the eco-efficiency of a product or service, and it offers a means to reduce the environmental burden of a product or service. The results of the calculations reveal the resource use along the life cycle of the product or service and help to focus attention on the most important measures to reduce its environmental burden.



**Figure 5.** In a cloud of clouds information about resources, products, production, logistics and consumers is merged by providing end-to-end visibility of the value chain.

# 5. Towards agile cellulose fractionation processes

Digitalisation, sustainability and demand for new kinds of materials will require new types of production processes. Novel fractionation processes, a transition from traditional pulp mills to modern biorefineries, and emerging mini-mills will enable a wide range of multiple products that will meet demand more precisely. Production will be optimised by the information flow provided from the different stages of the ecosystem – from the forest to the customer.

Modern biorefineries will play a crucial role in the exploitation of cellulose. Besides its high utility aspect, cellulose is fully renewable, recyclable, compostable, and can even be combusted. As a material it enables properties from soft to strong, ductile to brittle, and from water absorbent to water resistant.

Cellulose is not only a fibrous material with inherent properties for paper-making, it is also a versatile engineering material with several other features, such as super strong **fibrils**, highly modifiable surfaces, multiple crystalline structures and the ability to form composites. Safe, high-quality and sustainable products can be designed based on these inherent properties and their modifications. The first step in making these products is to separate the fibres from wood by chemical or mechanical pulping.

## **Fibrils**

*Building blocks of wood fibres.*

*Wood pulp types can be divided into two main classes; chemical pulp – currently mainly kraft (sulphate) or sulphite – and mechanical pulp. Chemical pulps are lignin-free fibres that are used mainly in high-grade paper and textile products, whereas mechanical and semi-chemical pulp fibres are used mainly in newsprint and packaging. Dissolving pulp is a special, high-cellulose grade pulp from sulphite and prehydrolysis kraft processes.*

## CURRENT PULP MILL CONCEPTS AND THEIR CHALLENGES

The processing of wood fibres into pulp has challenges that have led to the current pulp mill concepts. The chemical kraft pulping process has become the most dominant solution because of its superior efficiency to recover chemicals and produce bioenergy in a recovery boiler. In the future, new processes need to show higher agility, lower capital investment and added value creation from the same or an alternative raw material base.

Pulp production has three major challenges:

- Wet-dry processes have a high capital cost, leading to large production units.
- Heterogeneous composition of biomass leads to complicated biorefinery concepts.
- Reduction of CO<sub>2</sub> emission by means of improved carbon yield and later capturing to products.

Cellulose processes are typically water-based, and drying is needed. Wet processes are usually more expensive than dry processes. This handicap has been solved by energy integration. Utilisation of the heat energy that is available at the mill site improves the energy efficiency and lowers production costs, however the investment costs are substantial. Future biorefineries will benefit from energy integration, as does current paper production.

Old pulp mills in particular consume a lot of water, but modern pulp mills are markedly better due to the nearly closed water circulations and biological wastewater treatment. Consumption of fresh water in modern pulp mills can be less than 5m<sup>3</sup> per ton of products.

Cost competitive operations have been the leading target in pulping. Energy production and by-products, such as tall oil, have improved cost competitiveness. In turn, the latest investments in pulp biorefineries put even higher emphasis on full utilisation of the wood raw material, and a wider range of value-added products such as bark, lignin, tall oil, turpentine, base-chemicals, energy (both steam and electricity, biogas and fertilisers).

Cellulose fractionation from biomass is a demanding and rather complicated task. Instead of considering the side streams, such as lignin and bark, merely as an energy source, it is essential to recover the whole potential and value of side streams. For example, extractives and lignin can be converted into adhesives, glues, polymeric materials and composite fibres. These are examples of additional products that could make biorefineries economically attractive even on a small-scale.

Pulp mills emit mainly biogenic carbon dioxide. Old pulp mills are still using fossil fuels, but the newest kraft biorefineries are fossil carbon-free. A modern kraft pulp mill emits approximately 1.2 tonnes of biogenic carbon dioxide per produced ton of pulp, an amount that is comparable to emissions from bioplastics production<sup>8</sup>. However, in the case of a cellulose biorefinery, the emissions are mainly from steam and electricity production, which are valuable products. The high amount of carbon emitted from combustion is an indirect sign of insufficient conversion degree into products, so it therefore would be rational to increase the carbon yield by converting the maximal amount of raw material into value-added products.

## THE EVOLVING KRAFT BIOREFINERY

### Reduction of carbon dioxide emissions

The carbon balance of a pulp mill can be improved either by reducing CO<sub>2</sub> emissions or by capturing CO<sub>2</sub>. Recovery of lignin or other organic substances from the black liquor will directly reduce the CO<sub>2</sub> emissions from the recovery boiler. A direct way to reduce carbon emissions is to capture the formed CO<sub>2</sub> and utilise it at the mill site.

Currently, only a limited amount of lignin can be extracted from the kraft process without impeding the chemical recovery cycle and energy balance of the mill. Hence, most of the lignin in the black liquor, i.e., kraft pulping spent liquor, is combusted in the recovery boiler, resulting in biogenic CO<sub>2</sub> emissions. Other sources of CO<sub>2</sub> emissions are the lime kiln and bark boiler. At modern mill sites these emissions are also biogenic, as no fossil fuels are needed to operate the kraft biorefineries.

## *Reduction of carbon dioxide emissions will make kraft biorefineries the material refineries of the future*

Novel technologies for carbon capture and utilisation (CCU) via biotechnical and chemical conversion routes are already established at laboratory scale, but technological innovations are still needed before they can be realised in an operational environment. This topic is being extensively researched since pulp mills provide significant sources of biogenic CO<sub>2</sub> at relatively high concentrations. By 2050, kraft biorefineries with CCU integration may have expanded their product portfolio to include also CO<sub>2</sub>-based products. CO<sub>2</sub> emissions can also be diminished by implementing alternative technologies for chemical recycling and energy production.

