Aalto University
School of Chemical
Engineering

Kim Nguyen

INNOVATIONS OF THE FOREST INDUSTRY IN THE 21ST CENTURY

Master's Programme in Advanced Energy Solutions

Major in Industrial Energy Processes & Sustainability

Master's thesis for the degree of Master of Science in Technology submitted for inspection in Espoo, 20th of April 2020.

Instructor D.Sc. (Tech.) Antti Lindqvist

Supervisor Professor Jouni Paltakari

Aalto-yliopisto
Kemian tekniikan korkeakoulu

Aalto-yliopisto, PL 11000, 00076 AALTO
www.aalto.fi

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Tekijä Kim Nguyen

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Tiivistelmä

Metsät ovat tärkein luonnonvara Suomen yhteiskunnassa. Metsäteollisuus mahdollistaa pääsyn arvokkaaseen luonnonvaraan, joka on osa ihmisen jokapäiväistä arkea. Lisäksi metsäteollisuudella on merkittävä vaikutus Suomen taloudelle. Se luo työpaikkamahdollisuuksia edistäen samalla yhteiskunnan hyvinvointia. 2000-luku on ollut metsäteollisuudessa suuren murroksen aikaa. Samalla kun perinteisten metsäteollisuustuotteiden kysyntä on kääntynyt laskuun, metsäteollisuutta on kritisoitu saastuttavaksi alaksi, joka ei ole tarpeeksi innovatiivinen. Tämän suhteen metsäteollisuudessa on tehty jatkuvaa kehitystä, jotka ovat mahdollistaneet teollisuuden uudistumisen ja ennen kaikkea imagon päivittymisen tähän päivään asti. Tarkastamalla kehitystä mahdollistaneita innovaatioita voidaan osoittaa, miten metsäteollisuus on onnistunut innovoimaan suurien muutosten keskellä.

Diplomityössä tutkittiin metsäteollisuuden kehitystä ja uudistumista mahdollistaneita innovaatioita 2000-luvulla. Työn tavoitteena oli koota merkittävimmät prosessiteknologia- ja tuoteinnovaatiot teollisuuden eri aloilta ja teemoilta sekä tutkia innovaatioiden syntymistä ajavia tekijöitä. Tätä varten suoritettiin laadullinen tutkimus puolistrukturoiduilla haastatteluilla alan asiantuntijoiden kanssa. Haastatteluissa kartoitettiin innovaatioiden lisäksi saavutuksia, suorituskykymittareita ja asiantuntijoiden näkemystä alan tulevaisuuden näkymistä.

Työn tulokset paljastivat, että resurssitehokkuus on ollut merkittävin ajuri 2000-luvulla syntyneille laite-, teknologia- ja komponenttikehityksille. Toinen merkittävä ajuri oli kestävyys sekä siihen liittyvät ympäristöasiat, jotka ovat olleet inspiraatiolähde uusille materiaali- ja tuoteinnovaatioille sekä startupien kehittymiselle. Tässä työssä on onnistuttu tunnistamaan monia innovaatioita sekä innovatiivisia ratkaisuja ottaen huomioon tulosten saatavuuteen vaikuttaneet mm. muuttunut toimintaympäristö sekä kiristynyt kilpailu. Siitä huolimatta metsäteollisuuden innovaatio- ja tulevaisuudennäkymää pidetään positiivisena, ennen kaikkea biotalouden edelläkävijänä.

Avainsanat Metsäteollisuus, innovaatiot, prosessiteknologiainnovaatio, tuoteinnovaatio, kestävyys, biotalous, biotuotteet, innovaatioiden ajurit, megatrendit

Aalto University
School of Chemical Engineering

Aalto University, P.O. BOX 11000, 00076 AALTO
www.aalto.fi

Abstract of master's thesis

Author Kim Nguyen	
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Abstract
Forests are the most important natural resource in the Finnish society. The forest industry provides access to valuable natural resources that is part of people's daily life. In addition, the forest industry is a significant contributor to the Finnish economy by promoting employment and well-being of society. The 21st century has been a critical period for the forest industry. While demand for traditional forest products has started to decline, the forest industry has been criticized for being a polluting sector with lack of innovativeness. In this respect, continuous development has been conducted in the industry, which has further enabled the renewal of the industry and update of image to this day. By examining innovations behind the development, the performance of the industry in the midst of major changes can be evaluated.

This thesis studied the innovations enabling the development and renewal of the forest industry in the 21st century. The aim of the study was to compile the most significant process technology and product innovations from different fields and themes, as well as to study the factors driving the emergence of innovations. For this, a quality study was conducted through semi-structured interviews with experts in the field. In addition to innovations, achievements and their key performance indicators were studied, and further, experts' perception of prospects for the industry were inquired.

The results revealed that resource efficiency has been the most significant driver for equipment, technology and component developments during the 21st century. Another major driver was sustainability and related environmental issues, which have been a source of inspiration for new material and product innovations and above all, for the development of start-ups. Many innovations and innovative solutions have been able to identify in this work. It should be taken into consideration that the availability of results might have been affected by changing operating environment and intensified competition. Nevertheless, the future of the forest industry is considered as positive. Bioeconomy and sustainability challenges like climate change appeared to be the key factors driving the innovation in the forest industry.

Keywords Forest industry, innovation, process technology innovation, product innovation, sustainability, bioeconomy, bioproducts, innovation drivers, megatrends

Acknowledgements

This master's thesis is a continuation of the previous innovation study by the Forest Products Engineers (PI). Conducting a master's thesis has been a long process but at the same time a valuable experience. The thesis has provided great opportunities to cooperate with professionals and students in the field and thus expand one's own knowledge and perception.

First of all, I would like to express my gratitude to my instructor, Antti Lindqvist, who has guided and supported me throughout the process. I deeply appreciate his trust and patience until the finalisation of the project. I could not have asked for better thesis topic. I find the project not only interesting but also essential for developing better future.

The thesis could have not been accomplished without the contributions of professionals from industries and institutions. I am grateful to people who participated in interviews and helped me to find suitable persons for interviews. It has been an honour to listen what they have achieved in the past. Their passion and effort towards their work have inspired me in my work. Furthermore, I would like to thank my supervisor, Professor Jouni Paltakari, and PI team for helping, supporting and motivating me. Special thanks to my colleague Johanna Vainiomäki. Without her help in transcribing the data, the project could have delayed even longer.

I personally want to thank my family, relatives and friends. I am indebted to my family members for their continuous support and to my friend Mikko H. who has not only supported me but also shared his wise advice since my first study year. Lastly, I want to take this opportunity to express how grateful I am to my mentors. I have been lucky to have amazing mentors guiding and helping me to shape my future path.

Helsinki, April 2020

Kim Nguyen

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1 Introduction

The forest industry has played a central role in the Finnish economy. In Finland, 86 % of the land area is covered by forests. The annual growth of forest resources is around 100 million of cubic metres of which the forest industry uses approximately 80 million cubic metres. (Luke 2018a) The forest industry is well known as producer of paper, paperboard and sawn wood products which are part of people's daily life. Additionally, the forest industry is an important employer and exporter accounting about 15 % of the total manufacturing employment and about 20 % of the Finnish export. (Finnish Forest Industries 2018a)

The Finnish forest industry has been facing major structural changes during the past decades. Global competition and megatrends cause fluctuations in demand and production of forest industry products forcing the business environment of the whole forest cluster to change. While production of some traditional forest industry products has decreased and shifted towards lower manufacturing cost regions, the Finnish forest industry has been gradually shifting towards the era of bioeconomy. Bioeconomy can be seen as a strategic movement that combats current and future challenges like climate change and depletion of natural resources. In the bioeconomy, all business operations from production to final use shall rely on the efficient use of renewable resources exploiting and developing environmentally friendly clean technologies and innovations. (MEE 2014) In 2014, the Finnish government published a national Bioeconomy Strategy which emphasized biomasses from the forests to be one of the most important renewable resources in Finland. Innovations and new business opportunities like high added value products, technologies and services based on the renewable biomass resources have been acknowledged by national executives. (MEE 2014) The forest industry has taken advantage of this by providing innovative solutions and thus being a forerunner in the creation of bioeconomy.

The forest industries have perceived the importance of innovation not only in the promotion of the Bioeconomy Strategy but also in their strategic success. Therefore, innovation has been often included in the business strategies of forest industry companies as well as of other industrial sectors. An ample amount of literature related to business success in any kind of industry states innovation to be an essential factor for survival and prosperity in a changing business environment. (Alfranca et al. 2014; Hansen 2010; Hansen et al. 2006; Van Horne, Frayret, and Poulin 2006) Innovation as a study area have called interest of many researches from different disciplines to analyse the concept of innovation and its linkage to business success. (Damanpour 1992; Damanpour and Gopalakrishnan 2001; Gopalakrishnan and Damanpour 1997; Han, Kim, and Srivastava 1998; Hurley and Hult 1998; Nybakk, Crespell, and Hansen 2011) This has generated abundant amount of definition for innovation and theories about innovation process. (Baregheh, Rowley, and Sambrook 2009; Edwards-Schachter 2018; Kline 1985; Robertson 1974; Rogers 1983; Schroeder et al. 1989; Zaltman et al. 1973) How forest industries perceive innovation and how innovations of forest industries have been emerged? And what have been the innovations that have shaped the forest industry to this day? These have been the questions studied previously by the innovation group at the PI - Forest Products Engineers, which work has been also published in the report called *Summary of Innovations in Pulp, Paper and Paperboard Industry* in 2013. The Innovation report summarizes the most significant process and product innovations of the Finnish forest industry from mid-90s to beginning of 21st century. As a result, c.a. 300 innovations were collected based on the material that comprised 130 chronic. (Huuskonen et al. 2013) The variety of innovations and the industry itself have evolved since the publication of the report. Therefore, this thesis has been conducted as a continuation from the previous innovation study by compiling the most significant innovations of the forest industry during the first two decades in the 21st century.

1.1 Background

The innovation study originated from the idea of recalling actions and achievements that the members from the former Paper Engineers Association (PI) had done in the past. The idea matured quickly into action of compiling all the innovations of the Finnish paper industry from mid of 1990s to 21st century. Beginning from 2007, the innovation study was carried out by active members of the Association who searched for persons in charge of the development of a particular innovation and asked descriptions from their development work. The aim was to report all possible Finnish innovations of the paper industry into the website of the Association as long as the persons associated with innovation work were in the midst. Even though a large quantity of innovations were compiled, the actual number of innovations remains unknown, since there could have been a larger group of people involved in the innovation work without being reached. Nevertheless, the innovation work has been an outcome of numerous people not only in the paper industry but also other industries. Collaboration between paper companies, machinery suppliers and chemical suppliers has been a decisive prerequisite for the development work which has benefitted both paper companies and their customers as well as parties of the whole forest cluster. (Huuskonen et al. 2013) The Finnish forest cluster presented in the Innovation report (2013) describes the scope of innovation (Figure 1).

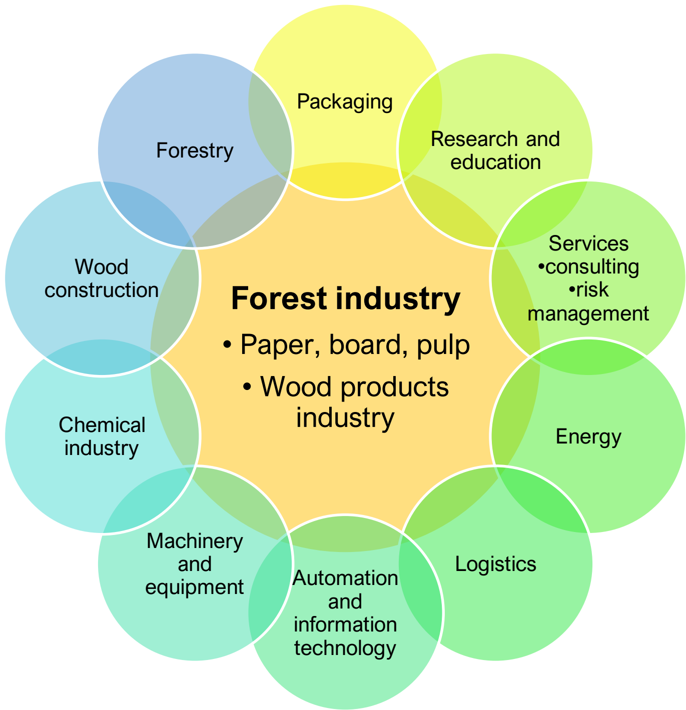

Figure 1. Forest industry cluster in Finland (adopted from Huuskonen et al., 2013).

The concept of 'innovation' has been defined in many ways. In the previous Innovation report, the innovation concept has not been precisely defined but rather left as open to various interpretation. The interpretation of concept was count on each author who had their own vision of innovation. Nevertheless, innovations were generally referred to novelties through which knowledge-based competitiveness could have been obtained. According to previous definition, there are two types of innovation factors: innovators and pioneers. Innovator is considered as creator or developer of the idea, concept, product or technology, whereas pioneer is an adaptor of it. Innovation can be considered Finnish, if the innovator or pioneer is a Finn at least. In the case of strongly Finnish-based innovation, both innovator and pioneer are Finns. Furthermore, innovations can be classified based on their aiming into pure process innovations, product innovations created through process innovations and new application areas created by product innovations. (Huuskonen et al. 2013) On the account of this statement, innovation can be either a variation of existing subject or a completely novel subject.

In the previous Innovation report, the documentation of innovations has been gathered from different topic areas focusing on operations inside mill gates. Therefore, e.g. the majority of development work regarding wood handling in forestry and logistics related to it have been excluded from the documentation scope. The documentation begins from the wood handling where wood has arrived at mill or woodyard. The following topics relate to the processing of wood to end-products or end use. In addition, energy balance, material usage and environmental impacts of industrial activities as well as development of automation and control engineering have been viewed. The scope of previous Innovation report is shown in the Figure 2.

Pulp, paper and paperboard industry	Wood handling
	Chemical Pulping
	Mechanical pulping and deinking
	Paper and paperboard manufacturing
	Paper coating and finishing
	Paper converting
	Chemicals and other raw materials
	Measurement and control engineering
	Byproducts and furhter processed products
	Energy
	Environmental protection

Figure 2. Scope of the Summary of Innovations in Pulp, Paper and Paperboard industry.

According to the previous Innovation report, a period between 1960s to 1990s was considered as the golden age of development and growth in the Finnish forest industry. During these 30 years, operations of basic industries were constantly developed in terms of increased capacity, quality and improved environmental impacts. At the same time, industrial plants were built abroad, and degree of processing increased. In the 1990s, globalisation and decline in the printing paper markets in Europe and USA forced the Finnish forest industry to secure their survival through company merging and acquisitions. A significant amount of production capacity in the paper industry was closed, while the paperboard and tissue markets continued to grow slowly. Cost competitiveness and service ability bulked large in the development work of the Finnish forest industry. The focus in the Finnish forest industry was on emerging markets, while production was shifted to lower cost countries. The past incidents led to irreversible changes in the structure of the forest industry as well as in the cooperative opportunities between companies. In the middle of increased competitiveness, opportunities to fill the pit left from the 1990s can be found in the bioeconomy. (Huuskonen et al. 2013)

The 21st century is the era of realizing the vision of bioeconomy with new businesses from wood or fibre-based products and materials. An essential thing is to find new end-uses for wood biomass. This requires agile actions to introduce innovations, which in turn requires long-term research output, investments and multidisciplinary expertise. Alongside new business opportunities, the traditional forest industry must be preserved. Traditional forest industry products remain as important source of export revenues for Finland. Therefore, investments in the development work of traditional forest industry need to be conducted, for example by exploiting new technological opportunities. Overall, an ecosystem encompassing both big and small and medium sized actors is needed, where common missions and visions are realized through an ability and willingness to cooperate. In addition, a high-level education and entrepreneurship are needed to guarantee the future of the industry. (Huuskonen et al. 2013)

1.2 Research questions and key objectives

The thesis provides a business-technical overview to a research problem that rises from the need for an updated data related to innovations emerged in the Finnish forest industry in the 21st century. As the thesis is a continuation from the previous work on innovation study, the thesis aims to cover the development of Finnish forest industries by identifying the most significant innovations and their key drivers. On the basis of these, the development and prospects of the forest industry are reviewed. Before investigating actual innovations, the concept and scope of innovation must be defined. Innovation is a multidimensional and complex concept that could rise as a sub-problem. Nevertheless, this thesis focuses mainly on process technology and product innovations.

The thesis poses following research questions:

i) What are the most significant process technology and product innovations of the forest industry?
ii) What are the key drivers of innovations and innovation development process in the forest industry?
iii) What are the aspects of industries and institutions on the drivers of innovation and innovation development process?
iv) What are the prospects for innovation of the forest industry?

The first research question aims to give concrete examples of innovations generated and adopted in the forest industry. The second research question aims to investigate the key drivers or factors driving the emergence of innovations. Drivers for innovation may be interpreted as tangible or intangible necessities or abstract concepts. For innovations, the intention is to determine, which has been the driving force behind the creation of an innovative idea. The key drivers for innovations and innovation process in the forest industry are determined in the literature and empirical part. The empirical part aims to highlight perspectives of industries and institutions on innovation and innovation process. Thus, the third research question covers this subject area. Based on the findings and results from the literature and empirical part, the fourth research question covers prospects for the forest industry. Whether the road of the forest industry is predictable in the changing business environment and what are the potentials of the industry, are determined in the last research question.

The thesis is conducted in cooperation with PI – Forest Products Engineers, and the results of the study are intended to be published in PI events and publications during 2019-2020. The study targets to include updated facts from literature and empirical study in which vision of industries and institutions are included. The updated version of Innovation report aims to keep the reader up to the date on the emergence of innovations and development of the Finnish forest industry over the past 20 years.

1.3 Scope and limitations

The scope of the thesis has been derived from the previous Innovation report (Figure 2.). However, possible changes in the scope must be considered in the study, as some challenges have emerged in the adequacy or availability of results for some themes. The scope for the study is presented in the Figure 3. The scope covers the fields inside the mill gates beginning from the wood handling. Further process themes are the processes of chemical pulp, mechanical pulp and recycled pulp and the processes of papermaking to converting. In addition, byproducts and further processed products from chemical pulping are reviewed as well as other process related themes included in the previous Innovation report like energy, environmental protection, chemicals and other raw materials. As a modification to the previous Innovation report, this thesis covers the themes of automation and digital technology instead of ‘measurement and control engineering’. Furthermore, additional themes like new wood-based materials and products and Finnish start-up companies have been included in this study. Contrary to the previous report, the wood products industry from mechanical forest industry has been included but reviewed generally.

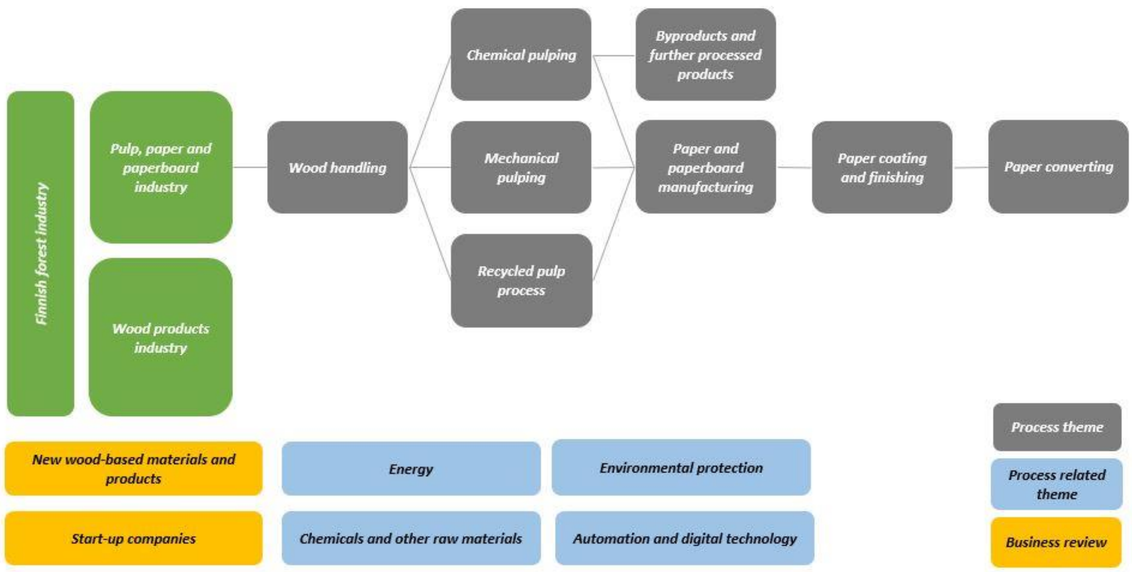

Figure 3. Scope of the study. (Nguyen 2019)

The thesis consists of two main parts. The literature review (Section 2) provides background about innovation concept and innovation process. In Section 3, the method and structure of the study as well as limitations related to empirical study are presented. Section 3 comprises the results from the empirical study. First, a technological overview from each process theme is described. The description of technological overview can be drawn based on literature or empirical data. Followingly, an overview of innovations and their key drivers and overall development of the field are compiled based on the results from the empirical study. For process-related themes and added themes, empirical results are presented as an entire overview of the theme. The results are summarized and discussed in Section 4, and conclusions are drawn in Section 5. The appendices include the questionnaire used in the empirical part and list of participants for the empirical study.

2 Related literature and theoretical background

2.1 Innovation

The early studies on innovation were discovered in the late 1880s but the most influential among them was probably Schumpeter and his theory of innovation in the 1990s (Śledzik 2013). Schumpeter's work was best known for his theory of economic growth and features associated with it. In the *Theory of Economic Development* (1934), Schumpeter described economic growth as a process that must undergo a transition from stationary state to revolutionary state. Economy with a steady flow between demand and supply refers to a circular flow in which the economic activity is at an equilibrium state. To shift from this statistic state to dynamic state of economy, Schumpeter emphasized the role of innovation and entrepreneur in the stimulation of the economic development process. (Schumpeter 1934) According to this theory, innovation is an activity of function that is performed by an entrepreneur. Schumpeter distinguished following features in innovation: introduction of a new product or production method, establishment of a new market, acquisition of new source of supply raw materials or semi-manufactured goods, and implementation of a new industry structure. Combination of these features creates 'new combinations' that refers to reallocation of economic resources and transformation of organisational forms carried out by entrepreneurs. The definition of entrepreneurs in this context does not denote a profession but rather a factor that has characteristics of being author, initiator, promoter and leader. In addition to previous, entrepreneur must have sources to exploit technological knowledge and capital to execute the production. (Schumpeter 1934; Sweezy 2016; Witt 2002) Schumpeter addressed entrepreneurship as a central of innovation activity and source of 'creative destruction'. Creative destruction is a term used by Schumpeter in his work of *Capitalism, Socialism and Democracy* (1942) to describe the impact of innovation on economic growth.

Since Schumpeter's theories on innovation have been some decades old, 'innovation' has been conceptualised and defined on the basis of dominant patterns of innovation over several decades. During the era of predominant manufacturing industries, innovations were mostly technology-based developed by large manufacturing companies that relied on the application of scientific and technological knowledge resulting often in technological innovations. At the time, innovation development involved efforts in research and development (R&D) activity and frequent patenting. R&D activity and intensity were used as indicators to measure technological competence and innovativeness of manufacturing companies. (Fagerberg et al. 2013) This kind of conception overlooked innovations that were not typical outputs from industrial manufacturing, involved little or no formal R&D activity, and were not patented. These types of innovation could associate with changes in business model, management or social structure of organisations. Previous innovation studies have enabled recognition of new and invisible features of innovation generating plentiful number of problems simultaneously. "What is the actual definition of innovation and how it is measured?" have been an interest field of study among the studies of various disciplines. Numerous theories and definitions have been provided but none of them answers the requirements of common definition. Based on previous findings (Baregheh et al. 2009; Edwards-Schachter 2018; Rowley, Baregheh, and Sambrook 2011), a common definition for innovation does not exist but it rather possesses diversified and inconsistent concept.

2.1.1 Definitions

The definition of innovation varies widely in the existing scientific literature. Numerous research papers have studied the nature and variety of innovation arriving at introducing new, updated and extended theories, models and frameworks to clarify the inconsistency of the concept. Despite the vast body of literature, definition of the term remains as an everlasting subject of debate as the term itself continues to evolve as less apparent characteristics of it are revealed. Nevertheless, it can be concluded that innovation is a complex concept that comprises several dimensions and relations between various disciplines. (Baregheh et al. 2009; Cooper 1998; Edwards-Schachter 2018) Most simplified definition of innovation was introduced by Roberts (1988) who considered innovation as a sum of invention and exploitation. In this definition, invention is limited to the creation of a new idea into exploitable application, whereas exploitation comprises processes of development, evaluation, implementation, commercialization and diffusion of a technology-based outcome. (Roberts 2007) Some overlap occurs between 'invention' and 'innovation', but they are two separate concepts with different intentions. Schumpeter (1934) distinguished invention from innovation as a creation and establishment of a new idea into a product or process, and innovation as a successful implementation of invention with profits. Main distinction between invention and innovation is a broader scope that innovation covers. While invention is an outcome of applied scientific and technological knowledge and skills, innovation is an outcome of deliberated intention of a new or existing subject that requires managerial and strategic skills apart from technical skills. Furthermore, the activity of innovation covers the entire organisation, contrary to invention, which is limited to R&D organisation. (Roberts 2007)

Multidisciplinary definition of innovation has derived from authors of different disciplines and perspectives within a specific discipline. Baregheh et al. (2009) analysed multidisciplinary definition of innovation and identified attributes of innovation that recurred in the literature of different disciplines, such as business and management, economics, organisations, innovation and entrepreneurship, technology, science and engineering, knowledge management and marketing. Baregheh et al. (2009) defined six common attributes of innovation based on the frequency of word that recurred in previous literatures. According to the results of analysis, definition of innovation can be classified based on the intention of organisation to create something new or improved (nature) from an idea that adopts a certain form, such as product, process or service (type). Innovation based on idea and creativity requires invention, technology and market (means) as resources. Meanwhile, the idea needs to go through multiple stages (process stages). Furthermore, innovation can be defined by actors; part of social entity (social context) that are involved in the innovation process, and factors affecting it such as environmental factors. Lastly, innovation can obtain its shape from overall result that organisation wants to achieve, such as competitiveness, success or differentiation (aim). The analysis acknowledges the fact that innovation is rather a process than a discrete event. The attributes of innovation are sequence to one another where the starting point of innovation is organisational depended and discipline specific. The starting point of innovation influences how innovation is carried out and achieved. From the technical point of view, for instance, the focus might be on product or technological development contrary to business point of view in which the focus is more on markets. Despite of the starting point, organisation or adopter of an innovation undergoes various stages in which tasks and organisational roles at each stage change. (Baregheh et al. 2009) Interactions between people and events influence subsequent stages leading innovation to advance or fail.