### **Lignin recovery**

Several new industrial-scale production units have been installed to recover lignin at kraft biorefineries, and more installations are expected in the future. There are a lot of research activities on-going to find the applications with most potential for lignin. Thermoset resins, carbonised materials including carbon fibres and activated carbon, biocomposites, and surface active additives are currently of great interest and the closest to market entry.

However, several of kraft lignin's inherent properties, such as its heterogeneous structure, thermal properties, low reactivity, colour and odour, still limit its applicability. This raises the need for proper pre-treatment technologies to convert lignin into high-value products on an industrial-scale or to find novel technological solutions to recover lignin in a more reactive form from the kraft biorefineries.

### **Alternative fractionation processes**

Raw material efficiency describes the overall aim to convert the raw material into high-value materials and products. High raw material efficiency has positive effects both on the economy and environment. With current pulping methods, material efficiency remains relatively low, with a yield of only approximately 50% of the feedstock. So far the goal has been to maximise the yield of pulp and energy, instead of developing a wide product portfolio that utilises all feedstock components.

Even though the currently utilised raw materials are mainly forest-based, in future the importance of new raw material fractions will gain more importance. Side-streams from agricultural production as well as fast-growing annual plants can be seen as possible raw materials of the future and have already been utilised in the production of speciality papers. In future, novel processing technologies will enable a more sustainable and environmentally friendly use of these raw materials. The novel technologies will also offer the possibility to further optimise and tailor their use.

The emerging technologies aim at selective fractionation concepts that separate wood components in mild process conditions. Degradation of the native polymers thus remains minimal, resource efficiency is increased and higher product yields are achieved. However, external renewable energy sources will be required if a maximised conversion to materials is required. The quality and functional properties of the cellulose components are expected to differ from those of the traditional kraft cellulose. In the future, maybe they can even be tailored for specific purposes.

Several possible solutions for more complete fractionation technologies have been proposed and studied, mainly at laboratory scale. These include



a variety of organosolv and alkaline treatments, as well as novel solvents like a deep eutectic solvents (DESs) and ionic liquids (ILs). ILs and DESs are classes of a new generation of green solvents with varying compositions and properties that can be used for fractionating lignocellulosic materials into their polymeric components.

Because ILs are able to dissolve wood fully or selectively, the potential is in complete utilisation of wood or alternative lignocellulosic biomass for material application, like composites, textiles or even carbon fibers. There are several benefits that could support the utilisation of DES as a pulping chemical but the technological breakthrough has not taken place yet.

The water footprint could be reduced as the process is based on solvent instead of water solutions. The new production plants could be markedly smaller and become integrated with, for instance, saw mills for the direct production of materials. Eliminating combustion of lignin would lower the energy independency of the plant, and reduce the supply of green electricity and heat to society, but also lower the overall carbon dioxide emissions of the plant.

Table 1 summarises the main differences between the current kraft and sulphite processes, and the new emerging pulping processes.

**Table 1. Product portfolio from softwood kraft biorefinery.**

<b>State of the art</b>	<p><b>Sulphate (kraft)</b> <b>Sulphite</b></p>	<p><b>Main products:</b> Pulp fibres for paper, paper board and textile production. Lignin for energy production.</p> <p><b>Low raw material efficiency:</b> Product yield ~50% of feedstock.</p> <p><b>Electricity production:</b> 600–900 kWh per ton of bleached pulp.</p> <p><b>Annual capacity:</b> 1–3 million tonnes of feedstock per production line per year. 0.5–1.5 million tonnes of bleached cellulosic pulp per typical production line.</p>
<b>Emerging pulping</b>	<p><b>Organosolv &amp; alkaline pulping (variants)</b> <b>Deep eutectic solvents</b> <b>Ionic liquids</b></p>	<p><b>Main products:</b> Cellulose, hemicellulose and lignin fractions.</p> <p><b>High raw material efficiency:</b> Product yield more than 80% of feedstock.</p> <p><b>Expected annual capacity:</b> 0.1–0.5 million tonnes of feedstock per production line.</p>

*Small-scale biorefineries – agile and resource-efficient production units close to the biomass source*

Even if new greenfield biorefineries (production units at new sites), were introduced, most of the pulp demand will still be met by kraft pulp production in 2030 as the kraft process is currently technologically the most reliable choice for a large pulp production unit. In addition, there are several possibilities to modernise kraft pulps mills into multiproduct biorefineries so future kraft biorefineries will also produce lignin and CO<sub>2</sub>-based chemicals, alongside the traditional products pulp, turpentine, tall oil and electricity.

## NOVEL FLEXIBLE SMALL-SCALE BIOREFINERIES

The first small-scale pulp-producing biorefineries that are based on novel technological solutions will emerge by 2030. These small-scale biorefineries will be located close to the biomass sources, and their production capacity will be much lower compared to the typical wood-based kraft biorefineries.

The most potential lignocellulosic biomass feedstocks for small-scale biorefineries will include residues from the forest or agro-industry, such as wood trimmings, straw, and bagasse. Local raw material supply will substantially decrease transportation costs.

The product portfolio of small-scale biorefineries will be more versatile than kraft biorefineries, with main products including speciality pulps, speciality lignin and hemicelluloses and/or chemicals. In addition, depending on the raw material composition, other substances such as extractives-based biochemicals or even proteins could also become valuable products. Flexible production planning between different products will mitigate the market risks. This will be enabled by digitalised systems and process concepts.

The recovery of all lignocellulosic polymers – cellulose, lignin and hemicelluloses – instead of their combustion will directly affect the carbon balance of small-scale biorefineries. If none of the components is combusted, no direct CO<sub>2</sub> emissions are generated. However, this will set pressure on finding sustainable and renewable energy sources for the biomass processing and chemical recovery operations.

Local business ecosystems will emerge around the small-scale biorefineries, as the production of several products at one mill site will involve a network of industrial companies. Each bio-based product will require specific downstream processing and further conversion into valuable products, as well as distribution and sales channels. These processes can be operated either by the process owner or by a separate operator at the same mill site or in a remote location. Sharing the same mill site enables process integration and creates synergies in use of energy, water and other means.

There are numerous types of process concepts under development worldwide which are at different technology readiness levels. The capital investment in these small-scale biorefineries should be significantly lower than in the kraft mills since a recovery boiler, the operation unit that requires the highest investment cost, can be avoided. In spite of the promises that small-scale biorefineries hold, they remain capital-intensive investments and have a relatively high technology risk due to the so far very limited industrial experience.

*Small-scale biorefineries will become business ecosystem cores*

# 6. An ecosystem of value-added cellulose products

Sustainability and performance requirements are increasing demands for novel materials and products, and cellulose-based materials have a great potential to cover these requirements. The inherent properties of cellulose and game-changing technologies will provide multiple solutions for the demands of different markets. Digitalised ecosystems of the forest-based value chain will enable tailored utilisation of materials and provide solutions for on-going challenges like replacing plastics, meeting the growing need for packaging and providing composites that are more environmentally sound.

## THE CELLULOSE MATERIAL PLATFORM

Relatively rigid cellulose performs a skeletal function in wood and other plants. The cellulose-rich fibres are extracted from wood in the pulping process. Fibres can be disintegrated further into smaller fibrils or even to their constituent molecules. All these structures have inherent mechanical and chemical properties that can be tailored as desired for use in new materials and products. Figure 6 shows the different raw materials obtained from wood and their end uses.

Cellulose has inherent properties that are either benefits or challenges in relation to the conversion technique and intended application. Development of novel materials is about finding ways to overcome challenges and benefit from these properties.

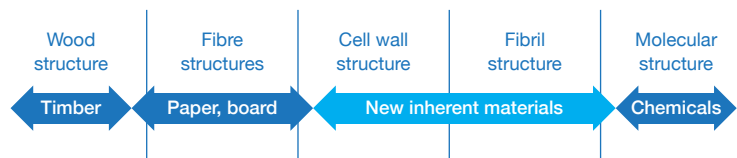


Figure 6. From wood to cellulose molecules - different types of cellulosic materials.

The inherent properties of cellulose that most often limit its direct applicability, especially in polymers and composites, include:

- Cellulose pulp fibres are short compared with many structural fibres.
- Pure cellulose is not thermoplastic. Only chemically modified cellulose can be melt-processed.
- Native cellulose adsorbs water because it is hygroscopic, unlike synthetic plastics.

The true potential of cellulose is derived from a set of properties that can be exploited as such or tuned by chemical or other modifications. These properties include:

- Cellulosic materials are relatively strong and flexible, but their density is low compared with glass fibres, for example.
- Cellulose fibres and fibrils easily form films that have special optical characteristics, such as transparency.
- The pronounced water-sensitivity and hygroscopicity of cellulose can be used as an asset.

By successful modification of cellulose fibres, the range of applications can be considerably widened. Examples of new products that have the power to extend, shift or replace current applications include:

- Packaging materials, with improved barrier properties and moldability that can be used instead of plastics, in packaging films for instance.
- Textiles that are able to replace cotton, especially in clothing. Alternatively, textiles that replace oil-based synthetic fibres in hygienic and technical textiles, like filaments, yarns and nonwovens.
- Composites that are environmentally acceptable and affordable compared to conventional materials, especially in short service-life applications that have medium performance requirements.
- Novel application of cellulose like cellulosic substrates for electronics and sensors that are easier to recycle and thus have better environmental acceptance.

## **Nanocellulose**

*Nanostructured cellulose.*

### **Raw materials for novel products**

Novel materials can be composed of traditional pulps, cellulose-based chemical derivatives, regenerated cellulose or recycled materials as well as structured celluloses (i.e., **nanocellulose**).

Commodity pulps include affordable hardwood chemical pulps, softwood chemical pulps containing long fibres, recycled fibre pulps and alternative pulps from sources such as annual crops. These paper-grade pulps will be available in high volumes far into the future and find uses as raw material for novel products. Mechanical pulp will gain a foothold in composite products, especially for the construction, transport and furniture sectors. Dissolving pulp is a speciality pulp that will find uses in textiles, including nonwovens, and chemicals.

Cellulose nanomaterials have many unique inherent properties, such as high specific surface area, film formation ability, strength and lightness, which give them potential in numerous applications. Some conventional high-volume products, such as in graphic or packaging papers, paints, concrete and biocomposites are in active research. Additionally, high quality requirements in novel, promising and rising application areas include food, cosmetics, medical, electronics, chemical and medical diagnostics, energy storage and membranes for water and gas purification.

To realise the potential of cellulose, totally new cooperative approaches to material and product development are needed. One of these approaches is the design-driven development concept applied by stakeholder ecosystems.

## **GAME-CHANGER TECHNOLOGIES**

Certain key technologies have the potential to bring about significant improvements in how fibrous materials are processed and converted into products. In the following, the most important technologies are presented.