2.1.2 Types of innovation

Types of innovation have evolved along with the concept of innovation over the decades. To clarify definition and terminologies of innovation types, Rowley et al. (2014) reviewed and evaluated definitions, models, frameworks and classification of innovation types from previous studies arriving at integrating them into an innovation type-mapping tool. Rowley et al. (2014) emphasized differences in the focus of innovation type frameworks across centuries from which the shift from 1970s and 1980s towards 21st century has enabled a recognition of wider range of innovation types. These models have been built up on binary models influenced by each author's interpretation and observation. (Rowley et al. 2011) Despite of some addition, exclusion and extension into the models, they all share some common parameters formulated just slightly in a different way. Most common innovation types appeared from organisational aspect are product, process, administrative and technology innovations (Cooper 1998; Trott 2005; Utterback 1994). Furthermore, innovation types can be classified into radical and incremental based on the degree of strategic and structural changes that organisation undergoes while adapting innovation (Tidd 2001).

Cooper (1998) has addressed adaption of innovation with a multidimensional model in which innovation types have been presented as dimensions. With this model, Cooper emphasized interaction between organisational characteristics and innovation types to determine the probability of organisations to adapt innovations. This model presents innovation types in a simplified and visual way in which types are set as contrasting pairs. In this positioning, product innovation is set against process innovation, technological against administrative innovation and radical against incremental innovation. In addition to Cooper's theory on innovation types (1998), Tidd et al. (2001) used a visualization method to determine innovation types. As a result, Tidd et al. (2001) illustrated innovation types into a two-dimensional matrix that determined a managing space of innovation in a square matrix. By combining these two models, a multidimensional approach model for innovation was illustrated in Figure 4.

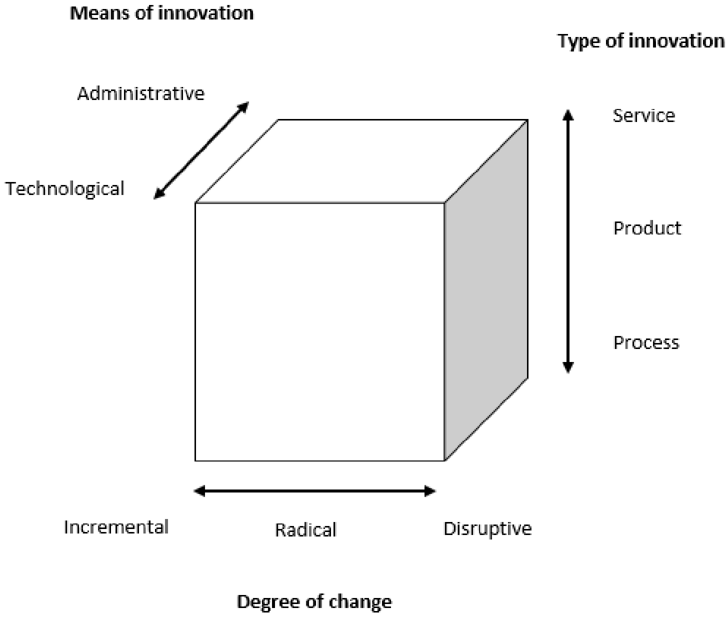

Figure 4. A multidimensional approach model of innovation. (Adapted from Cooper 1998 and Tidd et al. 2001)

Among all types of innovation, product innovation is probably the most common type of innovation. It is characterized as a new or significantly improved good or service that is introduced for the benefit of users (OECD 2010; Utterback 1975). Process innovation, in contrast, refers to changes in the way end products or services are produced (Utterback 1994). Usually, process innovation implies minor changes in process technology that results in enhanced efficiency, lower cost or reduced waste. In a contrary case, process innovation can be a completely renewed or invented process. Both product and process innovation undergo similar processes in technical means. Therefore, they are often related in a way that product innovation creates a need for new process innovation, or vice versa, process innovation generates a need for a product (Damanpour and Gopalakrishnan 2001) Adoption of a product or process innovation requires a target that the process of an innovation from idea creation to application produces an outcome with increased social or economic value. This process involves interaction between various actors and technical instruments to combine knowledge and practice into the exploitable outcome.

Technological innovations are often related to technological development of new products and techniques that originate from a technical specialist, such as engineer or adopter of science. Technological innovations are characteristics of manufacturing sectors which innovation activities often involve R&D activities. There have been confusions with the terms 'technological' and 'technical innovation'. According to the definition presented by Damanpour and Evan (1984), technological innovations originate from technological use resulting in advanced technology. Technical innovation, on the other hand, is a wider and more common context that refers to changes in a technical system and primary activities of an organisation. Non-technological innovation, on the other hand, is referred to administrative innovation that pertains to changes in organisational structure, administrative process and many other factors associated with social structure of organisation, such as human resources (Daft 1982). Thus, the difference between technological and administrative innovation relates to the operational core of organisation (Cooper 1998; Daft 1982).

Innovations can be also classified as incremental or radical based on the degree of change that organisation undergoes while adopting innovation. Incremental innovation relates to continuous improvement of already existing or known products, processes or models that have a marginal effect on existing practices. (Ettie et al. 1984; Normann 1971) Radical innovations, on the contrary, involve exploration of unknown, creating new inventions, patents and business models that bring about fundamental changes in organisation's activities and existing practices. (Dewar and Dutton 1986; Ettie et al. 1984; Henderson & Clark 1990) It has been claimed that the development of radical innovations is critical to the long-term survival of firms (McDermot and O'connor 2002), since they have a greater impact not only on firms but also on boosting economic growth (Chandy and Tellis 2000; Chaney et al. 1991). Adoption of radical innovation is usually a longer process compared to incremental innovation and entails higher level of uncertainties and risks that may lead to radical changes in firms or organisations (Edwards-Schachter 2018). The fact that radical innovation is often associated with first mover advantage and market dominance is totally a firm-specific case. In some cases, incremental innovation can have a more significant influence on firms than radical innovation. (Rayna and Striukova 2009)

Disruptive innovation is similar to radical innovation, but it has been introduced to describe the effect of innovation on markets. Disruptive innovation can be a product, process or business model innovation. (Markides 2006) The major attribute that separates disruptive from radical and incremental is that the implementation of a disruptive innovation creates market for new customers and disrupts former incumbent market leader and existing market, while radical and incremental innovation have minor effects on existing markets and are therefore referred to sustainable innovations. Disruptive innovation refers to market or business phenomenon rather than to technological breakthrough. (Christensen 1997; Christensen et al. 2015)

In alignment with earlier statement, the variety of innovation types is broad and dispersed rather than unambiguous. By now, the formation of innovation types has been an outcome of human reflection and response to external stimulus or changes. 'Change' being a part of human evolution is a central core in the determination of how human produces knowledge and performs social practices over time. By combining human knowledge production and external changes, innovation attains new dimensions or attributes that describe the new type of innovation. As Edwards-Schachter (2018) concluded in her study, global changes and changes in the structure of knowledge production have led to diversification, fragmentation and dispersion of the definition of innovation. New types of innovation have been recognized owing to divergent approaches, such as customer-oriented approach that has generated customer-driven innovations, social and design-driven innovations driven by economic and sociological aspects, and responsible and eco-innovations driven by sustainability and legislative forces. Global changes and external forces related to them are perceived essential not only in the creation of new types of innovations but also in the generation of innovations (Edwards-Schachter 2018).

2.2 Megatrends and drivers affecting innovation in the forest industry

The existing literature presents different interpretations of the factors affecting innovation. Some authors (Coccia 2014; Nidumolu et al. 2009) have considered factors affecting innovation as driving forces that act as sources for an innovative idea, while other authors (Bossle et al. 2016; Harmsen, Grunert, and Declerck 2000; Yalabik and Fairchild 2011) have considered these factors as tangible or intangible matters or needs that drive the implementation of innovation. Interpretations by various authors may cause confusion while trying to determine the factors driving innovation. For clarification, this thesis defines factors affecting innovation as two separate intentions: "what are the factors or drivers for the creation of innovation?" and "what are the drivers for the implementation of innovation?". In this study, factors affecting the creation and implementation of innovation are considered separately. This chapter aims to cover factors acting as driving forces for the creation of innovation, whereas the latter chapter aims to cover drivers for the implementation of innovation.

2.2.1 Megatrends of innovation

It has not been unexceptional for forest industry to have mentioned megatrends to drive the generation of innovation (Hänninen, Katila, and Västilä 2014). Megatrends derive from the term ‘trend’ that refers to a general tendency or direction of a development or change over time. Megatrends, on the other hand, are trends in a larger extent that have long-term and disruptive effects on society, economy, environment, technology and politics. (FTP 2014; Saritas and Smith 2010) For the forest industry, urbanization, digitalisation, population growth, environmental and sustainability challenges, such as climate change and resource scarcity (Figure 5.) have been the most significant megatrends in the 21st century that need to be addressed (Hetemäki et al. 2017a; Luke 2018b)

Figure 5. Main megatrends addressed in the forest industry in the 21st century.

According to the Organisation for Economic Co-operation and Development (OECD), about 70% of the world population will live in urban areas by 2050 (OECD 2016). Population growth and urbanization accelerate human migration from rural to urban areas leading to the rapid growth of cities and rise of middle class. As a result, consumption and need for goods and services will increase. It is expected that energy demand will increase almost 40 %, water demand will increase by 50 % and 60 % more of food is needed to feed over 90 billion people. (OECD 2016) Increased environmental consciousness and consumer awareness have enabled consumers to contribute to the environmental load with their choices. It is up to decision-makers and producers to provide solutions to these challenges. For the forest industry, these challenges have created many new opportunities to meet the consumers' needs. As awareness of environmental and sustainability issues increases among consumers, consumption habits change. Growing group of conscious consumers pay more attention to ethical and ecological aspects in their daily lives. This emerges in the consumption domains such as housing, food and clothing in which more sustainable solutions are sought from renewable and recyclable materials.

Due to population growth and urbanization, more people are likely to live in cities, which implies more buildings need to be built for people. According to the Ministry of Environment, buildings and construction use half of the world's natural resources and about 40 % of the world's energy (ME 2019). In addition, the sector generates significant amount of the world's waste and emissions. In Finland, the Ministry of Environment has published a road map for a low-carbon construction aiming to reduce carbon footprint of buildings and construction via legislation by 2050. (ME 2019) Most of the emissions from building materials and products are generated during manufacturing (UNEP 2018). The impacts during the life cycle of buildings should be examined using standardized calculation method. Impact assessment methods used so far have been alternative, which may have caused difficulties in obtaining reliable results. (Hill and Zimmer, 2018) Nevertheless, several studies (Buchanan and Levine 1999; Gardner et al. 2019; Lu, El Hanandeh and Gilbert 2017; Petrovic et al. 2019) have indicated that substitution of other building materials like concrete and steel with wood-based materials can have a significant contribution to reduced CO_2 emissions. The benefits of substitution depend on various factors like materials and energy used during manufacturing stage, construction stage, transportation, use stage and end-of-life stage. It has been suggested (Gustavsson et al. 2006) that the benefits would be the greatest, if wood residues from the production of wood building materials were incorporated into energy supply systems to replace fossil fuels. After all, the benefits of using wood material in construction are due to the low energy needed in the manufacturing of wood products compared to other building materials, the long-term storage of carbon in wood building materials and the increased availability of biofuels from wood residues. (Gustavsson et al. 2006; Gustavsson and Sathre 2006)

In Finland, the use of wood in construction has been perceived by administrative quarter who aims to increase the use of wood in urban development, public buildings and in large constructions (Riku 2017). Promotion of wood construction, particularly urban wood construction, has been acknowledged in the National Bioeconomy Strategy. (MEE 2014) In recent years, there have been developments in the technologies of engineered wood elements (EWP), such as cross-laminated timber products (CLT), laminated veneer lumber (LVL) and wood fibre insulation boards (WFIB) as well as in fire-safety-regulations, which have promoted the use of wood-based construction elements in the multi-storey buildings (Karjalainen 2017). By enhancing regulation and promotion of wood construction materials, EWP and other wood-based construction elements are expected to find market in both domestic and foreign market. Within a few years, new types of wood-based solutions like biocomposites have expanded from construction elements to interior design, decoration and consumer products to replace the use of fossil and non-renewable materials in conventional products. While wood-based construction materials and wood-derived composite materials are gaining more attention, they still have to face the challenges related to the technological feasibility, social acceptability and governmental incentive. The government can play a major role in promoting market visibility for wood-based construction materials.

General targets for carbon emission reduction also apply to the energy and transportation sector (Finnish Ministry of Employment and Economy 2014). In Finland, the energy sector comprises production and supply of energy that is distributed for the use of customers and other industries and sectors. From this share, industries use almost half of the total energy consumption. Second energy-intensive sector pertain to building and housing that account for one fourth of the total energy consumption. (Statistics Finland 2019a) Most of the building's energy consumption is covered by space heating where district heating (DH) is the most common form used (Finnish Energy 2018). District heat production aims for carbon neutrality in 2050 by replacing fossil fuels to renewables and increasing hybrid energy solutions into the district heating systems (Finnish Ministry of Employment and Economy 2014; Paiho et al. 2016). With the selection of fuel type and energy production technologies, energy efficiency of DH production and buildings can be enhanced. The share of wood-based fuels used in DH production accounts for about one third of the total fuel-based production (Finnish Energy 2018). The use of wood-based fuels is expected to increase not only in DH production but also generally in energy production due to the latest legislative proposal regarding the coal ban in energy production by 2029. Alongside the carbon neutral future, the Finnish Government has also set a target to increase the share of renewable biofuels in traffic to 30 % by 2030. (Ministry of Economic Affairs and Employment 2018) Replacing fossil fuels with biofuels is a potential alternative to contribute to the GHG emission reduction in traffic, but problems rise in the availability and price of sustainably produced biofuels and the impact on carbon sinks (Särkijärvi et al. 2018). Selection and management of raw material type, conversation technologies and end-use application affect the overall sustainability of biofuels (Cherubini et al. 2009; Correa et al. 2019; Kazamia and Smith 2014). Sustainability and efficiency are the main objectives in the production and use of biofuels (Uusitalo et al. 2017). Adoption of the use of biofuels still needs to overcome the issues on emissions released during the life cycle and cost-competitiveness on the availability of inexpensive and advanced technologies.

Technological advances in digitalisation have brough major challenges but at the same time new business opportunities for some sectors. Diffusion of digital technologies has shifted daily businesses to more digitalised and service-oriented society changing consumer behaviour. For the forest industry, the impacts of digitalisation have emerged in declined demand for graphic paper and in increased demand for packaging and labelling. Demand for packaging solutions covers an extensive range of markets including food and pharmaceutical industries which utilize smart packaging solutions to indicate the shelf life of a content and smart labelling solutions to identify individual products. Packaging business is an example of a rising business field that has managed to present upstream markets for intelligent solutions like radio-frequency identification (RFID). Integration of intelligence in the product value chain has enabled enhanced resource management, real-time visibility, operational and cost-efficiency and strengthened connection with customers and stakeholders. (Ben-Daya, Hassini, and Bahroun 2019) Adoption of digital technologies has also put pressure on industries to maintain their competitiveness while considering the efficiency and sustainability in their activities. Digital technologies have brought about new phenomena as Fourth Industrial Revolution (Industry 4.0) and Internet of Things (IoT) that are expected to cause disruptive changes to existing business models (Watanabe, Naveed, and Neittaanmäki 2018). (Ben-Daya et al. 2019)

2.2.2 Drivers of innovation

There is a vast body of theories regarding the drivers of innovation. Some authors have considered drivers for innovations as trends and megatrends while others have considered them as organisation’s internal resources and external forces. (Bossle et al. 2016; Näyhä 2019) Each author has had its own perception on the drivers of innovation, and therefore, a consensus cannot be reached in this context. The drivers for innovation vary depending on the context in which they are studied. Some authors have defined drivers of innovation in relation to the firm competitiveness (Korhonen et al. 2018), orientation (Harmsen et al. 2000; Hurley and Hult 1998) or adoption of a specific pattern like eco-innovation or bioeconomy strategies (Bossle et al. 2016; Korhonen et al. 2018).

An economic view to history indicates innovations to have been developed as a response to discrete events, history-specific problems and opportunities risen from emerging markets and technological development (Taalbi 2017). An example of a history-specific problem, energy and oil crisis in the 1970s induced the need for alternative energy sources to reduce dependency on fossil oils. In many Western countries, reduction of fossil oil-dependency initiated implementation of nuclear power programs, and fossil oils were substituted with coal and peat in energy production and consumption. This led to a moderate reduction in fossil oil-dependency but simultaneously to an increased contribution to various emissions, risks and hazardous wastes. Environmental impacts formed from previous implications stimulated a shift in energy policy and regulations, which stressed industries to take more sustainable actions. Sustainability implies responsible decision-making and activities that contribute positively to the environmental impact. Since the energy and oil crisis and subsequent environmental problems, energy and material efficiency have become one of the key drivers in many energy-intensive and manufacturing industries such in the forest industry. (Taalbi 2017)

The forest industry has been conscious of resource-efficient alternatives long time ago, but relatively small measures were implemented due to lack of incentives for a long-term R&D. Solutions for improved efficiency and reduced fossil-oil dependency required investments in R&D for which industries sought partners in cooperation and incentives. In this situation, government could contribute significantly to industrial activities not only with political and regulatory means but also with incentives and financial support that could stimulate R&D activities of industries. (Bergquist and Söderholm 2014) Although policies and regulatory pressures continue to drive industrial activities, it is sustainability in the end that emerges as the main driver for innovations in the forest industry (Adams et al. 2012; Nidumoly et al. 2009; Näyhä 2020; Triguero, Moreno-Mondéjar, and Davia 2013).

Innovating for sustainability has been a growing trend or almost essential among the forest industries. Innovation with an emphasis on environmental sustainability has generated various terms like “eco-innovation”, “green innovation”, “environmental innovation” and “sustainable innovation”. (Rennings 2000; Varadarajan 2017) Drivers for adoption of such innovations have been addressed in previous studies (Bossle et al. 2016; Nidumolu et al. 2009; Varadarajan 2017; Xavier et al. 2017). These drivers can be applied to forest industry innovations. Bossle et al. (2016) identified drivers and motivation for adopting eco-innovation ending up classifying drivers into external and internal factors. External factors comprised the drivers such as regulatory pressure, market demand, cooperation between customers, companies, distributors, suppliers and institutions, and technological opportunities. For internal factors, efficiency related to cost reduction, update of equipment, investments in R&D and certifications, quality of human resources and organisational capabilities, managerial concern and strategy emerged as distinct drivers. In addition to these, there are organisational characteristics that can have a moderate influence on the adoption of eco-innovation. These characteristics are related to company’s size and sector or industrial type, for instance. (Bossle et al. 2016; Hurley and Hult 1998) Some studies have further divided internal factors into tangible and intangible resources and capabilities of company. (Näyhä 2020) It has been previously stated that external factors can boost companies to develop their internal capabilities and resources, which can further boost companies to adopt eco-innovation based on sustainable innovation orientation. At the end, this contributes positively to the company’s performance. Thus, adoption of sustainable innovation can be considered as a source of competitive advantage for companies and industries, especially in the forest industry. Drivers for adoption of sustainability innovation have been presented in the Figure 6.

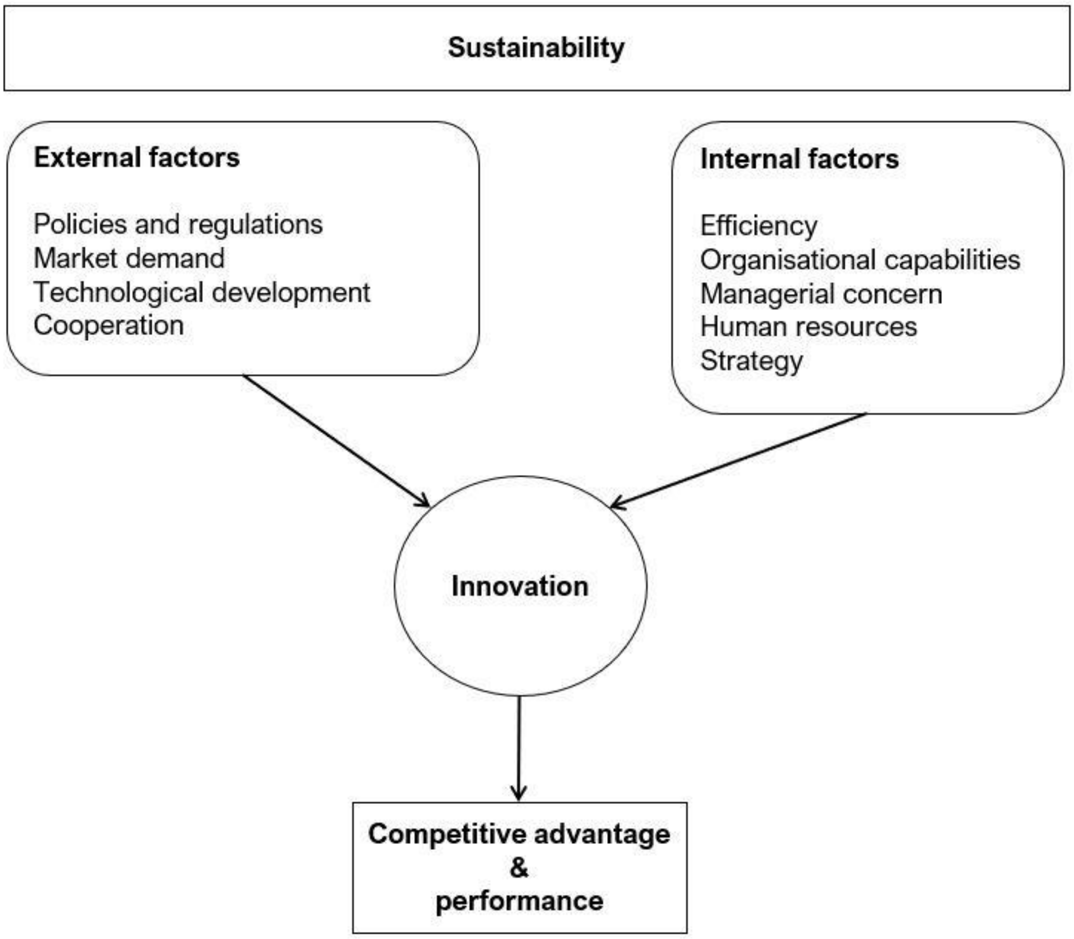

Figure 6. Figure 6. Summary of drivers for sustainable innovation. (Adapted from Bossle et al. 2016; Hurley and Hult 1998 and Näyhä 2019)

2.3 Innovation process

Early studies defined innovation process as the first commercial application of a new product or process that begins from idea generation and develops in a progressive and sequential manner (Clark and Guy 1998). The emphasis of early studies on innovation process was in product or process development that is based on the recognition of technological potential and exploitation of basic science. Furthermore, innovation process is constructed on intense R&D activities, manufacturing and commercialization. ‘Technology push’ is used to describe the innovation process of R&D or technology-oriented industries. (Clark and Guy 1998; Roberts 2007) Opposite to the ‘technology push’, ‘market pull’ portrays the innovation process as market oriented that is based on detection of customer needs and potential markets. The focus in market orientation is more on providing value to customers by placing them in a higher priority and being aware of existing market players (e.g. competitors). (Han et al. 1998; Harmsen et al. 2000) Which orientation is favourable for innovation success has been a long-term dispute. Majority of existing literature has connected market orientation to organisations' innovativeness and performance. (Han et al. 1998; Hurley and Hult 1998; Narver, John C; Slater 1991; Sandvik and Sandvik 2003) Some researches imply market orientation not to have a direct influence on organisation's innovation process and performance but it is rather a learning orientation promoted by market orientation that helps an organisation to promote innovativeness as a part of organisational culture and to develop capabilities to innovate. Thus, a mutual influence of market, learning and innovation orientation together with organisational characteristics (incl. culture) determines the innovation process and performance of organisation. (Han et al. 1998; Hurley and Hult 1998; Narver, John C; Slater 1991)

As previously stated, innovation is a process that consists of several stages. Innovation process can be viewed either as a 'unitary sequence model' or as a 'multiple sequence model'. The first model implies innovation process to be a linear sequence of events, whereas the latter refers to a complex process with multiple intersecting and diverging progressive events. (Gopalakrishnan and Damanpour 1997; Poole 1981) In this study, innovation process is rather viewed as a linear sequence of events. Simplified model allows identification of similar types of innovation processes and thus facilitates comparison of these models (Gopalakrishnan and Damanpour 1997). In the linear or unitary sequence model, innovation process can be divided into two distinct phases: generation and adoption of innovation. The first stage of innovation implies finding a motivative idea for innovation. The idea might derive from a recognition of a problem or a need that might meet technical or market means. This stimulates initiation of design, research and development of a project, which is followed by marketing and commercialisation of a product or process and further with diffusion of it. (Gopalakrishnan and Damanpour 1997; Van Horne et al. 2006; Roberts 2007) After a successful generation of innovation comes adoption of innovation. The stage of adoption comprises the process of initiation and implementation. Initiation is characterised by formation of an attitude towards innovation and its evaluation from organizational standpoint. Adoption of innovation implies marks in the beginning of implementation where innovation is merged into the organization. (Gopalakrishnan and Damanpour 1997) The stages of innovation process are presented in the Figure 7. Each stage in the innovation process involves several actors from different stakeholder groups. Application of basic research usually takes place in research institutions or in R&D department of companies. Instead, problem-solving, designing and development might be carried out by separate subunits within companies. Finally, there are management and administrative subunits who manage the marketing and commercialisation side. (Gopalakrishnan and Damanpour 1997) Thus, cooperation between companies, research and educational institutions, customers and investors form an ecosystem in which innovations are generated.