### **High consistency processing**

Processing equipment and consistency have a great impact on feasibility and fibre properties. Cellulose processing at high solid contents has the potential to be a game changer for the increased and broader use of cellulose-based materials in existing and new applications. The process condition together with processing equipment greatly affects viscosity and fibre properties, etc. Moreover, the capability to prepare functional cellulose chemicals or fibres through proposed technologies affects not only processing costs but may also make novel chemistries more effective, selective and suitable for rapid functionalisation of cellulose.

### **Foam forming**

Foam forming technology is one example of converting technologies that appear to be game-changers. In this technique, wet foam is used instead of water to deposit fibres and bond them into sheets or thicker mats. Foam forming technology leads to superior formation, enabling the use of a wider scale of fibre materials and tailored product properties. It also increases forming consistency, which results in water savings compared to current dilute processes.

Additionally, foam forming also gives the possibility to produce materials that are very thin and uniform, and have a controlled density or pore size gradient in the thickness direction, or mix materials that have different densities. For some grades, the foam technology offers an option to increase production by increasing the machine speed. It enables totally new types of thick or low-density products that are useful, for example, as thermal insulators or shock protectors in packaging replacing polyfoams like polystyrene. Novel functionalities can also be created by multi-layered structures.

### Enzyme-assisted modification

Enzymes are natural tools for fibre modification, as such, or combined with chemistry and physical tools. Enzymes are specific catalysts, which can be applied to targeted modifications of different pulp components. Enzymatic treatments can be carried out in mild reaction conditions and can reduce energy consumption in pulp modifications, for example in pulp refining. Both hydrolytic and oxidative enzymes can be used to increase fibre reactivity and improve the accessibility of chemicals. The full potential of enzymes has not yet been exploited, but the rapid developments in enzyme discovery will provide even more efficient enzymes for applications in the future.

### Ionic liquids and deep eutectic solvents

ILs and DESs are a new generation of green solvents that can be used for fractionation of lignocellulosic materials into their main polymeric components. The great variety of solvents with different composition and properties provide a means to totally dissolve the cell wall or partially remove selected polymers. Hence, these solvents will be used especially in delignification to produce cellulosic fibres or cellulose dissolution to produce long fibres for textile applications.

### 3D printing and personalised production

In the 1990s, manufacturing technologies became digital as product design turned into computer-aided 3D modelling. Grinding machinery was the first to be operated with numerical control. Soon the experiences with computer-control were adapted into additive manufacturing technologies. Additive manufacturing covers a range of different techniques referred to as 3D printing.

3D printing is a manufacturing method that is based on solidifying or joining materials under computer control into objects. It has become the most important technology platform that combines digital design methods with highly flexible production technologies. It opens up the possibility for people to manufacture items for their own use.

The first application area of 3D printing was rapid prototyping but it was soon also taken into use in personalised production that entails mass customisation and production of complicated shapes.

3D printing of thermoplastic polymers is an area that is growing fast. Thermoplastic celluloses are an ideal material for **direct writing (DW)**. Recently, high-consistency nanocelluloses have been proven suitable for on-demand printing.

### **Direct writing (DW)**

*Can mean any technology that can create two- or three-dimensional functional structures directly onto flat or conformal surfaces in complex shapes, without any tooling or masks.*

## PRODUCT ROADMAP

Currently, the manufacturing technologies of kraft pulp have reached their ultimate competitiveness through large production scales and modern forestry technologies. Packaging boards are currently compensating for the reduction of paper production, and the tissue paper offering is growing fast due to improved living standards around the globe. Wood fibre composites are increasingly used in constructions. Automation of industrial processes has reached high levels, and it helps in the harvesting and logistics of the wood raw material. Digital media is acting as a change agent and accelerating the industrial reorientation. Figure 7 shows the development of the cellulosic product offering.

By 2025, packaging materials and manmade cellulose fibres will clearly be the next growth markets. The biorefineries have become fossil free, and a high level of material efficiency has been reached. Utilisation of side streams and bioenergy recovery have become important routes for biorefineries to make a profit. The market is driven by the demand for biomaterials, which is boosting the demand for kraft and dissolving pulp as raw materials. Foam forming is commonly used, and nanocelluloses are finding wide uses as additives and components in high-performance materials. Digitalisation is enabling sustainable and efficient sourcing of raw materials and AI is starting to master the data flow in the highly integrated production units.

By 2030, integrated mini-mills are efficiently supplying speciality cellulose materials. Increasing price margins have shifted the focus to value-added biomaterials. Chemically and biotechnologically modified pulps have become ideal raw materials for new applications, such as technical composites,

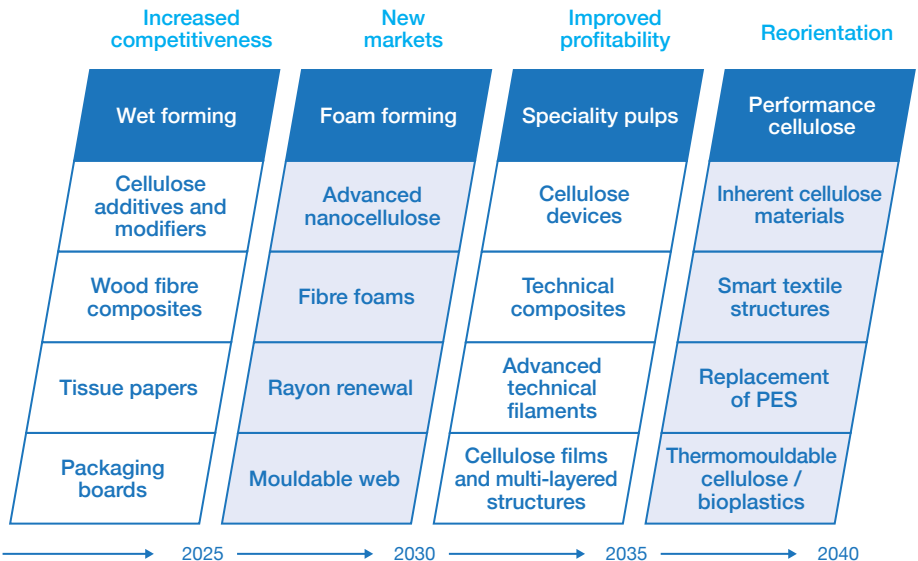


Figure 7. Development of the cellulosic product offering until 2040. PES = Polyester.

construction materials and high-performance filaments. Cellulose films are replacing plastics in flexible packaging applications. Cellulose-based devices are becoming common in rapid analytics, for example, in health and personal care. Digital design solutions have made product development and adaptation fast, and direct logistics the new norm.

*By 2035*, standalone small-scale biorefineries are becoming efficient plants for speciality pulp production. Very different cellulose materials are required for entering new markets with new products or renewing current product offerings. The inherent properties of cellulose, like optical performance and surface activities, can be fully taken advantage of by utilising ideal pulps that are produced with maturing fractionation methods, including ILs and DESs. These properties are especially useful in active and smart materials like smart textiles and structures. Thermoplastic cellulose has become the new norm, and it has replaced plastics. Digital solutions have become tools for personalised production and mass tailoring and AI is starting to enable individual design.

*By 2040*, the cellulose industry has transformed itself into a digital multi-branched value network, where sustainable high-volume cellulose has become the new plastic, and the inherent properties of cellulose provides high-performance personalised solutions. The industry has doubled its profit compared to the year 2015. Annual use of cellulose has increased from 300 million tonnes to 400 million tonnes (including recycled fibres)<sup>9</sup>. Cellulosic products and the industry manufacturing them have established a dominant role in stopping climate change, avoiding plastic pollution of the oceans and soil, and reducing arable land losses.

## EMERGING CELLULOSE-BASED MATERIALS

Packaging and textiles will be the standard products of the cellulose processing industry. Beyond that, there will be products such as personal appliances, vehicle parts, medical applications, construction material and electronic devices that are based on lesser-known properties of cellulose. These products and applications provide consumers with a perception of quality, safety and sustainability. In the following, the cellulose-based consumer good groups that have the most immediate potential for consumers are discussed.

### **Improved disposable products: hygiene and personal care**

The increasing demand for cleaning and hygiene products is evident and based on global changes in demographics and improving living standards. The hygiene, disposable cleaning and personal care product markets are expected to grow fast. The market's launches of advanced disposable products may even speed up the growth.

Cellulose fibres are an attractive option to satisfy the growing nonwoven market in the future – especially as consumers of nonwoven products are increasingly aware of sustainability and waste issues. However, the challenge



*New manufacturing technologies provide better and sustainable products from natural fibres*

*Cellulose will fill in the gap in cotton availability*

**Wood plastic composite (WPC)**

*Materials made of wood fibres and thermoplastic(s).*

is that disposable nonwoven products, such as wet wipes and tissues, are currently predominantly produced from synthetic fibres. Of all nonwoven products, less than 10% are currently made from natural fibres. There are no recyclable nonwovens, mainly due to hygiene issues with the disposed products and technical challenges with re-pulping.

Natural fibres are mainly used in wet-laid products, which is a marginal product segment compared to the dominating group of dry-laid nonwovens. The conventional wet-lay process suffers from certain limitations, with the main technical one being the short fibre length. In addition, fibres need to disperse well in water, the end product becomes dense, and high water content is required to maintain adequate product quality. However, the wet-laying process is fast compared to other nonwoven technologies.

The aforementioned foam forming is a technology that overcomes these difficulties. With it, natural or regenerated cellulosic fibres can be efficiently processed into nonwovens or speciality papers in an environmentally friendly way. Producers utilising wet-lay processes can use staple fibres, which bring the product properties closer to the dry-laid nonwovens mentioned above.

Cellulose-based textile fibres are divided into rayon and lyocell type fibres. Viscose is the dominant rayon fibre. The viscose process, however, has a chemical and environmental burden, which, as it has been suggested, could be solved by new processes like cellulose carbamate (CCA), enzymatically-enhanced dissolving (Biocelsol) or direct alkaline processes. Currently, approximately five million tonnes of viscose is sold annually, mainly as a staple fibre and applied for nonwoven materials and blends in different clothing. While the current viscose process has environmental challenges, the use of viscose fibres helps to reduce environmental issues such as synthetic fibres causing microplastics.

High-performance lyocell fibre production is significantly lower (around one million tonnes annually) than the production of viscose fibre. It is used, for example, in fashion and some technical applications, like filters. The future lyocell technology is developing towards liquid crystal structures that are possible to achieve with ionic liquid technology, and targets even higher performing fibres that can compete with synthetic ones.

**Cellulose composite materials**

Composites are made by combining two materials; the matrix that binds the material and the distributed reinforcing particles that improve the mechanical performance of the material. Materials where the matrix and particles are of the same material type (but present in different forms) have an advantage over multi-material composites, as they are easier to recycle.

It is possible to create composites consisting of only cellulosic materials. These all-cellulose composite materials are carbon neutral and they can be manufactured from sustainable raw materials growing in emerging markets. They are biodegradable, and their recycling is easy, though not always via traditional recycling routes.