Figure 7. Stages of innovation process.

2.4 Key characteristics of innovating in the forest industry

Innovation activity as its best promotes economic growth. On the other hand, an economic growth based on innovation can be achieved mainly through investment. Investment can be categorised as fixed investments and R&D expenditure. Fixed investments imply increase or substitution of production capacity as well as adoption of new and efficient technologies. Instead, R&D expenditure is referred to a systematic action to increase and apply knowledge for creating new applications. This includes basic and applied research as well as development work. (Pakarinen 2017) About a decade ago, Finland was one of the top countries in the comparison of the R&D expenditure share to GDP. (Lukkari 2020) Over the decade, the share has reduced from 3.7 to 2.7 %. (Statistics Finland 2019b) This has been partly due to collapse in the R&D expenditures of the Nokia cluster and government cuts in R&D which have dropped Finland in the middle caste in terms of R&D statistics. One of Finland’s national goals is to increase the share of R&D expenditure to 4 % by 2030. (Lukkari, 2020) However, this requires extensive investments in R&D from all sectors, particularly business enterprises and higher education sector in addition to government sector. It has been previously stated that government funding boosts business enterprises to increase their own R&D expenditures (Guellec and Van Pottelsberghe 2003). In recent years, business enterprises have increased their share from the total R&D expenditures. In 2018, enterprises accounted for about 66 % of the total R&D expenditures and 54 % of the total funding expenditures. Nevertheless, increases in the R&D expenditure of business enterprise sector over the past years have not been enough to fill the gap emerged in the past. In fact, business enterprises must double their R&D expenditure to reach the target of 4 % by 2030. (Sorjonen 2019)

The development in investments of industries including fixed investments and R&D expenditures are shown in the Figure 8. The fixed investments and R&D expenditure of forest industry and manufacturing industries in 2017-2019 are shown in the Table 1. Based on the Figure 8, a sharp decline in fixed investments of manufacturing industries can be observed after the peak in 2008. A finance crisis took place after the peak when equipment and machinery investments of industries decreased evidently. A gradual increase in investments can be observed from 2015. This has been mainly due to investments in the forest industries including building of bioproduct mill in Äänekoski and expansion and modernisation of existing mills. (Ali-Yrkkö, Kuusi, and Maliranta 2017) The bioproduct mill in Äänekoski started in 2017 after which the growth in investments started to slow down. Recently, there has been ongoing planning on large-scale investments in the Finnish forest industry. These include conversion of papermill and building of pulp mill and bioproduct mill among other investments (Liikanen 2015; Raunio 2017). Although investment in the forest industry seems to be rising steadily, the investment level in industries in general has been quite low.

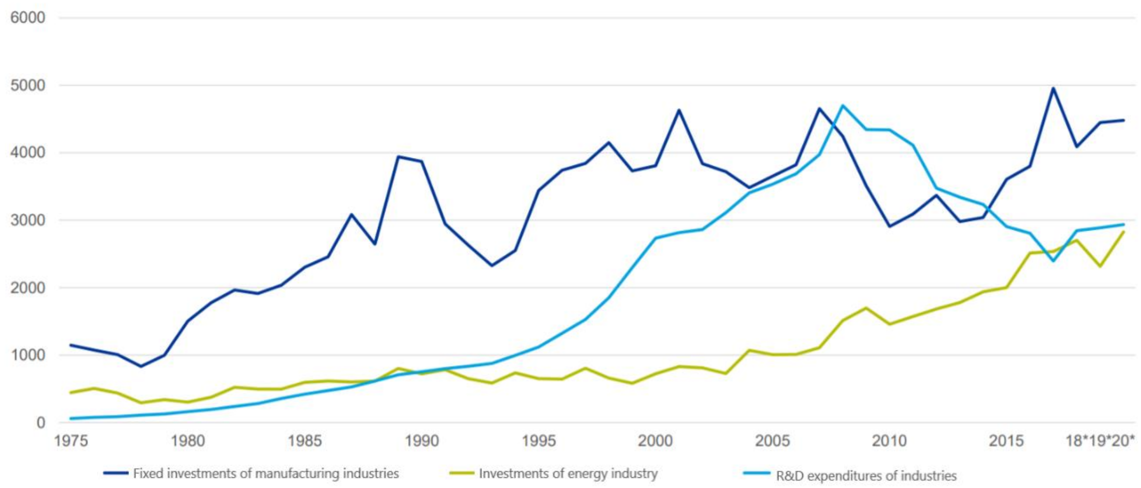

Figure 8. Development of investments in 1975-2020. (Statistics Finland 2018; Pakarinen 2020)

Regarding the investments and investment plans in the forest industry, it is difficult to draw a consistent conclusion on the correct numbers due to variability in study results. The numbers presented in the Table 1 have been taken from the survey drawn by the Confederation of Finnish Industries. Based on the investment survey, fixed investments in the forest industry have been declining since 2017. This decline has been due, for example, to the completion of the bioproduct mill in Äänekoski and other major projects in 2017. In 2018, there have been no such major projects in progress. (Kyytsönen 2018) Nevertheless, R&D expenditure in the forest industry has been on the rise since 2017.

Table 1. Fixed investments and investment plans of the forest industry in 2017-2020. (EK, 2020)

	2017 (M€)	2018 (M€)	2019 (M€)	2020 (M€)	2017-2018 (%)	2018-2019 (%)	2019-2020 (%)
Fixed investments							
Forest industry (fixed)	816*	705	588	525	-13.6	-16.6	-10.8
Manufacturing industries (fixed)	4250*	4089	4448	4481	-3.9	8.8	0.7
Forest industry/total (%)	**19.2***	**17.2**	**13.2**	**11.7**		**-**	**-**
R&D expenditures							
Forest industry (R&D)	98	106	104	-	7.7	-1.5	-
Manufacturing industries (R&D)	2395	2416	2516	-	0.9	4.1	-
Forest industry/total (%)	**23.4**	**21.8**	**23.2**	**-**	**-**	**-**	**-**
Investments and R&D expenditures							
Forest industry	914	811	692	-	-	-	-
Manufacturing industries	6,645	6,505	6,964	-	-	-	-
Forest industry/total (%)	**13.7**	**12.5**	**9.9**	**-**	**-**	**-**	**-**

* Investment inquiries, Summer 2019

3 Empirical study

3.1 Research method and structure

3.1.1 Research structure

The research was conducted applying a semi-structured interview as a qualitative research method. It is typical for a semi-structured interview to be scheduled and organized in advanced at a designed time and location. (DiCicco-Bloom and Crabtree 2006) Semi-structured interview is usually designed with a set of pre-determined questions that are given to interviewees to explore in advance. Contrary to a structured interview, semi-structured interview does not need to confine to a pre-determined framework but allows other questions and topics to emerge during the interview. (DiCicco-Bloom and Crabtree 2006) An active dialogue between interviewer and interviewee is formed allowing for certain flexibility and additional questions to be added.

The research was conducted first by gathering experts in the field from relevant companies and institutions. Suitable interviewees were selected according to the themes addressed in the thesis. Group of selected interviewees, comprised of experts from industrial companies, research institutions and universities, were primarily members of the Forest Products Engineers. The interviewees were approached by sending a participation invitation through email. The purpose of the study was explained and the interviewees' willingness to participate were inquired. Along with the invitation, the possibility to forward the questionnaire (Appendix 1) to a suitable expert was requested. The location and time for interviews were agreed individually. The interviews were carried out either with Skype or face-to-face at the office or at companies' headquarters. Seven interviewees were not reached, and thus, in total 23 interviews were conducted (Table 2). Among conducted interviews, one interviewer requested to participate in the interview by sending written answers and two additional interviews were conducted upon a request of retired persons in the field. Individual interviews are referred according to their job title as the names would not have been relevant in the study. The interviews took place from the end of August to November 2019, and the length of one interview ranged from 30 to 60 minutes.

Table 2. List of interviewees and their business areas.

Interviewees and their business areas	**Product portfolio and strategy manager** (Wood handling)
	Chief technology manager (Pulp, energy and bioproducts)
	Development manager, **Customer service and sustainability manager** (Pulp and bioproducts)
	Development manager (Mechanical pulping)
	Retired research fellow (Mechanical pulping)
	Senior technology manager (Recycled fibre)
	Senior purchasing manager (Papermaking)
	CEO (Papermaking)
	Retired director (Paper mills)
	Director (Packaging)
	Project manager (Paper board)
	Senior development manager, **Senior technology manager** (Paper coating and finishing)
	Associate professor (Byproducts)
	Business development director (Chemicals)
	Sales manager, **Account manager**, **Digital lead** (Automation and digital technologies)
	Manager of mill services, **Sustainability manager** (Environmental protection)
	Managing director (Wood products industry)
	Postdoctoral researcher (Wood products)
	Senior manager (Biochemicals)
	Production director (Biofuels)
	Vice president research (New wood-based materials)
	Business development director (Start-up companies)

The questionnaire used in the interviews (Appendix 1) was sent to interviewees along with the participation invitation. The questionnaire included a short description of the study background, purpose and aims with pre-determined questions and further information related to the questions. In the first question, interviewees were asked to give a brief description of the key processes and technologies of their area of expertise or given topic. In the second question, the most significant innovations and their drivers were inquired. In addition, interviewees were asked to select the main drivers from the list of further information and examples of the main drivers. Third question aimed to inquire the main achievements and key performance indicators of a specific area. Furthermore, interviewees were asked to describe the overall development of a specific area over the past 20 years. The last question inquired the future prospects comprising opportunities or challenges of the specific area. In the beginning of interviews, interviewees were asked to give a short description of their educational and work background. Additionally, interviewees were asked for permission to record the conversation before starting the interview. The recorded interviews were transcribed partly with the help of transcriber who used the *Express Scribe* software to transcribe recordings. In the end, all interviews were carried out in Finnish, although the questionnaire was made in English. The structure of the study with its process stages are illustrated in the Figure 9.

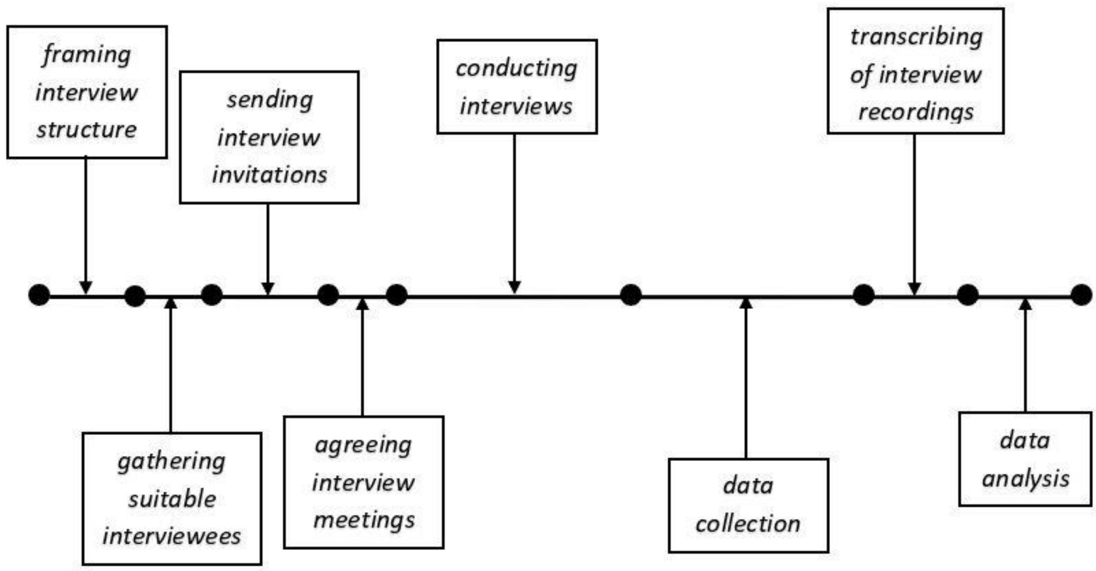

Figure 9. Process flow of the study structure.

3.1.2 Limitations

In the qualitative interview study, the adequacy and quality of results appeared to be challenging. After all, the number of interviews was more than planned. Originally, the number of interviews was assumed to be roughly equal to the number of contacts. However, most contacts acted as middlemen suggesting more interviewees on a particular topic or an additional topic. In addition, there were cases in which the interview material was not adequate enough. Inadequate interview materials were complemented with additional interviews leading eventually to expanded scope of the study. The quality of the results was partly influenced by the qualification and knowledge of interviewees on the topic assigned to them. Additionally, each interviewees have had their own interpretation of the interview questions and themes, which led to variability in obtaining results from each topic. Thus, valid interview material was obtained in some topics, while other topics had to be complemented with additional sources. It should be considered that the availability of public information of industrial companies and institutions have affected the validity of the study material. This concerns mainly future research subjects or innovations as well as process technologies used that might still be internal information of companies. Thus, some interviewees might not have provided in-depth answers to the interview questions, if it could have revealed company's or institution's competitive advantage. This has also reflected in the extent of results in some themes. Other possible limitations might have appeared during interviewing and transcribing. Probability of technical failures can always be present during interviews. In this study, technical failures occurred as breaks in Skype connection and recording. Some important information might have been missed due to these or due to misheard transcribing.

3.2 Review of key process technology and product innovations in the forest industry

This chapter covers the development of the forest industry in different areas. First, the key processes of obvious process themes are presented under the title of 'technology overview'. This is followed by the summary of innovations and their drivers. Finally, the developments and main achievements during the past 20 years are covered for each theme. In some themes, the description of the whole theme including review of innovations and developments has been presented briefly. This mainly concerns process related themes like 'chemicals and other raw materials', 'automation and digital technology', 'energy' and 'environmental protection'. Furthermore, other themes that have not been included in the previous Innovation report, such as new business areas emerged in the forest industry as well as mechanical forest industry, have been reviewed in a general level. There are varieties in the way how the results have been reported and presented in this chapter. The results have been incorporated in the description referring to the source of the results which is an interview in this case. Regarding the process themes, paper converting is an exceptional theme that has not been described thoroughly due to lack of an actual interview on this particular theme. Departing from the original scope of the study (Figure 3), paper converting is reviewed alongside paperboard manufacturing. Another departure relates to the aspects of industries and institutions on innovation. Since there were not many representatives from institutions among the interviewees (4 out of 23 interviews), this chapter compiles the key observations and findings collected from the interviews.

3.2.1 Wood handling

3.2.1.1 Technology overview

The technology process of wood handling can be divided into three different subareas that are log handling, bark and water handling and chip handling, respectively. Log handling begins from log receiving and progresses to debarking. A possible de-icing can take place between log feeding and debarking after which logs are chipped. Subsequent processes include bark handling, chip handling, screening, transport and storing of chips. (Product portfolio and strategy manager, Appendix 2) A typical arrangement for wood handling process is presented in the Figure 10. It can be claimed that changes in technology play a major role in defining the process arrangement as well as the process description of each stages in the wood handling. In addition, environmental regulations and requirements for raw material have a certain degree of contribution in modifying the process description in wood handling. Contribution of each stage in wood handling to overall cost effectiveness and quality of end-product has been considered more accurately in modern mills compared to the past. It is stated that the losses at the early stage of wood handling cannot be compensated in subsequent stages (KnowPap). Therefore, raw material efficiency plays a crucial role at each stage from wood handling to further processing. Significant improvements made in the wood handling associate with the automation of process stages. In modern mills, many personnel required stages have been replaced with computer control, monitoring and automated systems, which have brought not only savings in personnel costs but also increased the overall efficiency of wood handling plants. (Gullichsen and Fogelbolm 2011)

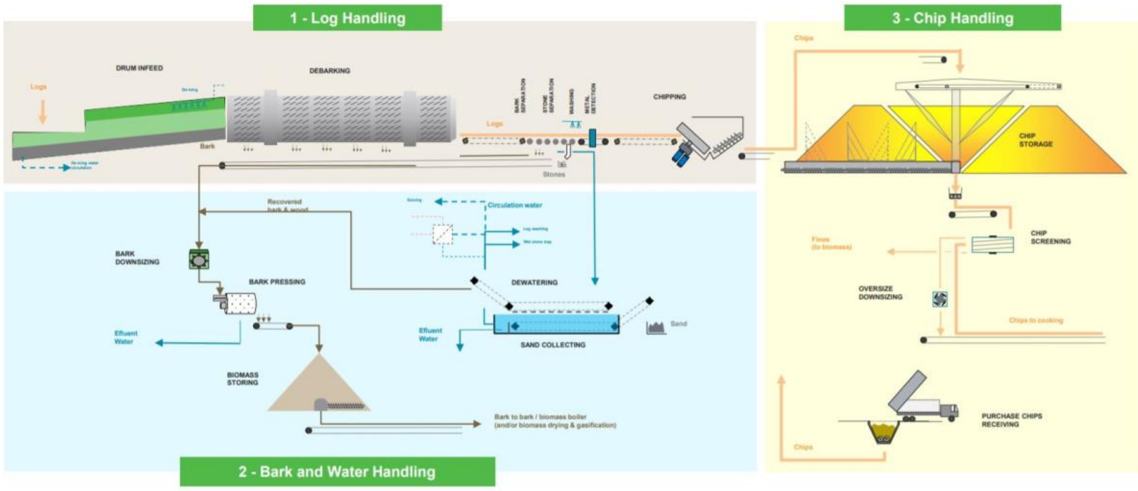

Figure 10. Wood handling process arrangement at a modern pulp mill. (Havu 2019)

Wood arrived in the mill, referred to roundwood, can be transferred directly to the process or to the storage. According to common principle, it is feasible to feed fresh wood into the process to obtain better chip quality and reduce amount of wood losses. In some cases, storages are needed, if wood logs cannot be fed as fresh due to fluctuations in mill production, harvesting or transport, for instance. Regardless of this, intermediate storing should be avoided due to the costs risen from each stored volume. Nevertheless, the optimization of wood flow from forest to the wood handling plant depends on the wood logistics. Speaking of shelf time, wood logs can be stored up to several weeks or months, while wood chips can be stored up to a few days to weeks. The risks of fungal exposure accelerate by prolonged shelf time that further leads to biodegradation of wood and increase of bacterial strains. (Product portfolio and strategy manager, Appendix 2) This causes changes in wood properties, such in moisture and brightness, which subsequently affect the pulp yield and quality. Wood properties, such as moisture and brightness, that diminish during storing, can be preserved by wetting or with other storage methods. However, an insufficient wetting can cause a drop in the moisture content promoting penetration of sap-stain fungi, and an excess wetting can cause discoloration that may impede removal of staining compounds during the bleaching. Subsequent storage method relies on cold storage enabling preservation of moisture content and brightness by covering the wood stack with snow. From economical aspect, the wood quality can be preserved by keeping the storage time short (normally 2-7 days) or by selecting a suitable storage method to meet the storing requirements of different wood species and types. (Lukkari, Hyppölä, Kärkkäinen, Lipponen, Mäkelä, Paananen, Pumpunen, Thesslund 2004)

Each process stage in wood handling influences the design of a subsequent and preceding stage. Whether wood logs are handled in bundles or individually, the transport method, as well as wood tree species, dimensions and weight of wood logs influence the choice of equipment. The wood logs can be handled in different ways depending on the choice of debarker. (Gullichsen and Fogelbolm 2011) In the selection of conveyor type, the applicability of wood raw material form is considered in relation to economic aspects of material treatment. In order to maintain wood fibre quality, wood logs should be treated gently avoiding dropping of wood logs between log transportation and debarking process. (KnowPulp) The objective in debarking is to avoid wood losses while bark and solid ground particles, for example sand and stones, are removed mechanically in the debarking drum. There are various models for debarking machine which varies from ring to drum types. (Gullichsen and Fogelbolm 2011) Typically, debarking is conducted in a debarking drum in which separated bark and other solid particles exit through bark holes. Debarked wood goes along a roller assembly through bark separation, in which possible bark remained from the debarking are separated, and further through stone separation, in which large stones are separated into stone catchers. Finally, wood logs are washed with warm water and screened through a metal detector before chipping. In modern wood handling plants, the water circulation system is nearly closed. Small amount of makeup water is still required in the water circulation process. Otherwise, water used in washing stations is recirculated and small part of wastewater is directed to the wastewater treatment plant. The use of de-icing in the process extends the water circulation system of a plant and handling process further. The wet bark from de-icing is needed to press for removing excess water. Before removing water from bark mechanically, the particle size of bark is adjusted by crushing. After this, the bark is forwarded through bark pile to further treatment. Typical treatment for bark has been its incineration or drying before its gasification and incineration in lime kiln. After chipping, the wood chips are screened before or after the storing depending on the process arrangement. By screening, fines are first separated from the process. Pins and sawdust are removed with bark to the incineration. Oversized chips are treated with either chip cutter, crusher or press before ending in the fractions of accepted chips for pulping. In addition to these, purchase chip or separate storing and receiving systems may associate with the process. (Product portfolio and strategy manager, Appendix 2)

3.2.1.2 Innovations and their key drivers

By overviewing developments in the wood handling over the past 20 years, innovation started in the 1990s along with the development of process automation. The automation level of mills increased by installation of programmable logic controller (PLC) and distributed control systems (DCS) that laid the foundation for building control systems in the mills. The development of process automation, process measurement and controls enabled optimization of processes that increased significantly the safety level at the mills. In terms of quality, more attention was paid to chipping techniques in which case more weight was laid on the chip sizes. Chipping geometry and chip thickness proved to have an influence on chip quality, which could support the pulping process. Thus, improved chip quality was obtained by increasing the length-to-thickness ratio that resulted in a thinner chip size. For this, chipping technologies were improved particularly towards optimization of length-to-thickness ratio of the chip and versatile utilization of the raw material. At the time, **thickness screening** was introduced to ensure uniform chip size for cooking by minimizing the share of unsuitable particles for processing, such as pins and sawdust. The thickness screening was already developed in the end of 1980s, but its use became common in the 1990s. At the turn of the century, the capacities continued to increase as the process automation developed at the mills. In the 21st century, process optimization started to gain more visibility, which led to improvement of machine vision and optimization systems for wood handling processes. In the chipping process, for instance, an optical analyser is used to monitor the chip quality which enables pulping process to be adjusted to the actual chip quality. In the middle of the 21st century, high volume round chip storages became more common among pulp mills. Established name for this type of storage is **circular storage** or **360° storage** which functions as a chip stacker and chip reclaimer. A stacker in the middle of the circular storage rotates 360° and builds a storage pile. At the same time, a rotating bridge-type scraper equipped with a movable rake reclaims the pile by driving against it and moving the chips to the centre of the pile where the chips are fed to the conveyor and carried away from the pile. (Gullichsen and Fogelbolm 2011) This resulted in reduced storage cost per stored cubic metre of chips, which proved to be a cost-effective storage system. (Product portfolio and strategy manager, Appendix 2)

The redevelopment of chips occurred in the 2010s when the safety factors were driving development of **2nd generation horizontal feed chipping**. Up to the present, the chipping has been carried out based on a vertical feed chippers where the wood logs have been directed to the feed spout at an angle of 45° and chipped against the chipper disc (in a vertical position). This type of chippers has been phased out by novel type of horizontal feed chippers due to the safety reasons risen from the discharge of jams in the feed spout of vertical feed chippers. In the novel horizontal feed chipper, the logs are chipped horizontally without a feed spout. This increased the uptime of chipping process, thus implying higher chipping capacity. Another remarkable technological development in the 2010s has been **gasification technologies**. In this case, the utilization of biomass in a new way can be considered as an innovation or new entry into the pulp mills. Intention in the gasification technology is to replace the fuel used in lime kiln that has been a heavy fuel oil or natural gas with biogas obtained from the gasification of bark biomass. First, the biomass or bark is dried from the moisture content of 50-60 % (in Finnish pulp mills) to the 10 %. After drying, the biomass is gasified in the fluidized bed gasifier and led to the lime kiln for firing. (Product portfolio and strategy manager, Appendix 2) Alternatively, there has been a brand-new bark press, commercially known as **HQ Bark press**, that enables higher dry solid content of the bark by a two-phase pressing. With higher dryness, more electricity can be generated from the same amount of raw material. (Chief technology manager, Appendix 2)

3.2.1.3 Development trends and main achievements during past 20 years

In general, process and cost optimization have been one of the main factors behind the development work. In the wood handling, process and cost optimization appear in the maximization of raw material use and in minimization of wood losses. Maximization of material use has been considered in the production of wood chips by improving chipping technology. The chip quality has improved due to developed chipping geometry and chip thickness. Besides, the safety requirements for the chipping have improved by tightened conditions for using the horizontal feed chipper. Since the 2010s, the use of horizontal chippers has become a requirement at the standard level. Raw material efficiency usually goes hand in hand with energy efficiency. In wood handling, energy efficiency appears in the efficient use of primary raw material as well as in the use of secondary energy sources. For instance, secondary heats from pulp mills are used for drying bark or biomass. This also applies to de-icing that aims to use secondary energy source instead of primary, such as steam from the steam generation. Additionally, fossil-based energy sources used in the lime kiln are replaced with the energy obtained from the gasification of pulp mills’ bark. It is a company-specific case, whether a pulp mill uses fossil-based fuels in its production. Nevertheless, a concept of fossil-free pulp mill has challenged companies to adopt new technologies related to the responsible and sustainable energy use. Redevelopment of gasification technology is an example as a result of this. It is about total optimization, when the overall energy economy of a mill is considered instead of focusing on the sub-optimization of single processes. (Product portfolio and strategy manager, Appendix 2)

It is claimed that the basic technology has remained quite the same in the wood handling. No major innovation breakthroughs have been occurred in the basic technology, but the capacities have rather increased. In general, line capacities of log intake have increased during the past 20 years, which have further reflected to the capacities of a whole wood handling process. The development trend of wood handling line capacities is presented in the Figure 11 that is used as one of the indicators to measure the performance of wood handling process. Since 1990s, the capacity has increased from around 200 to 400 solids over bark (m^3/h) on average. In the beginning of 2019, it was announced that Valmet delivers a wood handling line with the capacity of 470 m^3/h to the Joutseno pulp mill. (Valmet 2019a) The end for the trend has not been observed yet, although the trends for the line capacities have continued increasing up to 400-500 m^3/h. The drivers behind the development have probably been the growth of megamills' lines. Generally, the capacities have increased along with larger production lines that are considered as economically viable. (Product portfolio and strategy manager, Appendix 2)

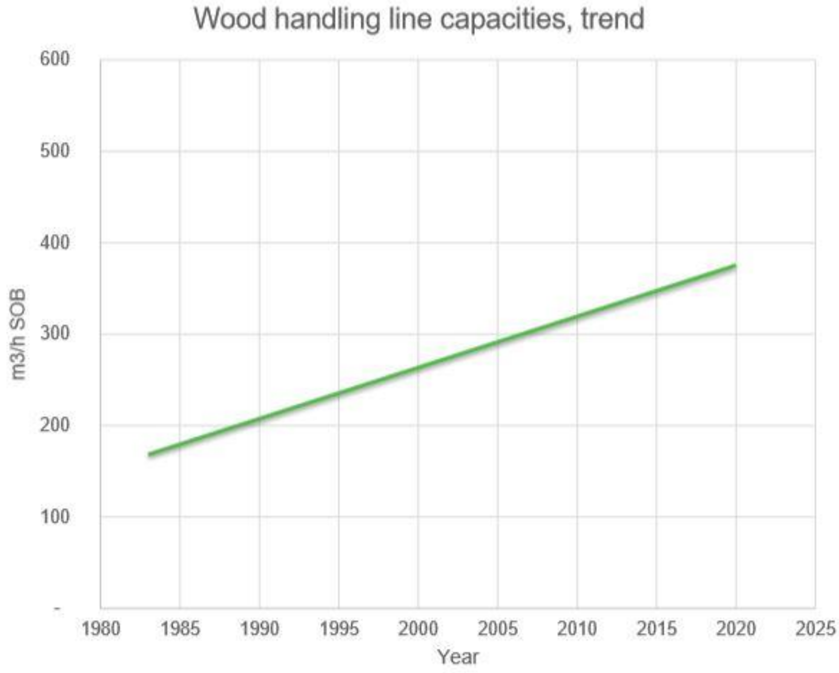

Figure 11. Development of wood handling line capacities. (Havu 2019)

High capacity as well as high up-time and yield describe the development trends of wood handling. High up-time has been achieved by minimizing the down time, for example the number of maintenance breaks have reduced by implementation of 2nd generation horizontal feed chippers. Meanwhile, high yield has been achieved by minimizing the amount of wood loss in debarking and generation of pin and fine in chipping. Developed chipping technology has contributed to the chip quality in the way that it meets the cooking requirements. Thus, the chip screening is not further needed. In Finland, Äänekoski mill is one of the first mills that does not use chip screening. This has also been influenced by improved cooking technology that has had a significant contribution to the chip quality. The quality control from log intake to chipping has been made possible due to improved process automation and use of process measurement to control the whole line. On the side of automation, IoT-solutions have been a distinct trend, but their utilization varies among the process fields. In the case of wood handling, IoT-solutions have mainly associated with single equipment. For example, installation of vibration transducer gives information about electric engines based on which anticipation on process operation can be made. A great number of measurements have been applied to the processes, but the challenges emerge when combining measurement data of a single process to another process or over the mill departments. A comprehensive data processing of the mill and between the mills is yet to realize, but in this case, a data ownership may act as an obstacle for large-scale utilization. (Product portfolio and strategy manager, Appendix 2)

As more mass flow is fed into the process, the line capacities including feed, chipping and screening have naturally increased as well as storing systems have become larger. Up to the present, circular storages have proved to be efficient and no other or newer inventions have been discovered to replace this. Thus, the development work has associated with these and furthermore, with the utilization of the pulp mill's own energy sources, such as bark and biomass, in the mill's internal process stages. (Product portfolio and strategy manager, Appendix 2)

3.2.2 Chemical pulping

3.2.2.1 Technology overview

Defibring process is carried out either chemically or mechanically. In chemical pulping, the defibring process bases on the use of chemicals that removes the fibre-binding agent, lignin. After removal of lignin and other impurities, the pulp mass becomes brighter and stronger. One of the first chemical pulping methods was the soda pulping invented in 1851. In the soda pulping, the pulp mass was produced by using sulphurous acid or sulphur dioxide. This method was limited to use of straw or hardwood as a raw material, which further led to the development of sulphite and sulphate pulping. Sulphite process was more complex for its cooking chemicals but was previously dominating due to its yield on brighter pulp and thus, it required less bleaching as sulphate process. As the bleaching and oxygen delignification technologies improved, it was easier to bleach and produce stronger pulp with sulphate process. Sulphate process or Kraft process today is the dominating method in chemical pulping due to its applicability on the use of wider range of raw materials in the production of various pulp grades. (Gullichsen and Fogelbolm 2011) In this chapter, the process of chemical pulping is reviewed referring to the Kraft process. The general arrangement of chemical pulping process is shown in the Figure 12.

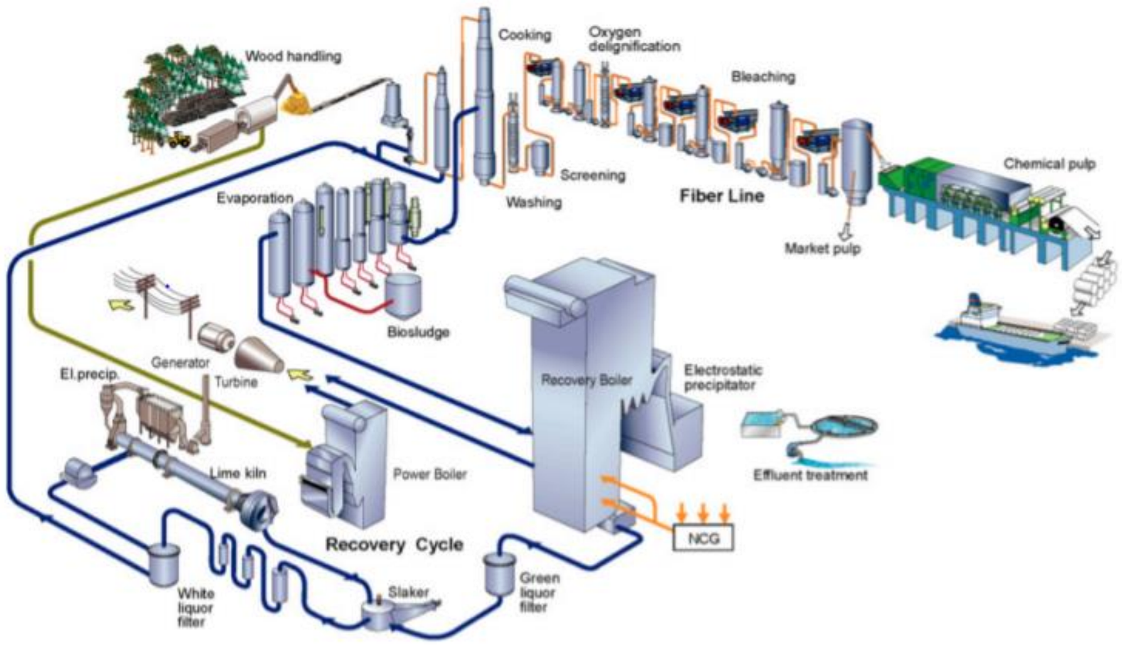

Figure 12. Chemical pulping process. (Isaksson et al. 2012)

The chemical pulping process is divided into two main processes, fibre line (pulp line) and chemical recovery, and into many smaller sub-processes. In the fibre line, wood transported to the mill is processed into suitable size and form of chips for cooking. The purpose in cooking is to defibrate wood chips by removing fibre-binding lignin with white liquor and black liquor (from previous cook) containing cooking chemicals. Sodium hydroxide and sodium sulphide act as active components of cooking liquor. The cooking phase is conducted either in continuous or batch cooking digesters. There are several washing stages between cooking and bleaching stages. By washing a brown pulp from cooking in a counter current flow, dissolved organic solids and inorganic chemicals are recovered with minimum amount of dilution water. This so-called weak black liquor is concentrated in a multistage evaporator chain to a dry solids content that supports the incineration. The subsequent process after washing of pulp is either delignification or the first stage of bleaching or in the case of unbleached paper and paperboard products, the bleaching is not required. In modern pulp mills, delignification is carried out by using oxygen or alkali (oxygen delignification) to remove a residual lignin left in the pulp, and hence, reduce the use of bleaching chemicals. In the bleaching, the objective is to improve brightness and cleanliness. Among bleaching chemicals, elemental chlorine free (ECF) and total chlorine free (TCF) chemicals began to phase out conventional bleaching chemicals containing chlorine and hypochlorite. The adoption of ECF containing chlorine dioxide became dominant in Nordic countries in the 1990s. The final stage in the fibre line is drying and baling of pulp mass. (Gullichsen and Fogelbolm 2011)

A modern pulp mill produces more energy than it consumes. The energy production is based on the incineration of black liquor in a recovery boiler that has two main functions: chemical recovery and heat recovery. Inorganic compounds of the concentrated black liquor are burned to form smelt that consists mainly of sodium sulphide (Na_2S) and sodium carbonate (Na_2CO_3). By dissolving smelt in wash water, green liquor is produced and subsequently causticized with burned lime (CaO) that has been slaked into calcium hydroxide ($Ca(OH)_2$). The reaction between calcium hydroxide and sodium carbonate forms dissolved sodium hydroxide and calcium carbonate (lime mud) that is recovered and reburned into calcium oxide in a lime kiln for recausticizing. The liquor filtered from the lime mud is so-called white liquor that contains sodium hydroxide and sodium sulphide and is pumped to the digester to be reused in the cooking process. The overall recovery cycle of Kraft process is described in the Figure 13. On the heat recovery side, the heat released from the combustion of organic compounds of the black liquor is recovered in the flue gases as high-pressure steam that is led to power generation to meet the energy demands of the mill. (Gullichsen and Fogelbolm 2011)

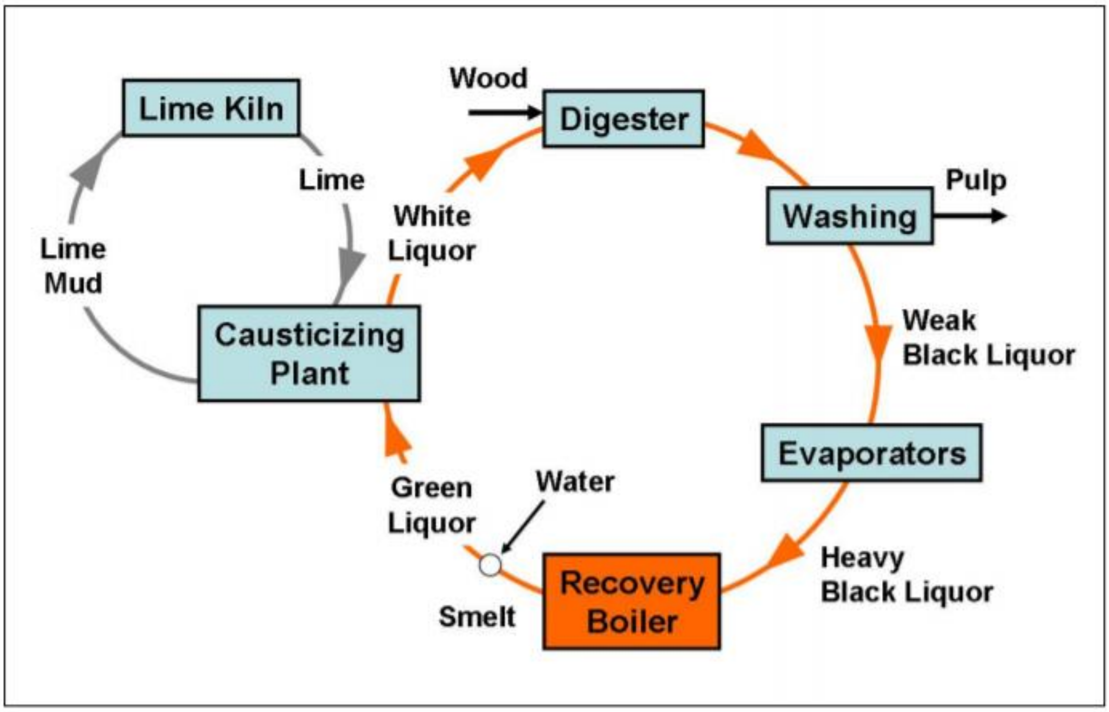

Figure 13. Kraft recovery cycle. (Tran and Vakkilainen 2007)

3.2.2.2 Development trends and innovations during the past 20 years

Current pulping process is based on the old technology that has been in use for long time. Thus far, there have not been major changes in the pulping technology, but the changes have rather focused on improving production efficiency of a pulp mill. (Development manager & Customer service and sustainability manager, Appendix 2) One of the most significant changes of this century has been the growth in the mill size. This is reflected to the capacity of a mill that indicates how many ton of pulp can be produced at annual or daily level. The increase in the mill size has been a result of numerous technological developments. When considering the factors behind this increase, technological developments on the energy side should be emphasized. Energy production and energy consumption or energy use in general have improved significantly at pulp mills, which has brought the mill efficiency to a new level. Modern pulp mills consume less energy and produce more energy in their production implying higher surplus of energy that can be sold outside the mill. Moreover, the energy use is optimized in the entire mill integrate. (Chief technology manager, Appendix 2) These developments are based on the efficient use of raw material from which the development trends of pulp mill originate. This chapter reviews the developments in pulp mills from the perspective of development trends. Current development trends of pulp mills are capacity, safety, environmental load, byproducts and IoT solutions, respectively (Figure 14). Instead, innovations emerged in the pulp mills are presented alongside trends.

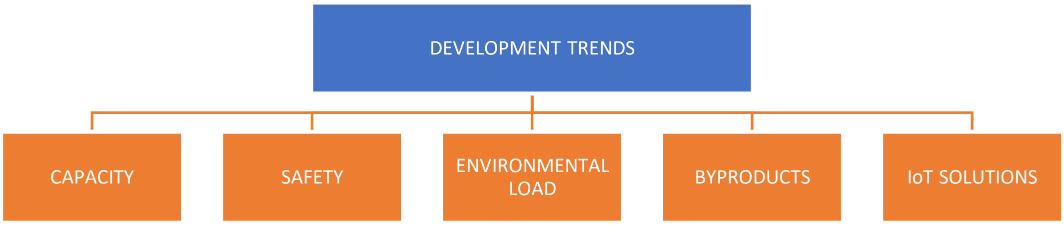

Figure 14. Development trends of pulp mill. (Adapted from Chief technology manager, Appendix 2)

When looking at the capacity of a single-line pulp mill (Figure 15) 20 years ago, the capacity was in the order of 2000 t/d. At that time in Finland, Joutseno and Kaukopää mills were both of this magnitude. In recent years, the order of 6000 t/d has been exceeded. The capacity has undergone a rapid growth in a short term. During the 1980s to 21st century, the capacity increase was in the order of 1000 t/d. By 2010s, the capacity had already doubled and by 2015, the number had tripled. This implies adoption of larger equipment and lines. One of the technology developments in this decade has been build-up of megamills. (Product portfolio and strategy manager, Appendix 2) Examples of megamills are single-line pulp mill in Äänekoski in Finland, that produces 1.3 million tonnes of pulp per year, and Fibria Horizonte 2 in Brazil (recently changed its ownership to Suzano), that produces nearly 2 million tonnes of pulp per year. The main driving force behind this development has been reduced investment cost per ton of pulp. This has put pressure on the technology side not only in the terms of scaling-up but also in terms of understanding equipment technology, and thereby, creating completely new equipment techniques and technologies. (Chief technology manager, Appendix 2)

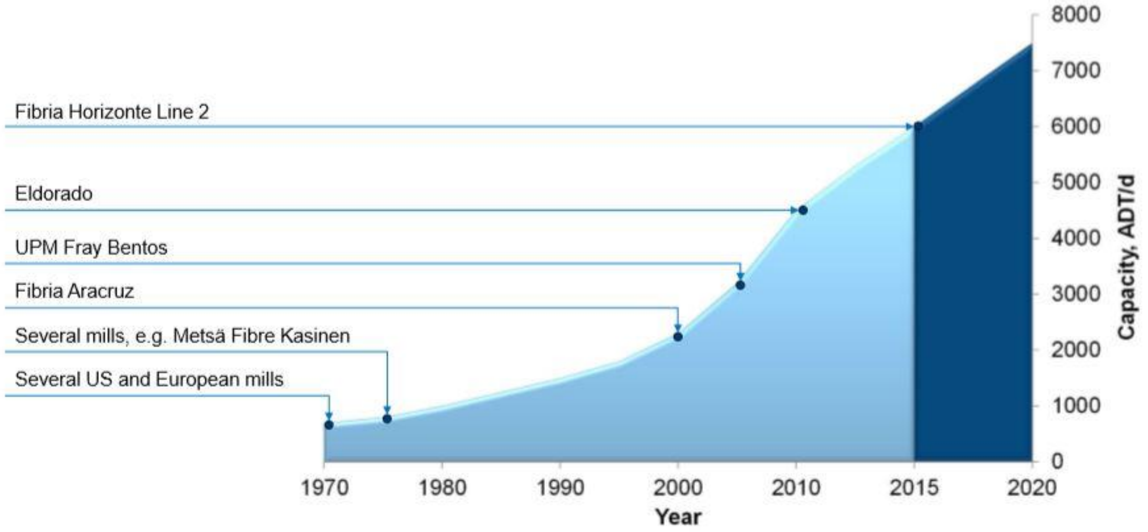

Figure 15. Development of single fibre line production capacities. (Andritz Group 2019)

The core of these development trends is the efficient use of raw materials. Raw material efficiency has been considered from the wood handling where the technologies have been improved to support the subsequent processes. In the wood handling, the chipping technology has been improved to produce high quality and homogeneous chips. High quality chips can be further cooked to higher kappa number, which implies more selective method for removing residual lignin in the oxygen delignification stage. It is claimed that oxygen delignification of high kappa pulp results in less damaged and longer fibres (Danielewicz and Surma-Ślusarska 2006), and thus, higher pulp yield can be achieved. Besides, the cooking process has a great influence on the high fibre yield. Alternative method for better cooking results is the use of **polysulphide** technology. Polysulphide is a cooking chemical that stabilizes and preserves hemicelluloses by inhibiting peeling reaction of carbohydrates' degradation. Another technological development that has been a substantial part in the realization of scaling-up of pulp mills is the **DD washer**. A single unit of DD washer can have one to several number of displacement washing stages where the incoming and outgoing wash fluids are kept separate and reused in the same unit. This has brought benefits to all fibre line washing applications contributing to the low energy consumption and chemical consumption in the mills. (Chief technology manager, Appendix 2)

As previously mentioned, technological developments related to the capacity increase have occurred on the energy side. Modern pulp mill consumes less energy than it produces. The change in the energy production and consumption of pulp mills has been illustrated in the

Figure 16. In the Figure 16, blue curve describes the electric power consumption in pulp mills and red curve electric power production, respectively. Growth of the distance between two curves indicates the development of net power production excluding the power boiler and chemical plant. The first big leap on the energy side occurred in the 1980s when Medium consistency (MC) – technology was introduced. The technique allowed pumping of a higher consistent pulp resulting in more homogenous pulp and improved penetration of chemicals. This brought significant savings for pulp mills in water, energy and chemical consumption. Subsequently, energy consumption of mills was reduced by implementation of speed control motors. In general, the energy consumption of the mills has decreased, while the line size has increased. This is due to proportion of waste heat decreases as the line size increases. Regarding the development in the energy production of the mills, another great leap occurred in 2004 was the development of **high energy recovery boiler** (HERB). This kind of boiler was designed for high steam values. The higher steam pressure and steam temperature, the more electricity can be produced (Chief technology manager, Appendix 2). Additionally, all the incoming and outgoing streams, concerning water and air streams in the HERB, are pre-heated enabling greater production energy and to selling of surplus energy to the electricity grid. (Chief technology manager, Appendix 2)

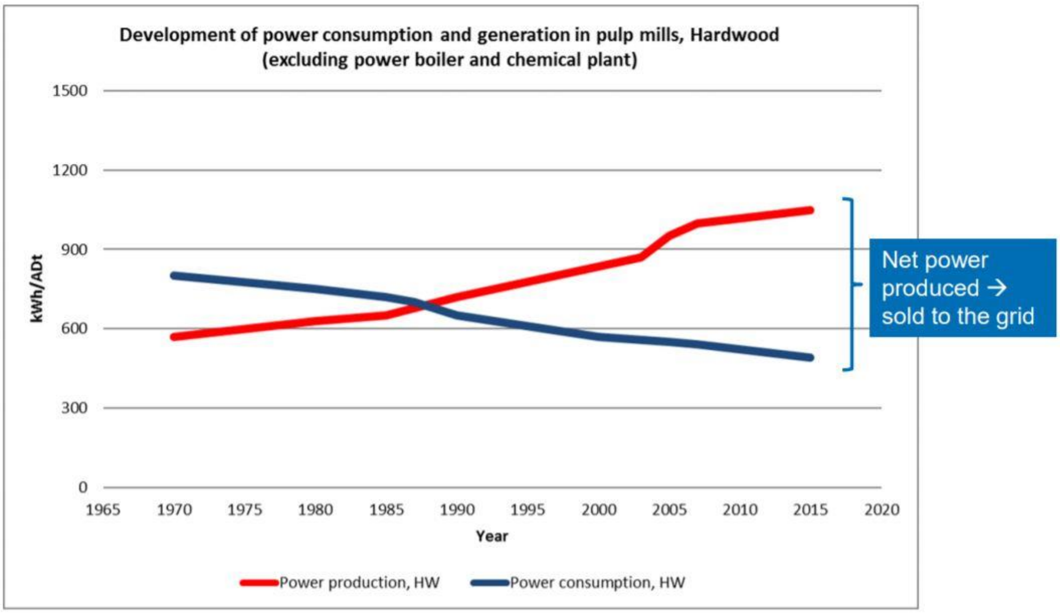

Figure 16. Development of energy consumption and generation in pulp mills. (Andritz Group 2019)

Developments in the recovery boiler have been in the centre of the growth in mill size. However, this has raised concerns about the environmental impact of pulp mills. Reduction of environmental impact or load has been a sustained driver and a megatrend. In the pulp mills, this trend has appeared as a continuous development of pulping technology and reduction of emissions and wastes. In recent years, more attention has been paid to NO_x emissions to which **selective catalytic reduction** (SCR) technology has been applied for removal of NOx from the flue gas of boiler. Respectively, non-catalytic reduction (SNCR) is applied for lime kiln. SCR technology is based on the same technology used in diesel engines where a reductant, such as urea or ammonia, reacts with NOx and converts them into nitrogen and water. A small amount of CO_2 is formed as a product when urea is used. With the SCR technology, reduction of NO_x from 50 % to 90 % can be achieved (Latha et al. 2019; Sorrels et al. 2016). In terms of wastes, legislation and environmental requirements have a great impact on waste reduction in the pulp mills. (Latha et al. 2019; Sorrels et al. 2016) It is extremely expensive to dump waste to landfill, and therefore, it is preferred to burn the wastes for energy production or process them into products. Processing into byproducts is more profitable than burning, but the challenges may emerge in the adequacy of quantity. (Chief technology manager, Appendix 2) Utilization of byproducts or side steams has brought possibilities to substitute energy and chemical consumption in pulp mill's own processes, for example gas product obtained from the gasification bark can be used in lime kiln to replace fossil oil or natural gas, and production of lignin, methanol and sulphuric acid for internal use to reduce the need for buying chemicals from outside. This has created the concept of **bioproduct mill** or biorefinery that is a typical change of this decade. (Chief technology manager & Product portfolio manager, Appendix 2) The term of conventional pulp mill has phased out by adoption of bioproduct mill or biorefinery.

Safety has been a major driver in the development of a pulp mill. Generally, safety standards have been playing an important role in equipment and process design as well as in projecting (Product portfolio and strategy manager, Appendix 2). In recent years, the safety has emerged in a completely different way in terms of process monitoring. A few years ago, monitoring of process was referred to control system or more precisely distributed control system (DSC). Today, Industrial internet and Internet of Things (IoT) or Industrial Internet of Things (IIoT) solutions, which are so called evolution of DSC, enable monitoring of process, quality and equipment condition in a completely new way. This involves a large amount of data that can be used in process monitoring. As an example, a quality index tool called **Fiber online index** (FOX) is used in monitoring pulp quality. (Chief technology manager, Appendix 2) The index is based on data processing which gives values from pulp quality, such as brightness and strength properties. (Development manager & Customer service and sustainability manager, Appendix 2) Followingly, a simulation and optimization tool, **Fiber GPS**, allows customization of fibre quality based on the data received from real-time, simulation and optimization models (Andritz 2018). These kind of solutions are commonly built under a larger system that comprises a set of state-of-art featured functionalities. An example of a system used in pulp drying, **EvoDry – pulp drying system** has been designed for improved operational performance and line efficiency with safety in mind. This kind of system is equipped with sensors and detection system that identify potential faults in line breaks, and thus, minimize the need for physical diagnosis. It can be stated that the nature of process monitoring is shifting toward predictive maintenance which further changes the way how maintenance work is conducted. This can appear in a longer time interval between downtimes instead of annual downtime. In addition to these, remote monitoring and remote solving will become more common not only within the mill but also between mills around the world. Thus, there is no longer a need for experts to be sent in situ to mills, but diagnostics and counselling can be done via remote access. (Chief technology manager, Appendix 2) Overall, IoT solutions promote mills to achieve improved production and profitability through optimization of resource use and process performance.