So far the main commercial biocomposite product by volume is **wood plastic composite (WPC)**. The most widespread use of WPCs is in

*Cellulose mono-materials will change the paradigm of composites*

low-maintenance and durable decking materials. Natural fibre composites are another class of biocomposites, in which synthetic fibres are replaced by natural fibres. The automotive industry has so far dominated the adoption of natural fibre composites to meet the regulatory demands of reduced carbon footprint.

Europe and the United States are the principal adopters of biocomposites to date, but Asia is currently the strongest growth region. Future growth and application areas of biocomposites will be strongly guided by the availability of raw materials. Waste and secondary source materials are increasingly recognised as biocomposite feedstock and by 2030 biocomposites will be mainly made of mechanical pulp, recycled wood, pulp and plastics, and forest and agricultural crop residues. Due to the increasing demand for the recycling of materials, the production capacity is expected to grow significantly. In 2017, the total European biocomposite production capacity reached 410,000 tonnes<sup>10</sup>. The amount is expected to grow to 1,600,000 tonnes by 2020<sup>11</sup>.

By 2030 there will also be many application areas for cellulose composites that are smaller in volume, but higher in value and with much higher demands for material performance. These include medical and home applications, as well as sports and leisure equipment. The first high-performance products, such as fishing rods, made of a nanocellulose-reinforced composite material are already on the market.

The possibility to reduce costs and meet regulatory demands on material recycling are among the main drivers for the adoption of biocomposites. In most cases, they are an efficient means to increase recycled content in products, while maintaining material performance. In high volume applications, such as furniture, construction materials, sporting goods and appliances, bio-based materials offer the possibility to offset CO<sub>2</sub> emissions by acting as carbon storage.

Until now, industrial utilisation of biocomposites has often been hampered by process robustness in industrial systems optimised for conventional polymeric mono-materials. Not uncommonly, earlier generations of biocomposites suffered from not having the same level of consistency as virgin homogeneous materials. With on-going advances in composite material performance, existing industrial processes can be adapted to overcome past limitations in process conditions, allowing for the adoption of new classes of materials in existing infrastructure. Alongside process robustness, the visual appearance and haptic characteristics of biocomposite materials should also be considered and tuned to meet the specific application needs.

In regulated application areas, in particular for the construction sector, there is an on-going dialogue about the legislative development to support the uptake of new biocomposite materials. This progress is not sometimes affected by regional targets for material recycling and reuse. While the EU has emphasised material recycling, it is now up to producers of biocomposite materials to ensure that their materials are properly incorporated into national and international building regulations.

By 2030, the mechanical properties of high-performance biocomposites will be competitive with glass and carbon fibre-reinforced composites on a per weight basis. For these applications, the efficiency of recycling, as well as branding, will strongly affect their market penetration. In particular for high-performance biocomposites, products will increasingly be recyclable rather than biodegradable.

### **Nanocellulose and its applications**

The onset of nanocellulosic materials has opened a wide range of new prospects for cellulose during the past decade. To date, cellulose-based materials have shown significant potential in several higher value-added application areas, for example as selective membranes for water purification, as substrates for printed electronics and sensing devices, as well as bioactive templates for diagnostics purposes.

The intrinsic electronic properties of the cellulose crystal itself can potentially be employed as components for things like LEDs, sensors and nanoelectronics. In addition, nanocellulose-based films have clearly shown their potential to act as nano-enhanced membrane materials, with the ability to capture heavy metals ions, or to filtrate organic solvents. Furthermore, due to the high hydrophilicity, the inherent properties of cellulose itself improve the membrane antifouling performance, which is a great benefit over the synthetic materials.

The production of nanocellulose films takes place via solvent casting directly from aqueous dispersions, without the harsh and tedious cellulose dissolution step. Water-scarce technologies enable not only resource efficiency but also facilitate the structural tailoring of cellulosic materials even in the submicron scale range. For example, via foam formation technology, highly porous and thick cellulosic aerogel structures can be manufactured by introducing air into the system.

### **Replacement of fossil polymers**

Fossil-based polymers dominate several markets, such as plastics in packaging and synthetic fibres in textiles. The competitiveness of certain synthetic polymers has even improved, as new feedstocks such as shale gas have been introduced. **Shale gas** has markedly lowered the production cost of olefins, such as polypropylene, the raw material for packaging films and nonwovens.

#### **Shale gas**

*Shale gas is a natural gas found in shale rock.*

*Novel cellulose materials can compete against plastics with high performance and functionality in products like films and yarns*

Replacing synthetic polymers and plastics with cellulosic alternatives requires improved performance and suitability to current converting processes from the new cellulosic materials. There should be high enough demand for these cellulosic alternatives to sustain a more attractive price margin. Producers and brand owners are looking for differentiation and engineering performance – for example automotive producers are seeking composites that improve the performance of car parts. Novel applications may find emerging markets and attractive sales prices, but in the long term, their price competitiveness against performance is essential.

Plastics are widely used materials not only in packaging but also in engineering applications, and as substrates for flexible electronics and low-cost printable electronics. Replacing plastics with biomaterials is the target of several strategies and roadmaps, but the performance of biopolymers has been questioned. However, there are bio-based polymers that offer high performance, such as polyglycolic acid (PGA).

Currently, fossil polymers such as PET are extensively used in packaging applications. Still, plastic replacement by biomaterials will dominate in packaging. The key factors contributing to the use of cellulose films in packaging applications are the growing food industry and macroeconomic factors such as rising disposable income, the rapid rate of urbanisation and a growing population. The main advantages of cellulose films include their biodegradability and compostability.

Only certain plastics are recyclable, and their technical performance and processability are good. To replace plastics cellulose should be thermoplastic. Cellulose could then be extruded into films or nonwovens in meltblown or spun-laid processes. Cellulose is not intrinsically thermoplastic, but plastic-like properties can be achieved through material engineering.