Regarding the energy efficiency, pulp mill is considered as one entity instead of separate departments. In this kind of consideration, PINCH analysis is often used to evaluate, in which department energy is produced and where it is reasonable to use. The energy use is not limited to one department, where it is produced, but it can be used in another department. This refers to the integration of departments that enables energy saving solutions to be implemented in the entire mill. Optimizing the energy use in the fibre line can save energy in subsequent processes. In the fibre line, for example, the dry solid content of black liquor can be adjusted to higher content, which implies less steam to be required in the evaporation of the black liquor in the subsequent stage. This is also referred to the total optimization in which the basis is on the efficient use of resource. In the pulp mill, resource efficiency appears in a chemical and waste recovery. Instead of feeding make-up water into the process, filtrate water from bleaching or other filtrates can be reused and recycled in the process. It is more energy efficient to use the filtrates in the process, once they have been heated. Pulp mills have been aiming to reduce the amount of solid waste. Nevertheless, waste is generated along with the process. At least, incineration for energy production is preferred instead of dumping in landfill. As an example, biosludge has previously been dumped in landfill but it can be incinerated similarly as bark and wood dust. (Chief technology manager, Appendix 2)

Over the past 20 years, the development trends have brought about changes at the pulp mill. Technological developments in equipment technologies have enabled scaling-up of mills. Development of automation and IoT technologies has ensured the reliability and profitability of production. Safety has been taken more into account in equipment and process design. Increased environmental awareness has generated cleaner and more efficient process solutions. Above all, combination of these trends and drivers have generated innovations, which have enabled redeveloped of pulp mills. The development of a pulp mill into bioproduct mill has introduced new products on the market and solutions for existing applications, for example 'new bioproducts from lignin', 'new textile fibre from pulp' and 'bio-methanol from purification of raw methanol'. Part of these solutions are still in a development phase. It has been demonstrated that small scale production of these and many other bioproducts is possible, but the profitability of large-scale production sets challenges, especially when commercialization is at target. Additionally, the challenges arise when it comes to the competition with oil-based products. In order to compete in the same markets with oil-based products, the price level of bioproducts must be at the same level or at least competitive as oil-based products. Currently, bioproducts compete with their status of being 'sustainable', but other alternatives, for example 'wood based', are needed. (Chief technology manager, Appendix 2) Nevertheless, sustainable trends, such as climate change and circular economy, have had a major impact on innovation, and thus, on the development of pulp mills.

3.2.3 Mechanical pulping

3.2.3.1 Technology overview

The main process stages of mechanical pulping are shown in the Figure 17. In mechanical pulping process, wood fibres are separated from wood matrix either by grinding or refining. In grinding, wood in the form of logs are pressed against a revolving grindstone, while refining uses wood chips that are refined in a disc refiner. The idea in mechanical pulping is to carry out defibration with the presence of water, heat and mechanical stress without dissolving anything from the wood. A small percentage of soluble extractives and other matters may dissolve during the process. Nevertheless, the yield in mechanical pulping is usually around 92 – 95 % that is higher compared to chemical pulping. On the other hand, mechanical pulping is more energy intensive. The pulp types produced through mechanical pulping are named based on the applied process and process conditions. Groundwood pulps are produced through grinding where process temperature and pressure can be adjusted. Mechanical work in grinding is converted into heat which raises the temperature of the wood resulting in the softening of fibres bonding lignin and releasing of individual fibres. Thermomechanical pulp types are produced in the refining process. Mechanical stress is achieved between wood chips and rotating disc or discs causing wood chips to break down into fibre bundles, individual fibres and fibre fragments. Water is added into the process to prevent wood from burning. At the same time, large amount of steam is generated that can be recovered into the heat recovery system. A chemical pre-treatment can be applied to wood chips to enhance the defibration process and the properties of pulp. Chemi-thermomechanical pulp is obtained through a combination of chemical pulping and mechanical pulping process. As in grinding, pressure conditions in the refining process are also adjustable. Thus, the main processes in mechanical pulping are stone groundwood

(SGW), pressure groundwood (PGW), thermo groundwood (TMP) and chemi-thermomechanical pulp (CTMP) processes (Höglund 2009). Furthermore, the brightness of mechanical pulps can be increased by peroxide bleaching or reductive dithionite bleaching of which the first one is more widely adopted. In general, mechanical pulps are used for producing newsprint, uncoated, supercalendered paper (SC) and lightweight coated (LWC) magazine paper. (Höglund 2009) Other application areas are different board grades and tissues. The mechanical pulping process generates shives and fibre bundles that have to be removed through screening and cleaning. Fibres produced in mechanical pulping might not achieve the same strength properties or long fibre content as in chemical pulping, but mechanical pulp has higher opacity and therefore, it provides good optical properties. (PI-Consulting Ltd 1997)

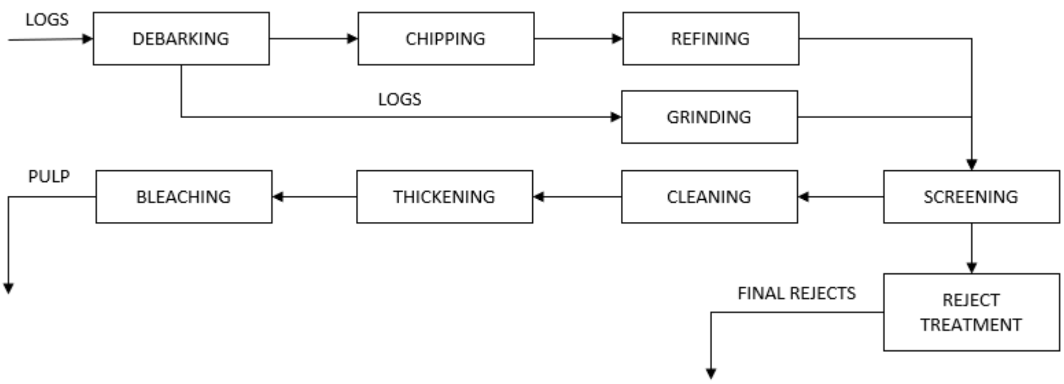

Figure 17. Main process stages in mechanical pulping. (Adapted from Suhr et al. 2015)

3.2.3.2 Innovations and developments during the past 20 years

In Finland, research of mechanical pulp has been traditionally carried out in a tight cooperation with KCL that has created a robust base for research in this field. The focus in researches has been varying depending on the owners' demand. During the 1980s and 1990s, more attention was paid on quality, while energy was of little importance. The importance of energy grew closer to the 21st century when energy saving projects became more significant. (Development manager, Appendix 2) On the TMP side, the focus has been mainly on the blade development, while on the CTMP side, process development has progressed in terms of energy requirements. On the whole, energy consumption has had to be reduced in all areas. At the same time, paper machine technique has developed to the point where the tear strength of paper has no longer been a significant factor. As a result, the quality requirements for the pulp have been able to change, which has furthered to bring down the energy consumption. In practice, this means that fibres can be cut more in the process. (Development manager, Appendix 2)

Grinding studies have mainly focused on reducing energy consumption or maintaining low energy consumption and thereby increasing the capacity. Significant savings in energy consumption and production costs have been achieved with a new grinding technology called **Galileo**. The idea behind the development of grinding technology was to replace to the old ceramic pulpstone used in the grinding process. Firstly, the ceramic pulpstone has disadvantages due to its ceramic material. Ceramic material is fragile and has a poor resistance to thermal shocks. Moreover, it is sensitive to abrasion, and thus, its surface must be conditioned at intervals of about a few weeks. Galileo technology is based on a steel core with interchangeable steel segments and single layer grinding surface of industrial diamonds. The core of innovation was the diamond surface; its design and what kind of diamonds were used. No changes were allowed to occur in the pulp quality, and therefore, it was important to achieve energy savings with the same pulp quality. About 300 kWh or 25 % of the energy savings were achieved increasing the capacity by the same amount. For customers, it is more lucrative to be able to increase the capacity of existing equipment with small investments. Following the financial crisis of 2007-2008, there has been little investments expected even in the projects of a very rapid repayment like Galileo. Afterwards, the central subject has been on the development of surfaces, especially durability of the surfaces. The durability of Galileo surfaces has been improved from half year to about one year, while old grinding pulpstones might endure three or even five years. In the case of Galileo technology, it must produce benefit by covering the deficit of shorter life with energy savings and uniform pulp quality. Galileo technology was applied first to SC and LWC grades due to their high energy consumption, and therefore, invested capacity has been the highest for these grades. Other grades like newsprint and board have been covered later with the Galileo -technology. (Development manager, Appendix 2)

Regarding the developments in the refining process, the major development from the 1980s has been the increase in capacity, particularly in TMP and CTMP processes. Back in the 1980s, these processes were characterized by high energy consumption with small equipment and a large number of components. The refining process comprised many lines in parallel in which the capacity of one refiner was around 200-300 tonnes. Today, one refining line can produce pulp for a large paper or board machine with the capacity of 1000-1,200 tonnes per day. Thus, the refining lines are much larger today. Behind these achievements have been developments in equipment, particularly in refiners and motors. An alternative refiner called **Conical Disc (CD) refiner** was developed which operating principle was based on the combination of a conical refiner and a typical disc refiner. The CD refiner enabled combination of two processes leading to a significant savings in energy consumption. This has required a large power source from electric motor which capacity has been constantly increasing. Apart from this, the developments in refiner blade has had effect on the energy consumption reduction, and thereby, increased the capacity. (Development manager, Appendix 2) One of the development trends has been simplification of processes. This has particularly emerged in the refining and reject treatment where the use of **low consistency** has been adopted. Before, the process stages in TMP had been conducted in high consistency due to the long fibre length. Low consistency processing has been used for years, particularly in the reject treatment, where thickening stages are not needed anymore. This has brought energy savings through simpler processes and cheaper equipment. (Development manager, Appendix 2)

A large part of the capacity of mechanical pulp is in newsprint, SC and LWC paper grades which demand has been continuously decreasing. In these areas, many production lines have been shut down, especially old production lines of mechanical pulp. Instead, the part of mechanical pulping capacity grows in board grades. Thus, most of the investments is targeted at areas where cheap raw material like eucalypt and other hardwood types as well as cheap energy are available. This implies using the CTMP process which is more suitable in the board manufacturing compared to the conventional chemical pulping process. Today, mechanical pulp is produced for board and tissue manufacturing which are the major growth areas. Mechanical pulp has been used in multilayer boards for long time. In multilayer boards, the properties of chemical pulp can be exploited in the board surface, while the bulk properties of mechanical pulp are better exploitable in the mid-part of board. (Development manager, Appendix 2)

Another trend among survival seeking mills has been conversion of existing production plants into linerboard plants, for instance. Part of the linerboard mass can be substitute with mechanical pulp or CTMP. Alternatively, greater investments can be conducted to existing mills referring to production of higher upgraded board grades like folding box board and liquid pack board. This requires conversion of the processes in paper machine, which increases investment efforts. Depending on the starting point, it is not profitable to convert all existing paper machines. Instead, there has been a need for developing cheaper conversion methods that has been the driving force to the development in the field. In the case of multilayer boards, for example, different layers can be processed in the same forming unit. This can radically reduce investment costs, and thus, enable the conversion of paper machines. Nevertheless, conversion technologies are still in the development phase in which the first changes to the paper machine have been applied. Most paper machines are suitable for the conversion to solid board like linerboard or fluting units. However, the share of mechanical pulp in these products cannot be large. This implies build-up of a mechanical pulp plant and fluting or liner plant adjacent to it, or in other words, combination of two separate processes. This may involve risks that the mechanical pulp may not fit into the products leading to the replacement of the mechanical pulp with the recycled pulp, for example. On the other hand, mechanical pulp is considered as a safe alternative to recycled pulp, especially in food packing boards, where barrier layer permeating oils are undesirable. (Development manager, Appendix 2)

3.2.4 Recycled pulp process

3.2.4.1 Technology overview

Recycled pulp is produced using recycled fibre as a raw material that is obtained from wastepaper. Grading of wastepaper generates fractions of raw material, where each material fraction has its own technical properties. Based on the raw material grading, the raw material processing can be designed to be suitable for its end-use. For some wastepaper grades, the process can be more complicated composing of various process stages and separate systems. This chapter focuses on two common processes to produce recycled pulp. First, deinking process refers to a separation of printing inks from recovered paper, which produces deinked pulp (DIP). In practice, the raw materials for deinked pulp can be household collections comprising old newspapers and magazines or sorted office paper (SOP). Today, deinked pulp is mainly used in tissue manufacturing or it can be used as white top in layered boards to replace part of the virgin pulp. Besides the deinked pulp, old corrugated containers (OCC) can be used as a raw material for fluting and testliner or similarly to deinked pulp, it can be used in a mid-layer of white-lined chipboard. (Senior technology manager, Appendix 2) The process of DIP and OCC line (Figure 18) are reviewed in this chapter.

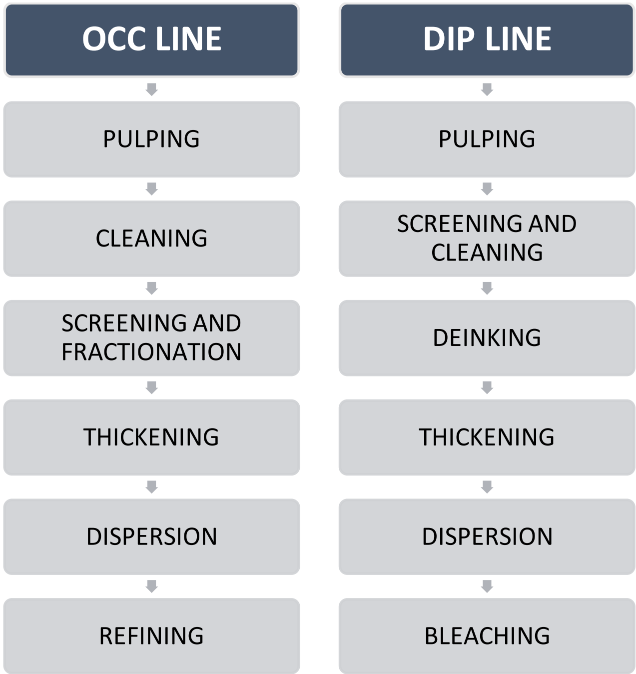

Figure 18. Main process stages of OCC and DIP -line.

In the OCC line, the raw material is delivered to pulper along with bale wires that are cut off (Senior technology manager, Appendix 2). The idea in the pulping is to homogenize the dissolving raw material into the easier form to be pumped and remove rejects like plastics, metals and other contaminants. The pulping system comprises pulper, its supply equipment and reject handling equipment. (Pesonen 2009) The amount of reject is about 4 – 10 % depending on the raw material, but the share of it has been increasing constantly. Thus, there can be secondary pulpers for removing bale wires and rejects. Bale wires can be removed before pulper or during the pulping with a ragger. The ragger uses a rope that spins along with the mass flow of pulper and is being pulled out from the pulper conveying attached wires and contaminants at the same time. (Pesonen 2009) The pulp suspension from the pulper is pumped to the high-consistency (HC) cleaner where large and heavy weighted contaminants, such as rocks and steel pieces, are removed. HC cleaning is commonly a two-stage process after which the pulp goes to the coarse screening. In this stage, medium sized coarse particles and contaminants are removed from the pulp, and flakes are defibred aiming to minimize fibre losses. The pulp goes further to the centrifugal cleaning for removing remaining heavy particles and sand after which it is fractionated. During the fractionation, short and long fibres are separated from the suspension. Short fibres are thickened to the consistency of 10 %, whereas long fibres are led to the fractionation. Simultaneously, remaining reject particles and stickies are removed. Afterwards, the long fibres are dispersed, and the consistency is raised to 30 %. Remaining particles are shredded at the high-speed heating system to the point of invisibility, usually below 70 µm. After dispersing, the long fibres can be refined before feeding to the paper machine. (Senior technology manager, Appendix 2) The purpose of refining is to improve the fibre properties, particularly strength properties. Overall, the proportion of coarse reject in the OCC process is about 5 %, which comprises small plastic particles, sand and stickies. The fibre loss is about 2 % and roughly estimated about 40 % of the total reject amount. The final yield of the process is around 90 %. (Senior technology manager, Appendix 2)

In the case of DIP, the process is normally applied to newsprint. However, the amount of newsprint has been decreasing due to the decreased collection of collected household paper. Fluctuations in the availability of raw material has brought about changes to the traditional DIP lines. Thus, there are different concepts for DIP lines depending on the raw material and its requirements for the final application. Nowadays, most of the collected household paper ends in tissue manufacturing. In Finland, there are DIP lines at the tissue mills of Essity in Nokia and Metsä in Mänttä, while there are OCC -lines at Stora Enso fluting mill in Heinola and at Corenso board mill in Pori. (Senior technology manager, Appendix 2) The DIP process uses typically a high-consistency pulper that is either a continuous drum pulper or a tub-type batch pulper. As in the OCC line, the DIP line includes HC cleaner and coarse screening after which the pulp goes to the flotation. The flotation is a separation method for removing printing inks from the pulp suspension. Air is injected into the pulp suspension and hydrophobic inks are attached to air bubbles that rise to the surface. Formed foam containing inks and impurities are then removed from the surface. The ink removal is commonly conducted in two-stage in which the foam from first flotation stage is supplied to the second stage. Furthermore, contaminants and ash from previous stages are removed in the second stage. The pulp coming from the main or first flotation stage goes through a centrifugal cleaning and coarse screening where sand and other rejects are ejected from the process. (Metso 2019; Meyer and Turnbull 2018; Voith) In tissue mills, there can be a washing stage before or after dispersion depending on the quality requirements of the paper waste grade. The quality requirements of paper waste grade and end product determine whether the process is one- or two-looped. In the case of higher quality requirements like tissue made of office paper or newsprint, the process comprises two loops. One-loop process is applied to collected household papers to make towel paper, for instance. Afterwards, the pulp is dispersed, and remaining stickies and inks are broken down into smaller pieces and detached from the pulp fibre. The final pulp is bleached to increase the brightness. The bleaching is usually done using peroxide after which the pulp is diluted. In the case of tissue mill, the pulp is supplied to the washer to remove remaining ash. After washing, a reductive bleaching can be done to higher brightness requiring paper grades. (Senior technology manager, Appendix 2)

3.2.4.2 Innovations and developments during the past 20 years

The DIP and OCC process have become quite established in the 21st century. The process itself has not faced any major changes apart from the adoption of some technologies that have improved the process further. As an example, the treatment of reject fractions has especially emerged in the 21st century. More attention has been paid on the separation of rejects into distinct fractions, for example into compostable waste and pure material streams that can be further processed. When considering technological developments of the field, the use of **drum pulper** has become a trend in the OCC process. More attention has been paid to the dissolution of brown stock or OCC, since it is more difficult to dissolve. Drum pulper has been used to dissolve collected household paper in the DIP process for long time. In the OCC process, the technology was first implemented about ten years ago, but it has increased significantly within 3-4 years. The idea of drum pulper technology is the efficient dissolution of stock that is separated from impurities in a different outlet. This has improved the energy efficiency of process. Energy efficiency or energy saving has been achieved in the side of water management. The **ultrafiltration** is a technology for paper machines' water treatment to reduce freshwater consumption by purifying the circulating water. Ultrafiltration has been already used in board mills, but it has been later modified for tissue mills. Besides the benefits in freshwater consumption, the technology has brought savings in energy consumption, since less energy is needed to heat the fresh water. On the refining side, a new concept for refiner called **OptiFiner Pro** has been developed and has been already on the markets for six years. The new refiner enables an even treatment of stock and improved refining of fibres with lower energy consumption. It is stated that 30 % of electrical energy saving can be achieved with the refiner. Energy savings have also focused on pumps which energy use should be low as possible. Due to this, a distinct trend has emerged in high consistency processing. For this, a **centrifugal cleaning** technology and **disc filter** have been developed. Disk filters were used for pulp thickening before conducting a centrifugal cleaning in a low consistency. Within five years, the consistency has increased from about 1 % to 1.5 % implying smaller equipment and less pumping to be required. The increase in the consistency has also led to the development of **foil and basket technology** in screening and fractionation. The foil and basket technology are applied to fine screening where stickies and small particles are removed. The technology is based on the function between a rotor and foil and basket and wires, which enable ejection of rejects efficiently from pure stock. (Senior technology manager, Appendix 2)

Increase in the technology and equipment capacities can be considered as the main achievements in the field. These have derived partly from customers who demand lower production costs and better production efficiencies and partly from manufacturers. It is strategically essential for manufacturers to be a leader in energy consumption, and therefore, the development work has focused on achieving less fibre loss and lower energy and water consumption. Moreover, the nature of development work has changed. The development work was carried out in-company in the 21st century. Joint ventures and other joint projects emerged more in the 2010s when customers have been also involved in RTD -projects during the past 3-4 years. Nowadays, the development work or precisely basic research is conducted in a cooperation with universities and research institutes even across the countries. Manufacturing companies have usually their own pilot plants where they benchmark the performances and changes of equipment. Typical performance indicators used in the recycling fibre process are separation and energy efficiency and different quality parameters. More quality describing parameters have emerged and their measurement have improved during the past decades. The development has occurred in the control and optimization of raw material and processes due to automated and systematized measurement techniques and expanded data processing. These are associated with Industrial Internet that has emerged as a new trend in recent years. Furthermore, environmental awareness, circular economy and sustainable future will have an influence on material use and recovery. (Senior technology manager, Appendix 2)

Currently, the use of recycled fibre in the paper and board manufacturing has increased. According to the statistics of 2018, the use of recycled fibre covered about half of the paper and other industrial uses as well as packaging materials in Europe. (Finnish forest industries 2019a) The availability of recycled fibre is strongly influenced by global markets. Current situation regarding the availability of recycled fibre seems to be on a good basis. This has been a consequence from changes in the global market in 2018, when China started to restrict imports for recovered paper and other wastes. China has been a huge importer of OCC that has been mostly exported from the USA. After the banning in the early 2019, the North American raw material for recycled fibre has been more available globally. Despite of the incident, the availability of recycled fibre is a territorial subject, and the markets for recycled fibre behave according to customers' needs for a specific raw material that are defined in EU standards. In Finland, wastepaper collection is managed and owned by paper companies that aims to use their own recovered paper grades in their production. (Senior technology manager, Appendix 2) However, unbalances between recovery and use will always be present. This appears in an oversupply or shortage of some recovered paper or board grades. Therefore, some recovered paper and board grades are imported into the country and exported to other countries. In general, the trend in the recovery degree of paper and board seems to be increasing. Higher recovery degree leads to deterioration of quality and increase of recovered mixed waste that is suitable only for brown stock. At the same time, the amount of fibre loss and impurities, including the share of oil-based inks in recycled fibres, increase leading to the need for more accurate separation. This set challenges to manufacturers to find solutions for possible problems and might further bring extra costs in investment. (Senior technology manager, Appendix 2)

3.2.5 Papermaking

3.2.5.1 Technology overview

The paper manufacturing is carried out either in the integrated or non-integrated paper mill. In the case of an integrated mill, the pulp is pumped from a pulp mill through a pipe to the paper mill without a need for a separate bale handling and pulping system. For a non-integrated mill, the pulp is delivered to the paper mill in the form of bales that must be handled in the stock preparation system before being pumped into the paper machine. The stock preparation begins with bale handling that covers the stages of dewiring and destacking of bales, metal detecting and feeding of bales to the pulper. Baled pulp is further slushed in the pulper where baled pulp is disintegrated into a pumpable fibre slurry and then pumped to the pulper dump chest. If there are fibre bundles or flakes remaining after slushing, defibration or deflaking is needed before refining. In refining, the properties of pulp fibres are modified to improve the strength of fibre network, smoothness of paper surface or formation of paper base. First, fibres flowing through refiner are selected from the grooves of refiner bars and are compressed and sheared between filling bar surfaces of refiner. Refined pulp goes then to the pulp chest or proportioning chest, where its consistency is adjusted, and it is diluted to a proper concentration to the blending chest. Each pulp type has typically a separate proportioning chest where pulp components, such as different pulp types and additives, are proportioned according to the paper grade requirements. Subsequently, the pulp is screened and cleaned for removing impurities. (Paulapuro 2008) Mixing and dosing of papermaking chemicals can take place at different points, but they are normally carried out before the headbox.

The actual web forming begins from the headbox of paper machine which main task is to distribute the pulp suspension evenly on the wire. The consistency of pulp suspension is typically 0.2-1.5 % when entering the headbox of paper machine. Headbox is located between the wire section and short circulation. On the wire section, water is removed from the pulp suspension by filtration or thickening resulting in a formed wet web. The consistency of the pulp suspension is around 20 % by filtration. Filtered water through the wire called “white paper” contains fibres, fillers and heat that are collected and reused for pulp dilution and supplied to the headbox before feeding into the paper machine. Circulation of white paper is called short circulation. The water from the web is further removed in the press section which is followed by drying section. After dewatering of pulp in the press section, the consistency increases to 35-52 %. The remaining water is removed in the drying section through evaporation that can be conducted in a cylinder-, air- or radiation dryer. After drying section, a small amount of moisture remains in the paper. Thus, the final consistency of a paper web is 90-95 %. (PI-Consulting Ltd 1997) The main sections of a papermaking process are illustrated in the Figure 19.