Traditional cellulose polymers, such as cellulose acetate, are thermoplastic but they are not as easy to convert as polypropylene or polyester, and they do not have comparable material properties. However, new developments have achieved thermoplastic celluloses that are more like polyethylene or polypropylene, compared to the old rigid cellulose plastics.

In the future, we also need melt-spun celluloses to compete with the wide range of synthetic fibres. Currently, cellulose acetate is not melt spun, but solution spun for filters. Other alternatives that have been shown as possible candidates for textiles include cellulose acetate propionate (CAP) and cellulose acetate butyrate (CAB).

*The thermoplastic cellulose films will revolutionise packaging*

# 7. The emergence of a new industry structure

An understanding of customer needs as well as their buying behaviour and desired user experience is essential for creating better products and services. At the same time, the sustainability of products and services is of importance for both consumers and society as a whole. Product design and development is a key activity that combines these aims. Through design processes, the impact a product or service has on the environment can be minimised.

In the future, AI will assist in converting the customer's current needs into an actual product design that is simple and efficient to produce. Finally, the product will be manufactured from raw materials that are sourced from several locations, with converting technologies and logistics that minimise environmental footprints.

In general, an end product should have minimal impact on the environment throughout its life cycle; and this should be verified with a lifecycle assessment. The environmental footprint of production can be affected by several factors. Products should be produced from renewable and recycled raw materials with best available technologies and production practices. Sustainable, good-quality materials and product design give the product a long service-life through maintenance, modernisation and repair.

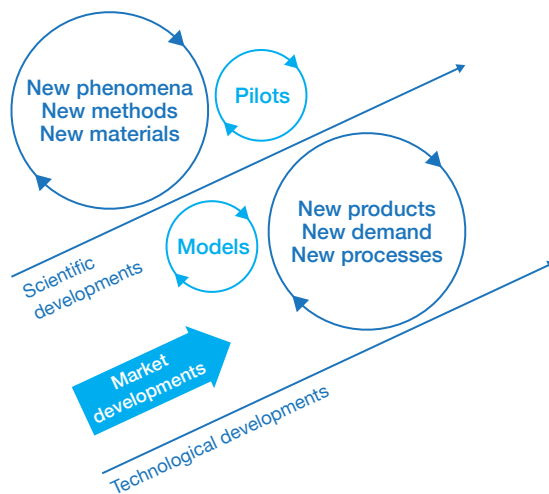


Figure 8. From laboratory via pilot to market.

## THE ROLE OF START-UPS

Start-ups have a critical role in taking products and processes from laboratories to pilots and finally to production (Figure 8). In the process industry, the piloting costs are markedly high, and there is thus a need for risk and benefit sharing mechanisms. Companies that develop and license technologies carry out important work in overcoming the dead value of development. Those companies have a key role in creating the new value networks.

Start-up companies enter new fields and create a connection between the industries. Their ability to rapidly adapt to end customer requirements is especially important for providing innovative solutions. The markets of cellulose-based materials will become more scattered but, due to specialisation, the margins will become healthier.

In the future, the focus will move from mere production to specialised end-user markets. Start-ups will create added value in specialised markets such as composites and electronics by launching production technologies and affordable materials. Basic bulk production will continue to serve large businesses in sectors such as packaging and textile.

## MEASURES OF CHANGE

The field has experienced eras of transformation before, and as discussed earlier, one is taking place again. Reorientation of the forest-based industry will start from declining or emerging technologies and changing customer needs. The industrial change has to start from small experiments and pilots, which are less time and capital intensive. Those experiments need to be boosted with the latest knowledge and novel technologies combined with design and market innovations.

In the future, organisations are expected to strive even more to innovate new products, processes, organisational set-ups and business models. To achieve in this, focus on innovation practices and speeding-up processes is essential.

Over the next 10 to 15 years new and different expertise, like design and consumer market know-how, are required from both individuals and organisations. This will put a particular onus on the talent pool of the forest-based value chain companies. To understand new demands across customer businesses, digital, bio-products that cater to completely different value chains, and cross-industry collaboration are needed.

In the coming years, the forest-based value chain will benefit from the advances in digital technologies, which will put into motion a massive reorientation of the whole field and enable fast growth in both emerging and current markets.



# The day after tomorrow

Foresight and visioning of the forest-based value chain was a process where we tried to bring up the most crucial developments that will lead the industry to a more sustainable, feasible and customer-centric path. Our vision reaches up to about the year 2040. We were, however, also eager to describe the world where the potential of digitalisation, AI and robotisation is fully exploited in the forest-based value chain, thus resulting in a sustainable future. Below we have depicted the possible achievements and developments that could be reached after the year 2050.

**THE FUTURE AFTER THE YEAR 2050.** The world population has reached 10 billion. The population growth rate did fall to a reasonable level a while ago, but the situation is expected to remain critical long into the future.

The effects of climate change are still causing problems that require attention and efficient mitigation measures. Extreme climate conditions are challenging the built environment. Forests have become more

abundant than in 2020. Plant fibres and their components are recognised as strategic materials, as they are cornerstones of the low-carbon era. The strategic materials started to circulate fully in 2050.

The vast majority of the population lives in the cities, and the centres of population densities are moving towards areas with milder climatic conditions. Standards of living have improved to a level that has not been experienced before. People have more leisure



time, and they focus their interest towards self-improvement and spiritual aspects of life. Slow life and different sports and games have become very popular.

Production units have captured  $\text{CO}_2$  from their flue gases for decades.  $\text{CO}_2$  is one of the most important resources, and it is converted into chemicals and materials. For example, biotechnical solutions are used to produce speciality cellulose and other carbohydrates from  $\text{CO}_2$  on an industrial scale.