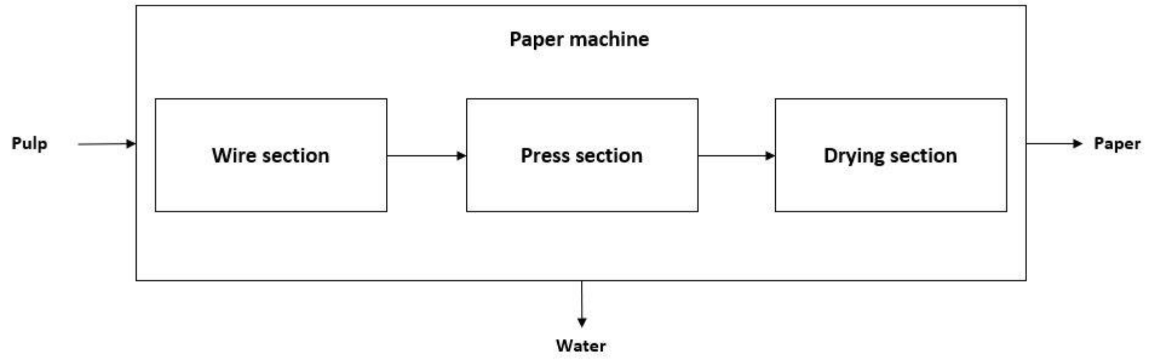

Figure 19. Schematic diagram of a paper machine sections.

3.2.5.2 Innovations and developments during the past 20 years

Although the main papermaking processes have remained very much the same, there have been continuous developments in the field over the past 20 years. These developments have been strongly driven by energy efficiency and environmental factors. The papermaking processes should consume less water, less energy and less raw material. In addition to these, production costs and quality improvement are considered to form the basis for development. An example of innovation developed based on these is the **TrumpJet Flash Mixing** system that provides an advanced mixing technology for mixing of papermaking chemicals. While conventional mixing of chemicals operates in a low volume and low speed of chemicals resulting in a low penetration and ineffective mixing, the TrumpJet mixing operates in a high volumetric injection flow created in a mixer resulting in a rapid mixing of chemicals. The mixing of chemicals into the main mass flow is achieved in one second. Compared to the conventional technique, where the mixing flow might be around 1 litre of pulp per second, the mixing capacity of TrumpJet is around 2,000 litres of pulp per second. (CEO, Appendix 2)

There has been a long delay time between mixing and web formation in the conventional method. This is partly associated with the charged chemicals which dosing points must have had a long distance from each other for about ten seconds to avoid reaction of charges. In the TrumpJet technique, the chemicals are brought close to the paper machine for about two seconds delay to the headbox. The same results were achieved with the TrumpJet but with 15 % less consumption. The installation of the mixing system near to the headbox was called as a **TrumpJet Flash Mixing Reactor**. With a high mixing speed, the properties of chemicals can be maximized reducing the chemical dosage. Furthermore, injection and mixing of chemicals is carried out in the circulated headbox flow eliminating the need for fresh or filtered water. Considerable amount of savings in energy, chemicals and water consumption have been obtained with the TrumpJet mixing system. Overall, reduction of 20-60 % in chemical consumption is achieved and 100 % of freshwater consumption in chemical dilution is achieved. Energy and chemical savings have been a significant method for paper mills to improve their economy when the demand for paper grades have been constantly decreasing. (CEO, Appendix 2)

Regarding the economy of paper mills, lower production and investment costs have been another major milestone. This has been achieved through an innovation called **In-Line PCC** process. The process generates a fibre-filler composite structure that can improve the properties of paper and board considerably. (CEO, Appendix 2) Precipitated calcium carbonate is normally produced in a plant of PCC -supplier located next to paper mill where calcium carbonate sludge is pumped from the plant to customer's process. PCC crystals are obtained by slaking lime resulting in lime milk that is carbonated with carbon dioxide obtained from the customer's power plant. In the In-Line PCC -process, pure carbon dioxide and lime milk are supplied directly via short circulation to the headbox. Thus, the PCC process can be integrated directly to the paper production line creating opportunities to reduce investment and product costs. (Wetend Technologies)

In the forming section, a **Sleeve Roll** -technology has been introduced to improve dewatering capacity and to reduce energy consumption. Sleeve Roll -technology is an extension from the OptiFormer Hybrid with blade technology that has been used in the forming before. The OptiFormer Hybrid technology equipped with a top forming unit has been replaced to a sleeve roll which outer layer is a sleeve-like. Dewatering pressure is obtained with the help of a shoe lied between roll and sleeve. Due to Sleeve Roll -technology, a vacuum top forming unit is no longer needed. (Valmet 2019b) Another technological development related to the forming section has been a multilayer solution applied to the headbox. **Multilayering** can be conducted with the same headbox without a need for additional headboxes. This technique itself has been developed 20 years ago but its commercialization has taken place in the 21st century. Furthermore, **deaeration system** has been improved in the papermaking process. (Senior purchasing manager, Appendix 2) In general, air and gases must be removed from the pulp to avoid formation of defects on the paper and papermaking process.

Deaeration process takes place in the depressurized deaeration tank of short circulation where vacuum pumps are often used. (KnowPap)

During the last decade, new opportunities have been sought from the **foam forming technology**. The technology was originally developed in the USA in the 1970s but was later reintroduced for research. In Finland, the first demonstration of the technology was conducted during 2008-2009 after which it was carried out for piloting. The pilot plant of foam forming technology was built in Jyväskylä in 2013 where the existing research environment was converted to be applicable for foam forming. (Vice president research, Appendix 2) The foam forming technology is based on the process in which water-fibre suspension is aerated with a considerable amount of tiny bubbles. Tiny bubbles prevent flocculation of fibres and enhance dewatering enabling production of light weight structures. (Metsä Board 2015; Wetend 2015) It has been demonstrated that the technology enables production of highly porous and thick fibre structures, while creating opportunities to reduce raw material and production costs. In recent years, there has been a project which aims to find out applicability of the current paper and board machines for foam forming conversion. The technology provides opportunities to paper and paperboard manufacturers to develop new types of fibre products which have potential to enter new markets (Poranen et al. 2013).

3.2.5.3 Drivers and main achievements during the past 20 years

Despite long-term reductions in the paper production capacity, there has been enormous technical progress in paper machine. As an example, Table 3 shows the developments taken place in the production of uncoated fine paper machines in 1980-2020. When considering the development of uncoated paper machine, the capacity has more than doubled in 20 years. Meanwhile, water consumption has reduced significantly. Efforts have been made to reduce the use of freshwater and the production of wastewater by implementing new and more efficient technologies to achieve high consistency in the paper machine and to recycle process water in internal purification. In general, more attention has been paid to the energy use in the papermaking process. Energy costs account for approximately one fourth of the total manufacturing costs, and therefore, continuous improvements have been made in simplifying processes by reducing number of components and increasing component efficiency. Currently, electricity is consumed mainly in drives and pumps. (Karlsson 2000) There has not been many changes in the width of paper machines in the past decade. The current width appears to be set up to 11 metres. Instead paper machine speeds have increased substantially and will continue to increase in the near future. (Senior purchasing manager, Appendix 2) Apparently, there are ongoing paper machine grade conversion in Oulu where the speed of new machine is expected to be 1,300 m/min (Valmet 2019c).

Table 3. Development of production parameters of uncoated fine paper machines 1980–2020 (Source: AFRY).

Uncoated fine paper	Capacity (1000t/a)	Water consumption (M^3/t)	Electricity consumption (MWh/t)	Speed (m/min)	Width (m)
1980	150–200	40–60	0.9–1.1	600–700	5–6
2000	400–600	20–30	0.7–0.9	800–900	7–9
2020	1 000-1 200	10–12	0.6–0.7	900–1 100	9–11

When considering the development of papermaking globally, the growth in paper has emerged later in Asia where larger and more modern machines have been able to develop. Contrary to Western countries where machines can be very old, and thus, the focus is on smaller development steps inside the mill. Environmental friendliness has come to the fore in paper mills through which the use of raw material and materials have become more effective. Less waste is generated, and more waste is recycled. Part of these developments have been come from legislation and part from company's own will. Competition has always been behind the development of papermaking. In the past, the growth in paper machine size was associated with the competition. It is no longer about the size, but it is efficiency or precisely cost efficiency that drives the development of papermaking. Although new paper machines are no longer built, paper machine capacities have been increasing. The same applies to paper products. New paper products are not expected to emerge except entry of some new markets like label printing or paper for special printer. Developments in this area have associated with the quality improvement. On the other hand, new paper products are expected to emerge on the further processing side. As an example, electronics and intelligence are added to the paper as well as odour. In addition, there is also an architectural sample book that utilizes paper to model a three-dimensional building. All in all, possible future thing may be in printed electronics. The remaining paper machines could possibly be converted into paperboard machines, some could be shut down or start producing something completely different. (Senior purchasing manager, Appendix 2)

3.2.6 Paperboard manufacturing and converting

Paperboards are manufactured on paperboard machine through the same process to produce paper on paper machine. Paperboards differ by higher square weight and end use. In general, paper or paperboard product is designed in such a way that it functions for the purpose for which it is intended (Director of technical marketing and packaging services, Appendix 2). There are various paperboard types that are classified according to their end use, for example folding boxboard is intended for setup boxes, linerboards for corrugated board boxes, and special boards for special end use. Paperboard grades have different requirements for their products indicating paperboard machine to be much larger and more complex than paper machine. (Director of technical marketing and packaging services, Appendix 2) Regarding developments in the paperboard manufacturing, single layer technique applied in the web forming was gradually displaced by multilayer web forming in the 1980s. The technique was applied first to chemical pulps, but later to other pulp types as well. (Project manager, Appendix 2) Multilayering technique enables better optimization of product properties, and therefore, its use has become more common in the paperboard manufacturing. (Director of technical marketing and packaging services, Appendix 2) By the late 1990s, mechanical pulp was added to paperboards along with chemical pulp. Subsequently, CTMP came in to enhance the bulk properties and stiffness of boards. This has allowed the square weight of paperboards to be reduced with the same stiffness or at the same time with increased stiffness. During the 21st century, the square weight has decreased in paperboards and the stiffness has increased along with the printing properties. Probably the most substantial change occurred within 20 years has been the trading in the paperboard industry. Trading by tons has shifted to squares. In other words, the benefit is achieved with lower square weight that meets the requirement of stiffness. This has certainly applied to the manufacturing of linerboards and cardboard cases, which has had an impact on consumer packaging and end-use. Over these developments, the requirements have been increased considerably not only in the board industry, but also in the food industry, which requirements reflect directly to the packaging manufacturers. Requirements for the product cleanliness and safety, such as taste and odour in the food packages, have been increasingly demanding in all respects. (Project manager, Appendix 2) These have led to the launch of **ecobarrier** products that can be used to replace plastic products in food packages, for example. (Director of technical marketing and packaging services, Appendix 2)

From the perspective of equipment suppliers, production efficiencies and capacities in the paperboard manufacturing have taken a huge developmental leap during the past 20 years. Old and narrow paperboard manufacturing machines have been replaced with more effective and rapid machines. The development of machine speeds has not been the first in order of priority, but rather how much tonnes per hour can be produced. Tonnes per hour is one of the indicators used in the paperboard manufacturing. In addition to this, profits and prices are usually tracked. (Director of technical marketing and packaging services, Appendix 2) For the process, different efficiency indicators are used, for example overall efficiency that is composed of time efficiency and material efficiency, and the multiplication of these indicates the improvement in efficiency. On the other hand, the overall benefit can be observed in the profitability of business. The profitability of business involves quality issues that are usually pursued by customers. Customer satisfaction plays an important role in this. Customers are not heard just through feedback or claims, but they are rather considered as partners in cooperation. (Project manager, Appendix 2) In future, cooperation is carried out with value chain actors, while the management of the entire chain will be more visible beginning from certified forestry to final product.

Potential growth prospects are in replacing plastic materials with renewable and recyclable materials in products. This promotes the use of paperboard which demand has been continuously growing and will continue to grow along with accelerating trends and megatrends like urbanization and digitalisation. These trends will bring about changes in commerce and distribution systems where e-commerce will increase demand for packaging products and solutions as well for intelligent solutions. **Intelligent packaging** solutions have already been adopted in several industries particularly in logistics and storage. By integrating a chip or RFID tags into packaging products, the location of products can be tracked, and thus, the supply chain can be managed. (Sales manager, Digital lead and Account manager, Appendix 2) The field of intelligent and communicating packaging is developing continuously particularly in food, medicals and pharmaceuticals to indicate the shelf life of products. Food industry or food service has become a new business area for the paperboard industry during the past few years, where the trend in replacing plastics with renewable materials has been gradually growing. This has promoted the use of renewable and recyclable paperboard material in food packaging that is finished with ecologic barrier and barrier properties. Innovative solutions have not only emerged in products, but also in the design. With enhanced **packaging design**, the structure of product packaging can be simplified and lighten. Additionally, possible plastic component can be removed and recycled in its own stream. In future, the use of paperboard will be driven by regulation, especially the Single-Use Plastic Directive that is gradually coming into effect, as well as consumers, who are demanding for more environmental and sustainable options in the end products. (Director of technical marketing and packaging services, Appendix 2)

3.2.7 Paper coating and finishing

3.2.7.1 Technology overview

Coating is applied to the paper's and paperboard's surface based on end-use requirements of wanted product. Considerable changes can be adjusted to the substrate's surface, but the extent of them depend on the type and amount of coating components, coating equipment and finishing treatment. In general, visual appearance and quality of the paper improve as the coating fills the cavities and covers the surface of base paper. It is assumed that 50-80 % of the coated paper properties depend on the base paper properties. Therefore, the properties of base paper are crucial in the end-product profile. Among the components of coating, pigment is the most important regarding the visual appearance and printing properties. Pigments are usually mineral based, for example kaolin and calcium carbonate. Other coating components are binders, additives and water. Surface sizing is commonly applied to the paper web surface before coating. Unlike coating, size mixture does not contain pigments, but it consists of water-soluble binding agents like starch or other chemicals like cellulose derivate carboxy methyl cellulose (CMC) or polyvinyl alcohol (PVOH). Surface sizing is carried out as a pre-treatment for modifying surface properties of the substrate. In the surface modification, the size mixture aims to reinforce the bonding between fibres that affects the strength properties of the substrate. (Paltakari 2009)

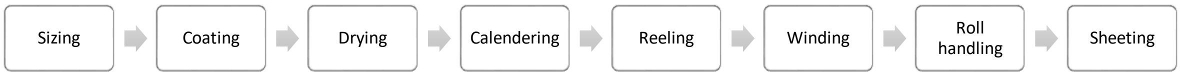

Figure 20. Process flow of paper coating and finishing.

Figure 20 describes the overall process of paper coating and finishing. The coating process comprises phases of application and metering of coating colour and drying. The type of application determines which coating station is used in the application of coating colour. Most common type of coating station has been a blade coater. Other coating types are rod, film transfer, air brush and curtain coater, respectively. In which station is the metering carried out, depends on its position in the coating process. Metering can take place in a metered size press and in a gate roll press, if it is applied before the application (pre-metering). Metering after the application, ‘post-metering’, can take place in a blade coater, rod coater or in an air brush coater. A simultaneous metering and application take place in a short dwell time applicator and in a conventional size press. (Paltakari 2009) Originally, the short dwell coating was developed to improve the runnability of printing paper lines and to reduce amount of line breaks. Thus, it was implemented into blade or rod coaters. The coating can be single or double-sided depending on the requirements of a specific paper grade. Printing papers are commonly coated for both sides, whereas single side coating is characteristic for paperboards. In a double-side coating, both sides can be coated at simultaneously or one side at a time. Following the application and metering, paper and paperboard are dried. Drying can be carried out in various dryers which are either air or infrared based. Infrared dryers are commonly used as first drying units and air dryers as following drying units. Final drying is carried out in a cylinder dryer in which the final moisture content of coating is adjusted. As one side of a paper or paperboard is coated and dried, the other side will repeat the same operations until desired number of coating layers have been applied to one or both sides of the substrate. Coating can be either single or multi-layered or combination of these depending on the end-product. Once desired number of layers have been applied, the paper and paperboard are reeled. (Paltakari 2009)

Paper and paperboard web are rarely ready to use after coating. Thus, calendering is conducted to optimize surface properties, such as smoothness and gloss, and printing properties and to control the caliper (thickness) profile of paper. In calendering, the thickness of paper web is reduced by a plasticizing effect and mechanical compression work from a nip system of two or more rolls. The result of reduced thickness is seen as in improved surface and printing properties and in reduced stiffness and optical properties. According to common classification, calenders can be divided into pre-calenders and final calenders. Additionally, calenders can be either on-machines or off-machines of which the first one refers to a process in the paper machine and the latter refers to a separate calendering machine. The purpose in pre-calendering is to modify paper properties before surface sizing and coating, whereas final calendering modifies the properties for further printing and converting. The variety of calenders have expanded as requirements for higher paper grades and capacities have increased. First calenders were equipped with two or more hard metal rolls in a nip system which was soon followed by invention of supercalenders. More effective calendering process was obtained with supercalenders that were multi-roll calenders equipped with alternating hard and soft rolls. Subsequent calendering technology developed was a multinip calender with polymer rolls. Contrary to supercalenders, multinip calenders are off- and on-machine types, whereas supercalenders are off-machines. (Jokio 1999)

For all types of paper grades, reeling and winding are required to convert paper web into an easier form to handle. At reeling, large-diameter paper rolls, so-called parent rolls, are produced with the reel by winding rolls to the reel spools and forwarded to the final winding process. At the winding, parent rolls are slit into a suitable width and length for customers. Winder is used to produce these customer rolls that are wound on cores. There are essentially two types of winder; two-drum and multi-station winder of which the latter is used for more demanding paper grades. Paper or paperboard rolls are either delivered for customers or finished at the mill for sheeting. Sheeting is usually conducted for any type of printing papers, commonly for commercial applications. Final finishing stage includes roll wrapping and handling systems which intention is to provide rolls a protective wrapping against climatic and mechanical rigours emerged during transport from winder to the warehouse. In addition, the rolls are labelled according to the purpose of end-use to ensure accurate logistics during the transport. (Jokio 1999; KnowPap)

3.2.7.2 Innovations and developments during the past 20 years

Up to the date, most innovations adopted in the paper coating and finishing are based on the techniques developed during the 1900s. Therefore, a historical view on the development in coating techniques and finishing process is necessary for understanding origins of current innovations. Speaking of developments in coating techniques, the first substantial leap was **blade coating**. In blade coating, a considerable amount of coating colour is applied on the surface of track and 90-95 % of it is scraped off. The technique has rooted from the 1950s and has been one of the basic coating techniques for many decades. As the production of coated paper grades increased, the demand for improved coating techniques became more central. As a result, a **short dwell coating** was developed from the blade coating by adding a short dwell time applicator into the blade coater. (Senior technology manager and Senior development manager, Appendix 2) The technique bases on a very short dwell time between application and metering of the coating colour. (Kuusipalo 2008) The coating process takes place in a small coating chamber in which the coating colour is applied to the web surface just before the metering blade doctors excess colour away. This caused less breaks in the process referring to improved runnability, but at the same time, a slight decline in the quality was observed. Improved runnability was also obtained with **film transfer technique**. Film transfer technique was originally for surface sizing, but its applicability in paper coating was discovered, when on-machine techniques became common. In film transfer technique, the coating colour is applied to the roll surface as a thin film and transferred to the paper web surface in a nip. Thin printing papers were mainly manufactured with this coating technique, but the coating quality and coverage did not reach to the ideal level. Development of coating techniques called attention of machinery manufacturers in the beginning of 21st century from which **curtain coating** was developed. Curtain coating technique originates from the 1950-1960s and has been especially used in the preparing machine for coating multi-layered photographic papers. In the curtain coating, the coating colour is extruded from the nozzle in a curtain-like method to the paper web surface. The principle of this technique is "everything that comes from the nozzle, remains in the paper surface" (Senior technology manager and Senior development manager, Appendix 2). It is almost a contact-free application technique, since the paper web is in contact only with the rolls and coating colour (Paltakari 2009). The curtain coating was first used in paper coating and later for paperboards. It became a popular technique particularly, when high coverage and layering were desired properties. Additionally, layering of multiple layers at once was viable with this technique. Today, the technique has two application areas: paperboards and special papers. Among special papers, thermal papers are most typical application area of this. In the case of paperboard, the curtain coating is used especially for obtaining high coverage and grease, moisture or gas repelling **barrier properties**. Another coating technique developed, particularly in Finland during the 1990s, was **spray coating**. Spray technique also belongs to the basic techniques used in surface sizing, particularly. The size is sprayed directly to the roll surface through nozzles, where it transfers from the nip to the paper web surface. The spray coating never made commercial success. The problems emerged in the quality and especially in the coating colour which should have been less viscous. In this case, higher water consistency of coating colour was problematic due to the excess water needed to be removed. Additionally, the technique suffered from cleanliness challenges. (Senior technology manager and Senior development manager, Appendix 2)

Prior to coating, it has been noticed that more attention should have been paid to calendering, since both processes impacts mutually on each other. During the 1990s, the development of **polymer coatings** for rolls enabled manufacture of printing papers and improvement of the whole calendering process. Further development targeted at control and design of calenders as well as coatings of rolls. Polymer coated rolls were implemented into the paper machine at first which calenders adopted later. Another invention adopted from the paper machine was a shoe press that was modified to **shoe nip calender**. (Senior technology manager and Senior development manager, Appendix 2) The shoe nip calender is a long nip calender in which the nip is formed between thermo roll and shoe roll. Despite of the benefits (including low roughness and high gloss) that the shoe nip calender provided, it did not become commercially successful. (Jokio 1999) Nevertheless, the technique was sold for a while during the end of 1990s and 21st century. New kind of calendering process, **metal belt calendering**, was developed during the 21st century in Finland. In metal belt calendering, a conventional calendering nip is replaced with a one-metre-long calendering zone. This zone is formed between a heated metal belt and heated thermo roll that enable calendering of both sides of web simultaneously. A significant preservation of bulk and stiffness can be obtained due to extended dwell time and effective plasticization of web surface, which further contribute to significant savings in raw material. (Jokio 1999) Currently, the metal belt calendering is used particularly in paperboard making to achieve lighter end-product and higher surface quality. (Senior technology manager and Senior development manager, Appendix 2)

In the 1990s and 21st century, the development of new reeling concepts made available more alternative reeling parameters, which subsequently enabled reeling of large diameter rolls. Recently, a new type of reeling concept, **linear reeling**, was developed in Finland. This new type of reel is simpler, more reliable and applicable to handle large diameter rolls. Development of reels has been focused on the development of technology for demanding rolls and for reducing reel changes. The increase in running speed has brought challenges in the development of reels, especially running speeds of demanding paper grades. As for the winding, a new type of winder, **WinBelt**, was developed during the 1990s. In the conventional (two-drum) winder, the roll is formed on two drums. As the roll diameter increases, the roll weight increases causing a nip load at the drums. For this, a belt-supported winding, in which the winding geometry is modified by replacing the front drum with a belt-bed, enables distribution of the nip load from drum to belt-bed. The nip load of belt-bed can be controlled by belt tension that allows reeling of large diameter rolls with low nip-induced defects like crepe wrinkles. (Jokio 1999) A reasonable innovation during this decade has been **dual unwinding** technology that minimizes the time of parent roll change. This is based on an automatic load of the primary unwind stand with a parent roll received from the second unwind stand. This increases the capacity for winders and the whole production. (Senior technology manager and Senior development manager, Appendix 2)

Some recent inventions from this decade has been **aqua cooling calendering** that is based on cooling of web before calendering. (Senior technology manager & Senior development manager, Appendix 2) Better calendering results can be achieved by evaporating water from both sides of the web with cool dry air. In addition, substantial energy and material savings have been achieved through this technology. (Ilomäki and Yamazaki 2015) Regarding the drying of web, **high intensity air dryer** has been the invention of this decade. In general, drying is an energy intensive process and therefore, possible energy savings can be achieved by improving dryers. High intensity air dryers are used to dry the coating of web with hot air blown from air dryer nozzles. (Valmet, Air dryers) A recently released technology for surface sizing has been **hard nip sizing**. (Senior technology manager & Senior development manager, Appendix 2) This method uses hard cover or compensated rolls for reinforcing bonding between paper fibres, which leads to better penetration of starch. The starch is first sprayed on the rolls and transferred to the web with high pressure from the roll nip. (Valmet, Hard nip sizing)

3.2.7.3 Developments, drivers and main achievements during past 20 years

Innovations described previously have indicated how much development work has been put into the processing after the papermaking. What have been done in the development work of this field up to the present and why, have derived from the requirements of the end-product. In the past, the development work was heavily influenced by the current trends and needs according to which various technologies were developed. For example, as the production of coated paper grades increased, more effort was put into the development of coating techniques. As a result, the basic blade coating technique was upgraded by installation of short dwell time applicator, and film transfer and curtain coating technique were developed. These improved the runnability of paper that was one of the most common parameters to optimize in the everyday papermaking. Curtain coating and blade coating (in a slightly modified form) are still sold techniques today. Contrary to short dwell coating, utilization of this technique was phased out due to the overcapacity in the production of printing papers. Coated printing papers are hardly considered as a target for investment, but there is still investment in fine papers at some extent. Among coating techniques, curtain coating can be considered as a breakthrough invention of this century. In addition to the good coverage and layering possibilities that curtain coating provides, the technique enables manufacturing of paper-based products with barrier coating layers. A very dense coating layer is applied directly in the paper machine, when previously it was carried out in a separate post-processing machine or at a different location. (Senior technology manager and Senior development manager, Appendix 2)

Integration of coating machine and calender into the papermaking line as an online section has been the innovation of the 1990s and 21st century. In the past, the paper had to be reeled from the paper machine to the coater and further to the calender. This led to increased yield loss and higher operating and investment costs, as there had been more separate machines in the line. (Senior technology manager and Senior development manager, Appendix 2) In fact that higher production yield is achieved with online machine, its efficiency depends on how well it runs. A break at the line will halt the production, so the time efficiency of machine is lost in breaks. However, technological advances in coating and calendering as well as in papermaking have reduced number of breaks and increased the runnability of machines, and thus, favoured online machine lines over off-line. Integration of both coating and calendering online sections into the machine line is called an all-on-line-machine that has become more common in the manufacturing of various paper grades. The driving forces behind the development of online and all-on-line machines have been the pressure to reduce investment and operating costs. (Jokio 1999) This has been made possible through advanced automation and machine automation as well as control and measurement systems. In general, the automation level of machines has improved greatly in the last decades, thus the safety level and number of monitoring parameters have increased. For these, various indicators are used for different purpose. Production indicators measure produced tonnes and surface areas. Properties associated with the surface area, such as printing area, are considered as more important parameters today. Focus on the development of surface properties contributes to the raw material and energy savings in which case the efficiency appears as a driving force. (Senior technology manager and Senior development manager, Appendix 2)

In the past, the driving forces derived mostly from the business where case higher capacities including higher speed and efficiency were aimed in the development of machines and techniques. Today, environmental issues, such as sustainability, emissions and efficiencies, are more apparent in the development of new techniques and machines. In the future, replacing plastic will become more substantial and at the same time, the recyclability of materials will be more important. (Senior technology manager and Senior development manager, Appendix 2) For the part of machinery manufacturers, these bring challenges in developing techniques and machines to meet the requirements for demanding applications. There has been a need and an opportunity for innovation, but prioritization and investment set limits for it. Time span of the innovation process varies from case to case depending whether it is a device component or new device. It is a process of at least three to ten years to get the idea commercialized. The time span for development is long and customers are therefore involved at the early stage of the development process. Additionally, there are various key performance indicators used as a tool in the innovation development. An indicator of new product sales, for example, implies how much of the sales have been new products and thus is used to evaluate the contribution of innovation activity in relation to the sales and to the growth of business. In addition, firms need to contemplate and understand customer and end-user needs in the development of innovations. (Senior technology manager and Senior development manager, Appendix 2)

Also in the future, the raw material savings and efficiency will drive the development work in the field of paper coating. Savings in raw material is already aimed in the papermaking where reduction in bulk volume has brought challenges. (Senior technology manager and Senior development manager, Appendix 2) High end-product quality must be achieved with less raw materials without deteriorating paper web properties. Raw material savings have been achieved with innovative inventions, such with metal belt and aqua cooling technology in the calendering process. At the same time, these have contributed to the energy savings along with improved drying technologies. Improved technologies in reeling and roll handling have accelerated production capacities in terms of speed and yield, while the reeling can be carried out smoothly and gently. Automation has been a major factor behind these developments, and it will be one of the key factors in the realization of advanced Industrial internet. Industrial internet and remote monitoring are increasing by relying on automation and intelligent automation that keep tracking and monitoring equipment and process performance. The issue at stake is a plant or mill-wide optimization, instead of partial optimization. The development trends will be raw material and energy savings that will be obtained through total process optimization at the mills. Only a few companies in the world work on the process development in this field. There is a lot of investment in process and product development, but less in paper machines. In Finland, fewer invest in new paper machines nowadays, except Kotkamills, whose paper machine is one of the only newest invested lines. The company’s paper machine was converted into folding board machine in 2016 that also produces barrier coated boards. Barrier coatings will play an important role in the replacement of plastics, especially in coating materials. Innovative paper-based solutions with barrier functions have already been introduced on the market, but their actual breakthrough is yet in prospect. (Senior technology manager and Senior development manager, Appendix 2)

3.2.8 Chemicals and other raw materials

In the pulp and paper industry, the use of chemicals varies depending on the quality and properties of desired product or process. Paper industry uses chemicals like coating agents, fillers and additives in the papermaking process, while pulp industry uses chemicals in pulp cooking and bleaching. Otherwise, chemical additives are used to improve process quality and efficiency by maintaining process cleanliness and preventing breaks during the production. Over the past decades, the use of chemicals in the pulp and paper production has been targeted with cost and environmental pressures. With the pressures, new types of chemical solutions have been introduced to the pulp and paper industry leading to significant cost savings. Probably one of the most considerable changes in this area has been the **neutral pH papermaking** through adoption of calcium carbonate as a filler and coating pigment. Papermaking with neutral pH originated from the 1990s and became more common by the 21st century. Before, clay, kaolin and talc that is like coarser calcium carbonate were used as fillers and coating pigments. Subsequently, the neutral papermaking was improved by using precipitated calcium carbonate (PCC). The drivers behind the use of PCC were higher brightness and higher opacity, or in other words, customer and market demand were the drivers. Higher filler loading and better gloss and opacity properties were achieved with PCC. (Business development manager, Appendix 2) Additionally, PCC can be produced on site at the paper mill contrary to traditional fillers and coating pigments. In total, PCC has improved the cost and process efficiency in papermaking. Regarding the retention polymers used in the papermaking, retention agents or aids are added in the wet end of paper machine to improve retention of fillers or other papermaking chemicals. Instead, **structured polymers** can be added in the process to improve the filler loading. Simultaneously, the use of structured polymers reduces the consumption of retention aid. (Business development manager, Appendix 2)

Regarding the process efficiency and process cleanliness, adoption of **oxidizing biocides** subverted the entire field of biocides. (Business development manager, Appendix 2) Generally, biocides are biocidal products used for eliminating micro-organism in various industrial applications and systems. On the other hand, oxidizing biocides have the same principle but work through oxidization process. (Christophersen 2006) There are several types of oxidizing biocides among which monochloramine biocides were introduced into papermaking process to improve process cleanliness. New type of process cleanliness was achieved, which further improved efficiencies of equipment. These oxidizing biocides were originally applied in water treatment but later commercialized in the paper industry. In the papermaking process, oxidizing biocides have been able to generate from two separate components on-site or on the paper machine. (Business development manager, Appendix 2)

Chemicals used in papermaking have also been targeted by environmental and sustainability issues. The share of **biobased raw materials** and their use in paper coating is gradually increasing. The use of biobased starch has been used for long time to replace fossil-based latex in paper. Other biobased raw materials like micro- and nanocellulose as well as microfibrillated cellulose (MFC) and polylactic acid (PLA) have been introduced later in the fossil-based coatings. In recent years, "biobased" and "carbon neutral" alternatives have called attention among end-users and brand owners through which biobased materials come into use. Nevertheless, the share of fossils in papermaking chemicals is still dominating, although the share of biobased is increasing. (Business development manager, Appendix 2)

Bleaching chemicals used in the pulping have been developed for long time. Besides the conventional bleaching methods like elemental chlorine free (ECF) and totally chlorine free (TCF), **enzymatic bleaching** was introduced afterwards. The enzymatic bleaching has been under development for over 20 years, but the actual innovations in it has been its right use and application that have been discovered within ten years. Less bleaching chemicals required in the process, or raw material and cost efficiency through optimization, have been the achievements in this field. (Business development manager, Appendix 2)

The development of chemicals has gone hand in hand with the demand for grades. During the golden period of paper industry in the 1990s, customer driven market opportunity drove the production of graphic paper, in particular of coated fine paper, wherein high brightness, opacity, gloss and printability were obtained with chemicals. Afterwards, the downfall of graphic papers changed the drivers of innovation in the field, where innovations were generated through cost and process optimization. Cost and raw material efficiency are still driving the operations of these industries, especially the paperboard industry, where the environmental profile has emerged as a new issue. A major change has occurred in the understanding of environmental profile of material, its use and its recyclability from the aspect of both brand owners and consumers. With this change, the chemicals side has a huge potential for developing new products and biobased solutions. In addition to this, another major driver will be AI as well as opportunities from digitalisation. Only a fraction of related achievements has been discovered. (Business development manager, Appendix 2)

3.2.9 Automation and digital technology

From the perspective of automation technology and power suppliers, a major change has probably occurred in the focus of the forest industry. While bulk products such as newspaper have been gradually disappeared from the market, speciality products and new wood-based business areas like biofuels have emerged. Over the past decades, the role of special products has become more important than bulk products. Nevertheless, more and more attention are paid to the quality of pulp and paper. Thus, the emergence of new business areas and stricter quality requirements have brought about challenges for suppliers as the customer portfolio has expanded and diversified. At the same time, the portfolio of suppliers has expanded as well. This is partly related to competition and differentiation between companies and industries on how to add value to customers and stand out as a partner. Besides the traditional products supplied to customers, the systems built around them have a great influence on the customer choice. As a result, various systems have been developed for the needs of industries. Automation emerges in process control for which **process control systems** (PCS) and many other systems have been developed. Process control system encompasses various types of controllers and other systems which enable industries to control and manage their processes. In addition to this, **manufacturing execution system** (MES) has been introduced to improve production processes by optimizing process conditions. These systems represent part of the complex that encompasses several operation managerial software and systems. When it comes to digitalisation, **data acquisition systems** and related analysis services have enabled a new way to monitor equipment condition. In the early 21st century, there were no information available on the condition of the equipment during the process. Back then, equipment was serviced based on the experience of suppliers and maintenance personnel according to which maintenance programmes were created. Today's condition monitoring systems are similar to data acquisition systems, where the basis is on a multiple ability to collect data and to monitor equipment status by connecting them to joint systems. The innovation in this is the amount of data generated in the production process which has multiplied over the years. (Sales manager, Appendix 2)

According to the suppliers, the quality requirements of the forest industry have increased, especially for equipment and measuring systems. Nowadays, defects are no longer accepted in the same way as they were 20 years ago. Back then, it was typical that several frequency converters were damaged within a year. Today, no such damage is actually allowed. With increased requirements, suppliers have had to develop more reliable equipment and systems. Regarding quality measurement, very much the same quality parameters are measured today as 20 years ago. However, considerable improvement has occurred in the measuring accuracy. This is due to technological advancements which have expanded the scope of measurement technology. For example, **non-contacting measurement** method has been introduced for thickness measurements. As a continuation of measurement technology, **virtual or soft sensors** have become a hot topic, especially for strength measurement of paperboard. Soft sensors can be used for on-line monitoring of paperboard machine, where the strength parameters cannot be measured directly on the machine, but they can be derived by mathematical methods from other measurements and correlated with laboratory measurements. Furthermore, with improved control algorithms and control strategies, the quality output can be stabilized in a completely different way. (Sales manager, Digital lead and Account manager, Appendix 2)

The development of digitalisation has been a continuous process that has taken over the industries. For the forest industries, automation and digitalisation-based solutions have played an important role in improving production processes, but also in creating a more efficient mill. Future outlook will be focused on support services, and remote support services will increase in particular. Remote services have been already introduced for industrial operations aiming at networking and sharing information between suppliers and customers. Even customers have found that problems are better solved within a group than at the mill level. In addition to remote services, another trend will be predictive maintenance systems that will bring changes to the runnability of mills in the very short term. The aim is to maintain runnability without breaks for as long as possible. In the case of pulp mills, for example, there would be downtime every other year instead of annual downtime. This requires completely new aspect to the usability from the maintenance device. Overall, digitalisation will affect the entire mill enhancing process predictability, maintenance, service and usability, and through this, automation will be enhanced. So far, the number of employees has fallen sharply as the degree of automation have increased. The development of automation will inevitably lead to the point where human labour is reduced for cost-effectiveness. Up to the present, there have been discussions about robotics and how to increase their use in mill operations. In the forest industry, the use of robotics is still at the early stage. Thus, the vision of 'black mill' or mills without physical labourer may not be realized in the same way. Instead, artificial intelligence will emerge at some point to support human assistance. Artificial intelligence will appear as computer-based expert systems that will continuously analyse incoming data mass from production process and propose further steps to prevent process faults and to optimize running of production processes. In the future, changes in the forest industry will also affect the operations of suppliers. From the perspective of suppliers, the general brand and view of the forest industry have become even more climate change preventing and sustainability centred bringing advantages and challenges to suppliers. The current challenge has been the use of forests globally. Regulations on harvesting quota will in some way limit the development of the market implying more efficient energy and resource use from the forest industry. On the other hand, this can support the supplier market that has to offer to meet the challenges of the forest industry. (Sales manager, Digital lead and Account manager, Appendix 2)

3.2.10 Byproducts and further processed products of pulp

Byproducts have been produced for long time alongside pulp production. There is a growing need for efficient use of raw material which in turn has led to the increase in the number of byproducts. This, among other things, has created a new of a pulp mill which is called a bioproduct mill. Traditional pulp mill acts as core of the bioproduct mill where bioproducts are produced from its side streams. Current established bioproducts include tall oil and turpentine as well as bioenergy products in various forms. One of the key starting points of the bioproduct mill is to diversify its product range to new biomaterials, biochemicals and bioenergy products. (European Union 2019) This chapter presents typical byproducts or further processed products from pulping process. New types of bioproducts and bio-based materials will be reviewed in the later chapter.

3.2.10.1 Tall oil and turpentine

Traditional byproducts of pulp are tall oil and turpentine which availability varies depending on the wood species and growth conditions as well as conditions relating to the handling of wood. Tall oil is obtained from the sulphate pulping process of a coniferous wood, where fatty acids and resin acids saponify in the alkaline liquor and separate on the surface of liquor as soap mixture. Crude tall oil is the acidified product of soap which can be further refined into various tall oil products. The products of tall oil can be used in adhesives, paints, varnishes and detergents, for instance. Turpentine, on the other hand, is an odorous fluid recovered from volatile terpenes in off-gas condensers that is further distilled from crude turpentine. Terpenes are organic compounds found in confers' resins. As a major component of turpentine, it is used as a solvent or diluent in paint and pharmaceutical products. (Papermaking Science 2008) In addition to these main byproducts, other established byproducts are cellulose-derivates carboxymethylcellulose (CMC), microfibrillar cellulose (MFC) and microcrystalline cellulose (MCC) and dissolving pulp that are produced from altered sulphate process. Another less attention received raw material is lignin that makes up about 30 % of wood composition. Normally, lignin has been removed in the kraft pulping process and used mainly to produce energy in the recovery boiler. Instead of firing the lignin in the recovery boiler, part of the lignin can be recovered and used for other purposes. (Chief technology manager, Appendix 2) Lignin as well as other raw materials in the pulp production have received a lot of attention in researches during the last decades. Long-term researches in these fields have opened new possibilities for the use of these materials, of which part of them are reviewed in this chapter.

3.2.10.2 Lignin

Extraction of lignin from the black liquor gives modern kraft pulp mills a great opportunity to develop economical revenue by using lignin within the pulp mill to reduce production costs or selling it for external use. With respect to these, a technology to extract lignin from the black liquor called **LignoBoost** was developed. The LignoBoost process is integrated with evaporation from which the black liquor is taken to precipitation. The precipitation is carried out by lowering the pH of lignin with CO_2, after which the precipitated lignin is dewatered with pressure filters and dissolved in the spent wash water and acid for sodium separation. Further treatments are dewatering and washing of the product producing pure lignin cakes. First industrial scale LignoBoost plant was adopted by Domtar that started the production of commercial lignin in 2014. (Decision databases 2015) Second LignoBoost plant was set up at the Stora Enso Sunila mill in 2015 and has a capacity of 50,000 tonnes of dry lignin per year. (Stora Enso 2019) Extracted lignin has numerous application possibilities. Common applications of lignin have been its firing in lime kiln to replace the use of fossil-based fuel reducing the need for purchasing external energy sources and simultaneously reducing CO_2 emissions. In addition, lignin has been used to replace fossil-based phenols and formaldehyde in phenolic resins used for plywood and other wood-based materials. (Business development director, Appendix 2) Other applications and end-use areas for lignin are biofuels, biochemicals and bioplastics, where lignin can be used as additive or structural component. Recently, there has been a project funded by EU that exploits an oxidation technology to convert lignin into workable format for various applications. The lignin oxidation technology **LigniOx** was demonstrated by VTT and exploited principally in concrete plasticizer. Traditionally, expensive synthetic materials or rare organic based materials have been used in concrete plasticizer. The project involves contribution of business partners and companies that provide help in raw material manufacturing and introducing of products to customers, for instance. (Krabbe 2018) (Business development director, Appendix 2) Currently, there are studies on-going related to exploiting lignin in carbon fibre and in many further processed products, but the challenges arise in finding appropriate value chains. Further processing of lignin becomes profitable when there are enough markets for it. Nevertheless, the firing of lignin for energy production remains profitable until the production and market for lignin encounter. (Development manager & Customer service and sustainability manager, Appendix 2)

3.2.10.3 Methanol and sulphuric acid

Besides the lignin, other byproducts of the pulping process are methanol and sulphuric acid. Both methanol and sulphuric acid can be purified and processed further into commercial products. (Chief technology manager, Appendix 2) In the kraft pulping process, methanol is a byproduct waste formed as in digester and evaporator condensate that needs to be disposed or removed. It can be removed either by treating it as BOD – biochemical oxygen demand in the effluent treatment system or treating it in a stripper system that releases methanol as SOG – off-gases. Most mills have incinerated this SOG in the lime kiln or the recovery boiler, which however has not been efficient due to high moisture content of SOG and variability in the produced SOG amount. Besides, untreated SOG or methanol has high nitrogen and sulphur content leading to the higher NO_x and SO_2 emissions during the incineration. Solution for this has been sought from the liquefaction of methanol. The methanol is converted into liquid through a condensation process that reduces the water content of methanol. In this form, the methanol is easier to handle and can be combusted more efficiently in the lime kiln or boiler. On the other hand, methanol can be treated before producing liquid methanol. Valmet with other industry partners has developed a purification process to remove nitrogen and sulphur from the SOG. (Valmet 2018) An industrial scale **methanol purification plant** was installed and demonstrated at Metsä Board's Husum mill in Sweden. (Wennberg 2017) Alternative method for methanol purification is a mineral oil-based extraction process of which first commercial scale purification plant has not been implemented yet. (Chief technology manager, Appendix 2) Purified methanol can be used as a low NO_x fuel for incineration or it can be sold as a renewable fuel or chemical for transportation fuel. The current EU Renewable Energy Directive aims to increase the share of renewables in transportation fuels making purified biomass-based methanol to have a favourable conditions to contribute towards this aim (European Union 2018).

In the Kraft pulping process, sulphur and sodium are the main elements that appear in different forms at various stages of pulping process. Many mills are facing problems related to the chemical balance of sulphur and sodium in the pulping process leading to the intake of purchased chemicals. Therefore, implementation of internal sulphuric acid production can solve the problems in chemical balance gaining simultaneously economic and environmental savings. Sulphuric acid can be produced from sulphur containing non-condensable gases (NCG) that are normally formed during the pulping process. The non-condensable gases are the main source of sulphur emissions causing acidification of soil and release of odorous air emissions. Thus, these harmful odorous gases normally collected and incinerated in the recovery boiler, lime kiln or in a separate NCG boiler. In the incineration of NCG, sulphur compounds are oxidized into sulphur dioxide that is further oxidized into sulphur trioxide through a catalytic conversion and condensed with water vapor to form sulphuric acid. The first large-scale **sulphuric acid plant** started at Äänekoski mill in 2017 and produces sulphuric acid for the production of tall oil. In addition, internally produced sulphuric acid can be used in the production of chlorine dioxide. This has reduced the need of purchased chemicals increasing self-sufficiency of the mill at the same time. (Development manager & Customer service and sustainability manager, Appendix 2) Integration of byproduct plants, such as lignin plant, methanol purification plant and sulphuric acid plant into the pulp mill have been illustrated in the Figure 21.

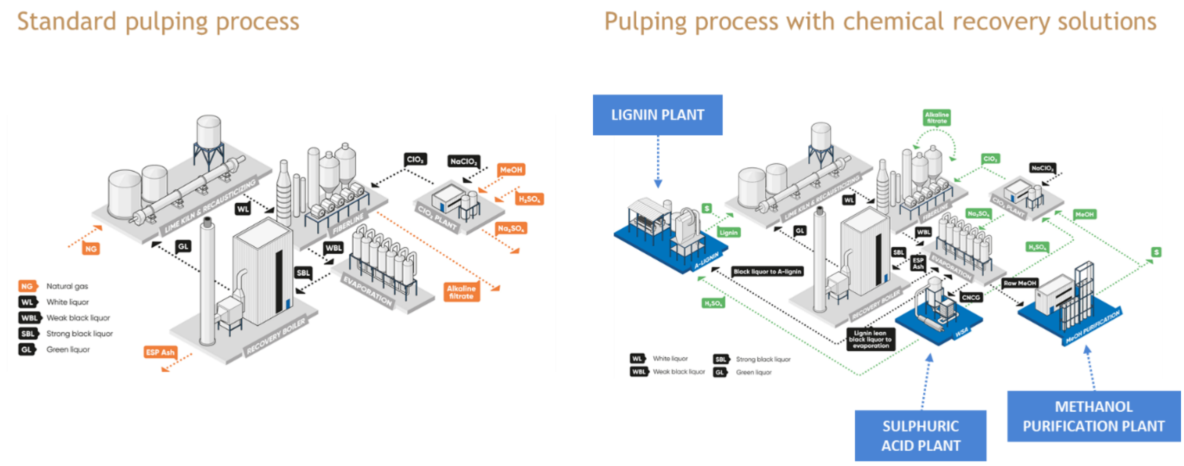

Figure 21. Integration of chemical recovery solutions alongside the pulping process. (Adapted from Andritz)

3.2.10.4 Other byproducts and processes

Among the cellulose-based products, microcrystalline cellulose (MCC) invented in the 1950s has been used widely in pharmaceuticals, food products, cosmetics, paints and oil industrial applications. (Chief technology manager, Appendix 2) It is a purified and partially depolymerized cellulose that is mostly obtained through a hydrolysis of cellulose material with acids. The use of hydrolysing chemicals in the manufacturing of MCC can generate chlorine, sulphur or nitrogen containing effluents impeding the recycling and recovery of chemicals, and thus, causes extra costs. (Vanhatalo 2017) For this, a new method to obtain MCC was developed in the Aalto University. The **AaltoCell** technology works with much lower acid amount saving costs in further process stages. The technology is claimed to have much lower environmental impact compared to the traditional method and provides economical advantage when integrating into the pulp mill. (Vanhatalo 2017)

Regarding the cellulose-based byproducts, dissolving pulp can be produced through a continuous **pre-hydrolysis cooking** in which hemicelluloses are removed and the remaining cellulose is used to produce textile fibres like viscous. In Finland, dissolving pulp has been produced since the 1980s, but the production stopped totally until Stora Enso adopted the production of dissolving pulp in 2012 (Mäntyranta 2013). Initially, there were challenges in maintaining the quality of fibres in the production of dissolving pulp with a continuous cooking. After several years of experiments, the process of producing dissolving pulp was modified resulting in modified equipment components for the continuous cooking. This received a huge acceptance in Asian countries like China where the markets for textile fibres are the largest. Up to the present, about ten pre-hydrolysis equipment has been sold reminding of a great leap that has taken place in the field. (Chief technology manager, Appendix 2) In recent years, the textile fibres have increased their visibility considerably. In general, the markets of textiles are increasing enormously for both clothing industry and industrial textile. Since the production of cotton textiles has stopped up to the point, where it can no longer be cultivated in accordance with sustainable development, it has been replaced with fibre extract like polyester over time. Polyester is one of the materials causing the release of microplastics into the environment. This has boosted Finnish companies as well as start-ups to focus on the development of wood-based textile fibres. (Business development director, Appendix 2) During the last decades, many interesting innovations and start-ups have emerged related to this area. Some of these are introduced in the chapter of innovative start-up companies in the Finnish forest industry.

3.2.11 Energy

Energy saving has in one way or another been a driving force behind many innovations. Energy saving can be interpreted as an effort to improve energy efficiency or to reduce consumption of energy. The forest industry has been constantly aiming at improving energy efficiency by replacing fossil-based energy sources to renewables, recycling water and material streams within processes and utilizing the raw material up to its last fibre. Simultaneously, efforts in energy saving promotes other environmental aspects like environmental protection. Energy saving and environmental protection may have very mutual effects, but this chapter focuses on achievements and developments in the energy field through technological developments.

The forest industry consumed about one fifth of the total electricity consumption in Finland in 2017 (Finnish Forest Industries 2018b). Among the forest industries, pulp and paper industry are the most energy-intensive industries consuming over five times more electricity than other forest industries. The electricity consumption in the forest industry during the 21st century is illustrated in the Figure 22. Since the 21st century, the electricity consumption has decreased by 6,676 GWh. (Finnish Forest Industries 2018b) According to the research that determined the impacts of structural changes like unit closures, start-ups and conversions on energy efficiency in the Finnish pulp and paper industry, the major factor affecting the reduction of electricity consumption was related to the energy efficiency improvements. Structural changes accounted about 20 % of the total energy efficiency improvement, while the remaining 80 % derived from improved technologies and changes in modes of operations. (Kähkönen et al. 2019)

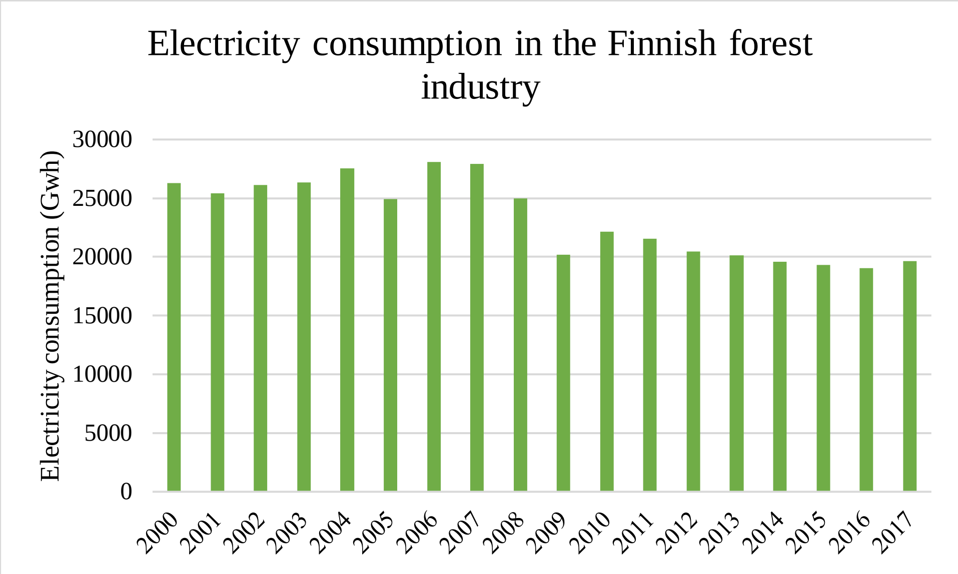

Figure 22. Electricity consumption of the Finnish forest industry in 2000-2017. (Finnish Forest Industries 2018b)

One of the trends among pulp mills or integrated mills has been a target to become fossil-free. A shift towards fossil-free operation has increased the use of mill's own energy sources, such as bark or biomass, in the mill's internal processes. This has brought so-called old technologies to new use, for example gasification of bark biomass. The use of bark biomass in lime kiln gasifier has eliminated the need for fossil fuels in this unit. Alternatively, **pulverized fuel firing** solutions have been used. In pulverized fuel firing, the sawdust is dried and pulverized for firing directly in the lime kiln. This type of solution exists in Stora Enso Enocell mill. Another solution for the use of bark biomass is so-called **steam explosion** system. In the steam explosion system, the bark is directed through drying to further processing where it is treated in high steam pressure. The steam is discharged, and pellets are produced from the bark residue. Another source of energy production is biosludge that can be burned rather than end up as waste to landfill. Despite the fact that many of these are old inventions, the actual innovation has associated with combining of these solutions into complete processes. This generates new types of processes which can be considered as innovations. (Product portfolio and strategy manager, Appendix 2) Adoption of the technologies mentioned has not only increased the share of renewable fuels but also improved self-sufficiency and cost-efficiency of mills.