The ultimate poverty problem has been solved. The global energy supply depends today on carbon-free solutions. Energy is harvested wherever possible, and low energy solutions are continuously developed. Intelligent systems have optimised all major activities, from communication and living to food production. Agricultural and forestry robots became common, and farmers were freed from time-consuming and tedious tasks and could thus focus on overall productivity improvements. This was necessary to cultivate and harvest renewable resources and increase their yields.

In the 2050s it became a common practice to produce food in vertical farms. In these farms, the plants grow on cellulose-supports in aquaculture. Traditional green walls are still used as a means to improve indoor climate and to capture carbon. The aquacultures are part of the buildings waste treatment systems.

Severe undernourishment has become rare. Food production does not require fields anymore since everyone can produce their protein and carbohydrate sources in their own kitchen from atmospheric  $\text{CO}_2$  and nitrogen. The boosting effect of digitalisation has been fully realised, particularly due to the major impact of robots and artificial intelligence on productivity.

The Mars expedition was successful in the year 2030. The artificial biospheres are now just about to be established on the moon as a stepping-stone on a way to Mars. The novel life technologies developed for these new conquests are applied on Earth as well.





## Composites, performance chemicals, artificial leather and medical spare parts

Today, high consumption of cellulose is an essential part of the worldwide carbon storage system. Cellulose composites managed to replace plastic materials in the 2040s and are now widely used in construction.

Because of land-use limitations, alternative resources for cellulose are becoming more important. Cellulose from side products of the food chain, such as straw and bagasse crop residues, have exceeded the use of wood cellulose. These new raw materials are suitable feedstocks for the fractionation

technologies developed in the 2030s, including hot water extraction and dissolving with ionic liquids, for example. The kraft digesters that are still operative are equipped with active carbon capture and storage technologies for performance chemicals.

Enzyme-based technologies are vital in producing speciality pulps from easy-to-dissolve cellulose and converting them into cellulose chemicals.

It has become common practice to grow biosynthetic cellulose in bioreactors for tailored applications. Resources are not wasted, as bacterial strains consume the leftovers from cellulose production. Bacterial celluloses find uses in synthetic foods, artificial leather-like materials or medical spare parts, such as active skin.

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## Cellulosic parts in vehicles

Long ago, in the 2020s, drones started to independently deliver parcels and packages, and take care of minor maintenance work. Agricultural and forestry robots cultivate and harvest renewable resources. Autonomous traffic minimised the number of vehicles that society needed, and their mileage. Cellulose-based carbon fibres and nanocellulose fibril-composites and yarns became natural solutions for vehicle body parts in electrically powered vehicles due to their low weight.

Accumulators are already old technology, and now electricity is formed in fuel cells. Fuel cells are devices that convert the chemical energy of a carbon-neutral fuel, such as hydrogen, directly into electrical energy. An essential part in the cell is a membrane that is nowadays routinely made of cellulose.

## Cellulose as an active super material

At some point, it became evident that in densely populated areas new technologies were needed to capture the released carbon dioxide and heat.

Cellulose-based devices that combined biotechnological approaches were able to achieve that. These devices were taken into use to capture CO<sub>2</sub> and convert it into useful substances, such as food components and construction materials. In practice, electro-synthesis replaced photosynthesis and is now taking place in nanoporous cellulose matrices.

Active cellulose-based films are harvesting energy from light and heat. Energy harvesting is done at a very broad electromagnetic frequency band because cellulose materials have the inherent ability to trim for desired wavelengths. These films are capable of storing marked energy contents and releasing them in a controlled and efficient manner.

Passive nanocrystal displays utilise a minimum amount of energy, even if we are now living in an environment that is highly augmented with computer-generated information.

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## Tall self-growing buildings

Wood is among the best composite materials due to its mechanical performance vs. weight, and it has many benefits as a construction material. Wood is also naturally comfortable, as it can stabilise moisture and temperature fluctuations.

New combinatory technologies of material science and biotechnology have made it possible to grow construction components, such as beams and frames. The carbon in these composites originates

from industrial, agricultural and forestry sidestreams and carbon dioxide emissions from the building. The building is a living organism that extends itself organically according to the use of the building and people inside. Artificial wood meets the highest quality standards and benefits from the inherent structure of the wood in the construction. It also tolerates extreme weather conditions, such as tornados.



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<b>Title</b>	<b>Cellulose goes digital</b> <b>VTT's vision of digital cellulose-based industries</b>
<b>Authors</b>	Ali Harlin, Stina Grönqvist, Vafa Järnefelt, Anna-Stiina Jääskeläinen, Harri Kiiskinen, Heli Kangas, Hannes Orelma, Sara Paunonen, Jarmo Ropponen, David Sandquist, Tekla Tammelin
<b>Abstract</b>	<p>VTT has envisioned the next generation of the forest-based value chain, where multiproduct biorefineries will have a central role. The digitally assisted business ecosystems between industries will develop value-added cellulose products and revolutionise bio-based material markets.</p> <p>In the future, forest-based value chains will exploit the most out of cellulose and make it available for novel value-added applications. The chemical processes for separating cellulose fibres from wood will develop further, and novel technologies for dissolving pulp will emerge. A rich ecosystem of new products from cellulose raw material will be brought to life with networked, design-driven approaches, and a value-adding consumer market will emerge. The adoption of digital technologies will speed-up these developments and disrupt the whole value chain from forest through pulp processing to novel products and consumer experiences. Digital transformation necessitates efficient data and information management and processing in a cloud of clouds, where information about resources, products, productions, logistics and consumers can be merged.</p>
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