In the pulp mills, probably the most substantial change has occurred on the energy production side. The amount energy produced in modern pulp mills is over double than the amount of energy required in the processes. (Chief technology manager, Appendix 2) Thus, more surplus energy can be sold. This can be explained with technological improvements of equipment. In modern recovery boilers, higher steam values and higher dry solid contents have led to higher energy output, while the amount of emissions have remained in the moderate levels. More efficient washing equipment have reduced energy and water consumption, while water and filtrates can be washed and reused in the same equipment unit. Furthermore, the use of heat value in the secondary and waste heat sources have had a significant impact on energy efficiency. (Product portfolio and strategy manager, Appendix 2) In the mechanical pulping, adoption of new Galileo grinding technology has resulted in savings of specific energy consumption by 250 – 300 kWh/bdt (Tuovinen 2019). In the papermaking, there has been a continuous improvement in frequency converters. (Digital lead, Appendix 2) Frequency converter is a conventional invention that enables adjusting of rotational speed in electromotors resulting in significant energy savings (Rouhiainen 2010). After all, there have been numerous innovations that have led to either minor or major energy savings. Some of these innovations might relate directly to the energy production, while others might relate to the reduction of energy consumption. Nonetheless, energy savings and energy efficiency will run through the whole energy consumption of the mill.

3.2.12 Environmental protection

There are currently two crucial issues in this field: climate change and circular economy. How the forest industry takes climate change and how it is reflected in the companies' strategies. Furthermore, how to recycle forest industry products and how to realize new life or second life of products. Climate change has been one of the major drivers over the past 20 years, whereas circular economy has emerged more distinctively during the last 5-6 years. Recyclability has become important over these trends. The industry has shifted to the production of more complex products, where recycling of products is impeded by material separation and fibre recycling. (Manager, mill services, Appendix 2) Besides the current and prospective challenges, the industry has taken a great leap in the promotion of environmental protection. An efficient use of water and raw material as well as energy have contributed to the several improvements at the mills. In this chapter, improvements in water use and emissions to water, air and landfill are reviewed.

Regarding the water use, significant change took place in the 1990s when activated sludge plants were introduced to mills. (Manager, mill services, Appendix 2) Activated sludge process is an old technology that is commonly used in wastewater treatment. In addition, ultra- and nanofilters were introduced, but did not break through in the water treatment. (Business development manager, Appendix 2) Furthermore, the use of tertiary treatment became more common, particularly in modern mills. It can be based on flotation, filtering, oxidation or membrane technology, for instance. (KnowPulp; Manager, mill services, Appendix 2) There have been some cases of the use of tertiary treatment for a long time. It is more commonly used in Central Europe and in China. In the meanwhile, Finland has been somewhat conservative in water treatment. At least, membrane technology has been introduced, but it is still under development. Recently, there have been activities on the biogas production from wastewater with **membrane bioreactor** (MBR). (Manager, mill services, Appendix 2) Membrane bioreactor is a biological water treatment that combines membrane filtration and activated sludge process (KnowPulp). There has been continuously an increasing pressure on the water use. A lot of efforts have been made to improve the efficiency of water use in existing mills, but the actual actions are company specific. Each company or mill has its own environmental permits that drive not only the water use but also energy and raw material use. In other words, existing environmental permits must be maintained, for example control of COD load within its limits. (Business development manager, Appendix 2) Figure 23 shows the reductions in COD and other emissions in the Finnish pulp and paper mills.

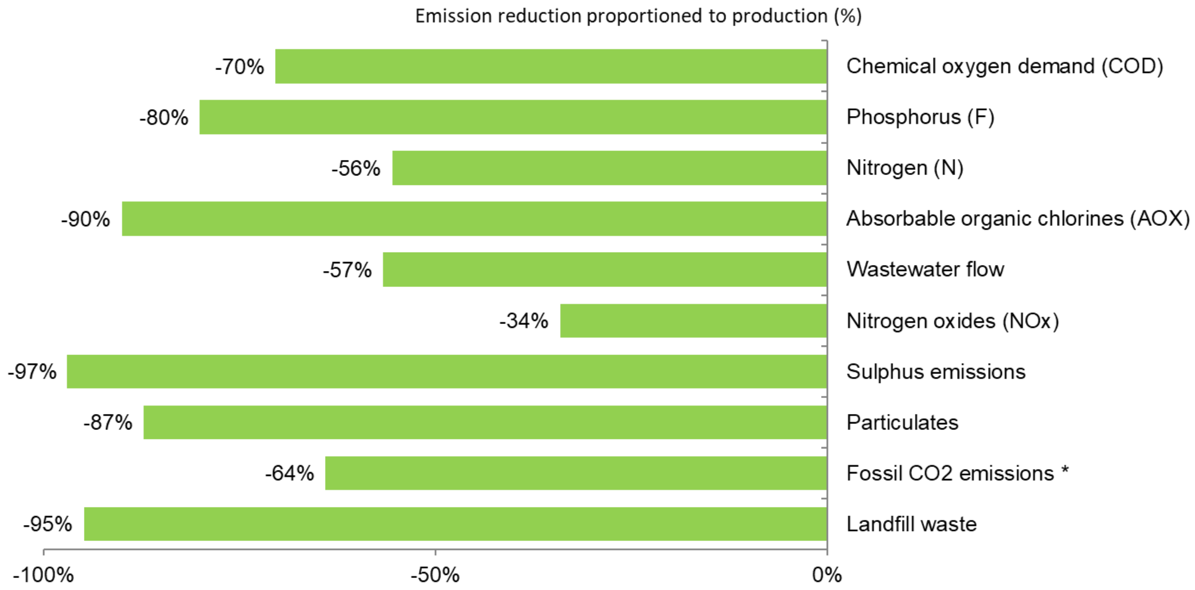

Figure 23. Emission reductions in pulp and paper production in 1992-2018. (Finnish forest industries 2019b)

Enormous progress can be seen in the reduction of air emissions, landfill waste and wastewater flow. Regarding the water consumption, Figure 24 shows the development of water consumption in pulp mills. Within 30 years, the water consumption in pulp mills has reduced from around 50 m^3/t to 2 – 4 m^3/t. During this period, the water circulation systems at pulp mills have shifted from completely open to almost closed system. A little amount of fresh water is needed in the system, otherwise taste and odour problems occur. (Business development manager, Appendix 2) The change in this can be explained with recycling of clean fractions and filtrates and reuse of treated effluent (Andritz 2019). More efficient washing equipment have been partially involved in the development, but actual innovation has been rather in process diagnostics through which process control could have been achieved. (Business development manager and Chief technology manager, Appendix 2) Thus, adoption of process diagnostics, analysis and online methods have enabled monitoring of water quality. Regarding the diagnostic, a method to diagnose wastewater plants called **LumiKem** measures micro-organisms through ATP concentration in wastewater. This can, for example, optimize the use of chemicals for wastewater and thereby control the water processes. Furthermore, hydrophobic particles in water can be measured online. This is used particularly for forecasting possible breaks, patches and dirt in papermaking process that can be controlled with chemicals or with other process solutions. Thus, major changes and breakthroughs are expected to occur in diagnostics and measurement as well as in data processing which are sort of brought by digitalisation. (Business development manager, Appendix 2) Digitalisation plays an important role in the environmental side. Over the past 20 years, digitalisation has enabled adoption of improved monitoring and control systems. On the other hand, environmental permits and EU Industrial Emission (IE) directive have also impacted on the adoption more advanced controls and technologies. These have required mills to report their environmental performance using KPIs. (Manager, mill services, Appendix 2) Common environmental KPIs are related to the emissions to water, air and to land. Additionally, there are KPIs indicating safety performance and financial performance. Thus, the methods for reporting the environmental performance and the entire performance of mills have become more complex, since the variety of KPIs have expanded.

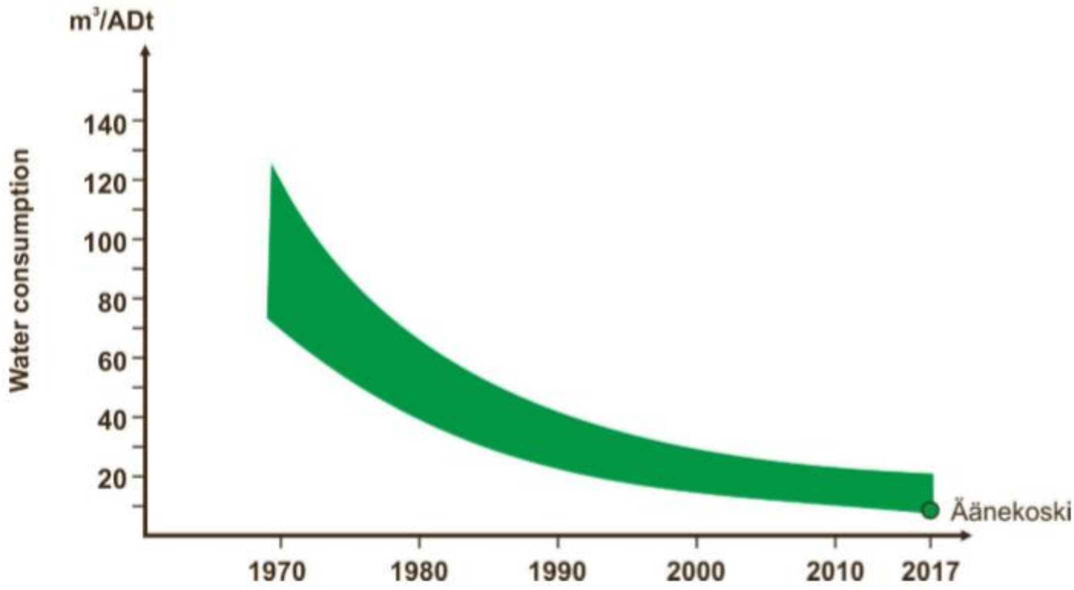

Figure 24. Water consumption in pulp mills in 1970-2017. (Finnish forest industries 2019b)

In terms of environmental performance, significant achievements have occurred in the amount of landfill wastes and air emissions. The amount of waste dumped in landfill has decreased, since the ban of dumping organic waste came into effect in 2016. (Sustainability, R&D manager, Appendix 2) The purpose of the ban was to reduce greenhouse emissions released from the wastes and emissions into waterways from the landfills and to improve sustainable use of resources (Ministry of the Environment 2013). For this, sewage sludge is for example incinerated for energy production. Furthermore, ash can be used as a stabilizer for excavating or as a fertilizer for forests. (Sustainability, R&D manager, Appendix 2)

Regarding the reduction in air emissions, major change has been the result of efforts to handle NO_x emissions. Not much attention was paid to NO_x emissions of recovery boilers 20 years ago. Afterwards, SNCR technology was implemented to recovery boilers. This has been continuously under development. There are two methods for the flue gas treatment. Flue gases can be directed to the recovery boiler or they can be treated in a separate flue gas scrubber or in a substitute incineration site. For air emissions, the technological improvements like the efficiency of an electrostatic precipitator, reliability and capacities have improved. (Manager, mill services, Appendix 2)

3.3 Review of developments in the wood products industry

The wood products industry is a business of approximately 8 billion euros in Finland of which sawmill industry accounts for slightly less than half. Other industries under the wood products industry are wood-based panels industry, joinery industry, construction carpentry industry and building industry. In Finland, the wood-based panels industry consists mainly of plywood industry. Other wood-based panels industries are chipboard and fibreboard. There is one mill carrying on chipboard industry, while fibreboard industry has been edged away in the country. The joinery industry is focused mainly on furniture and fittings, whereas the focus of construction carpentry industry is on building products like windows and doors and on further refined building elements or building space elements. From a lobbying perspective, log building industry is considered as one part of the wood products industry, but its sales volume is relatively small from the total sales. The sales volume of log building industry accounts for 200 million of the total 8 billion. The building industry also comprises detached house industry of which 90 % of all detached houses in Finland are wood based. (Managing director, Appendix 2) The wood products industry (Figure 25) is commonly referred to mechanical forest industry which also includes the industries of fibreboard, furniture and engineered wood products. There is not a common classification for these, but one way is to classify them either according to the degree of refining or the end-use.

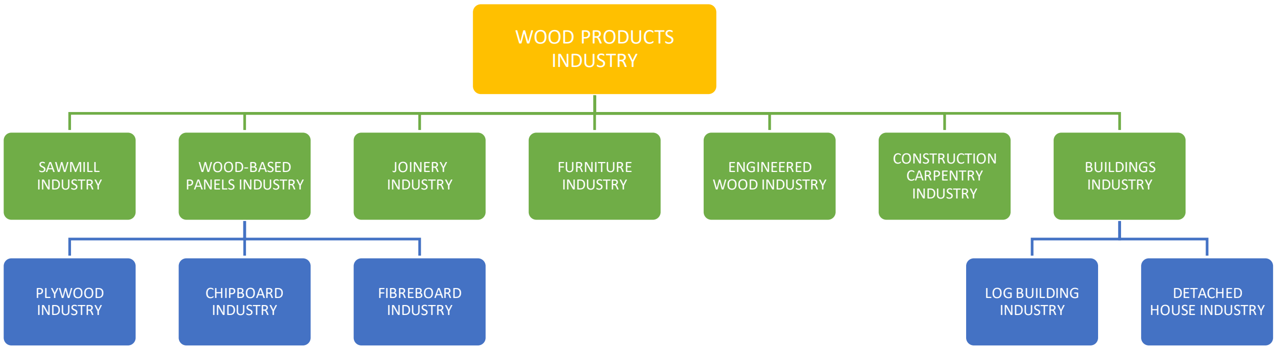

Figure 25. The summary of Finnish wood products industries. (Sipiläinen 2018)

Regarding the developments in the sawmill industry over the past twenty years, most of the main equipment are from the 1990s implying no major technological development to have taken place in the sawmill industry. Apparently, a major project will be launched at the Rauma sawmill next year, where the intention is to carry the technological development on. Up to the present, the most significant developments in the sawmill relates to the machine vision. Adoption of **laser and x-ray measurement** has enabled deeper examination of wood raw material allowing profitable conclusions to be drawn on how the log should be sawn and in which end-use it would be best to use it. Thus, machine vision has had a conclusive significance in sawmill yield and labour demand. It has speeded up and enhanced the whole process. Process and cost optimization have been a substantial driver behind these improvements along with OHS. Since no major technological leap has taken place in this area, the efforts have been targeted at adjusting of the current processes. During the past twenty years, some developments have taken place in drying techniques and technologies related mainly to yield or how drying can be conducted to achieve desired final moisture content without destroying product in the process. In sawing process, the technological development has related mainly to information transfer and processing. Today, more information is transferred faster from the forest to the sawmill. The information is transferred to the log already at the stage when the wood is cut down in the forest, and that end-use of the log is optimized partly in the forest and further in the sawmill with additional information. (Managing director, Appendix 2)

In the industry of wood-based panels, there are three significant plywood mills in Finland that produce conifer or birch plywood or mixed plywood. There has not been any significant technological development in the production process of plywood. The plywood industry is still very labour-intensive, which appears as burden. Therefore, recent investments from the Finnish companies have been directed towards countries of lower labour costs. In Finland, labour costs have impeded the development of the industry. Instead, there has been progress on the end-products' side. The Finnish plywood has been started to use in LNG tanks due its lightness. In addition, formable plywood has been developed for the needs of furniture industry. In this, development in adhesives has been crucial for resisting thermal treatments. The key drivers in the development of adhesives have been emissions from the products and to surrounding environment mainly or environmental values, in general. The use of lignin has called attention of plywood manufacturing companies to substitute fossil-based materials in their adhesives. Currently, there are adhesives on use that are based on 50 % non-fossil raw materials. In future, the aim of taking off the use of fossils will be a central subject in the development of adhesives. The long-term durability of adhesive may emerge as a challenge, since it must be resistant and functional in varying weather conditions and various structural solutions. Recently, the behaviour of the adhesives has been studied, for example in fire situations. High temperature resistant adhesives have been developed for studying the fire behaviour. However, the issue is how to make the bulk use of adhesives cost-effective. (Managing director, Appendix 2)

During the past twenty years, probably the most significant development has occurred in **engineered wood products**. The most common three types of engineered wood products are glued laminated timber (GLT), laminated veneer lumber (LVL) and cross-laminated timber (CLT). In recent years, CLT has probably received the most attention among these particularly in urban development and among architects. The product was originally developed in Central Europe in the 1990s when it was first used in building solutions. It is a quite young product, but its market has been steadily growing. In addition, GLT has also been a significant growing product in the global markets, although it has received less attention compared to CLT. It has been traditionally used in a roof structure of halls or as a pillar in large-scale constructions. Nowadays, its use has been increasing in multi-storey buildings. The key advantage in the use of GLT has been the resistance between joints that are less susceptible to changes. The third common engineered wood product is LVL that resembles GLT but is made from veneers glued together. There are two major companies in Finland that produces a significant amount of LVL on a European scale. Currently, its market is growing as fast as markets of CLT. In general, these engineered wood products have enhanced the position of wood in urban development due to their homogenous tensile properties, and in terms of construction design, they are homogenous and measurable products, whereas sawn wood is not. (Managing director, Appendix 2)

Sawn wood and veneer-based wood panels as well as planed wood, which is an upgrade of sawn wood, represent the basic products in the Finnish wood products industry. Regarding the developments in this field, **finger joint** has been introduced in the manufacturing of planed wood products for twenty years. Before, only knot-free plank wood or sawn wood was considered good for planing. Nowadays, knotty parts in the wood are cut off and the parts are joint together to form a solid homogenous plank. Thus, the result is visually surgeless. By machine vision and automized cutting and adhesive bonding, visual features as well as certain measure and dimension are possible to be conducted industrially. This kind of industrial prefabrication has further enabled upgrading of products. For upgrading industries like window and door industry, this has brought an accurate and qualitatively homogenous raw material base. In the window and door industry, the development trend has been energy efficiency, especially improvement of efficiency in window and door products. In practice, wood-aluminium window has passed over traditional wood window. In the wood-aluminium window, the exterior pane is equipped with an aluminium frame that responds to weather fluctuations more effectively, and thus, longer maintenance interval is obtained for window. Furthermore, the energy efficiency of window has been improved by adding number of planes and gases for heat insulation. The challenge of increasing the number of planes has been the weight of product that should be adjusted for convenient handling in manufacturing or at construction side. (Managing director, Appendix 2)

The Finnish furniture industry has not taken any giant leap in terms of technological development. There has been considerably more operation in the furniture industry twenty years ago, but today, the operation has been very SME-intensive. Perhaps more substantial issue has been the role of design and reasonable marketing channel for it, where digital marketing and social media attain unpredictable value, particularly among small companies. As the furniture industry, the fitting industry has neither undergone any significant development in technological means. Probably a noteworthy output has been the role of recycling and how to manufacture long-term resistant fittings from composite materials, especially in kitchen fittings. In general, recycling has seen as a challenge in the Finnish wood products industry. In most cases, wood ends up in incineration for energy use. It is reasonable to burn the wood product for energy production after its end-use, but on the other hand, it does not promote the recycling degree of the industry. In addition to this, other industries have also their own challenges, for example the building industry in Finland. In the Finnish building industry, the decrease in the markets of detached houses has been radical. Within twenty years, the market of detached houses in Finland has decreased from 15,000 to 7,000 houses. This has put the building industry into situation of struggle for survival. The crucial factor for this has not been technological development, but rather improvement in the production. Although the markets for detached houses have decreased, the share of log houses is increasing in the country. The market share of log house from the markets of detached house is nearly 25 %, and the significant technological development behind this increase has been the **non-settling log** innovation. Traditionally, log structure has had to be tighten due to its tendency to settle down when drying. A laminated log product was developed to eliminate the phenomena of settling. This innovation has increased the energy efficiency of log construction, and at the same time, it has expanded the range of use of the log material to other large-scale construction. (Managing director, Appendix 2)

In the construction carpentry industry, the primary change in recent decades has been entry into new markets. This is referred to the markets of urban development or **urban wood construction** that has also been a significant trend in the wood products industry. The key driving forces for urban wood construction have been urbanization and population growth associated with it. These have created the need to build more housing units at higher rate, which has further affected the labour demand at construction site. Potential solutions for labour shortage were sought from the mill side where industrial pre-fabrication was considered as a solution for it. In this context, wood appeared as a good alternative particularly to concrete due to its light weight and ease in transport. Thus, wood material proved to be effective for the prefabrication of wall elements or complete modular elements, especially in the construction of wood based multi-storey buildings. In Finland, a new tabular dimension came into force in 2011 allowing construction of eight-storey wooden building. Despite the tabular dimension, it is possible to build even higher wooden buildings, for example a 14-storey wooden building is found in Joensuu and the tallest wooden building in

Europe is currently an 18-storey located in Norway. (Industry Europe 2019) Nevertheless, the construction of multi-storey wood building requires more expertise and separate systems compared to the traditional buildings. On the mill side, wooden structures or elements are fabricated based on the design work of architectural, mechanical and electrical engineering and building engineering among many other fields of engineering. The crucial factor is how the designer can design using wood products and how the implementation of design work can be industrialized. (Managing director, Appendix 2)

In future, the emphasis will be on climate change and its environmental impacts which will promote the use of renewable materials. On the grounds of this, the basis of the wood products industry is in a positive light. As the world population grows and urbanization continues accelerating, agile solutions are needed for the growing housing needs. Thus, urban wood construction is a potential solution to the challenges emerged in the urbanization. The use of wood products has a positive contribution to the neutral construction due to carbon bound by the wood retains in the wood structure for long time ,and thus, serves as a long-term carbon sink. Therefore, the use of wood in construction should be promoted by administration of different countries. It is important that carbon footprint is taken account into building regulations, since reduction in the footprint of construction is included in the national Climate and Energy Strategy (Kuittinen 2019). By 2050, building regulations in Finland will have requirements for carbon footprint or restrictions on carbon footprint, which is expected to promote the use of wood products in construction. Currently, wood construction is claimed to be costly compared to the concrete construction. This can be affected by adopting process technologies and digital technologies to increase the process efficiency. The wood products industries are at the different stages in the adoption of digital technologies. Digital technologies have not emerged in a large extent in the production of the building industry. The production of fibreboard is highly automated, and the production of sawmill has already adopted firsts robots. Instead, automatization and adoption of robotics in the plywood production have remained as a challenge. It is a matter of whether the labour costs exceed the costs and benefits of automatization. Cost competitiveness emerges as a challenge for the Finnish wood products industries, since the labour costs, logistic costs and raw material price are considerably higher compared to other European countries. This reflects to the competitiveness of the Finnish wood products industries in the global market. Currently, the market share of exports is approximately 3 billion of the total 8 billion business. The share of export is crucial to the Finnish wood products industry, since some industries are still heavily dependent on the domestic markets. An abrupt decline in the domestic market will turn over the industry, and therefore, the impacts of different markets on the industry can be balanced by promoting export. In addition to the competition in the global market, the wood products industries are competing for a skilled labour, and thus, the competence will be one of the major bottlenecks in the long run. (Managing director, Appendix 2)

3.4 Review of new wood-based materials and product innovations

The forest industry has been built on the production of traditional forest products that are pulp, paper, paperboard and sawn wood. The production of these traditional products has generated valuable side streams that can be converted into byproducts or utilized for creating new value-added products. Unlike traditional byproducts, new value-added products represent novel solutions for existing applications creating new business areas to the industry. Traditional forest industry products form a solid platform for the development of wood-based value-added products, and thus, serve as a prerequisite for the rise of these products. New wood-based products and materials have opened opportunities for current companies to expand their product profile, and at the same time, boosted new start-ups to start their businesses. In recent years, promising wood-based products, such as biocomposites, biofuels and wood-based textiles have been already introduced on the market. Other products that are waiting for their market entry are biochemicals, nanocellulose- and lignin-based products, for instance. Despite the wide range of use of wood-based products, commercialization of products might be impeded due to their poor cost-effectiveness or lack of innovative end-use. Sustainability, biodegradability and recyclability are not sufficient criteria to maintain the competitiveness of wood-based products, but the entire business of them must be profitable form the production costs to the end-user satisfaction. This chapter includes some distinct wood-based materials and products emerged in the interviews and reviews their development to their current situation.

3.4.1 Nanocellulose-based products

Among the new wood-based materials, **nanocellulose** has emerged as a distinct trend among researches in recent years. There are numbers of research publications on application potential of nanocellulose, but an actual breakthrough in this area is still anticipated.

Nanocellulose is a microfibrillated cellulose material that has two principal forms: cellulose nanofibrils (CNF) and nanocrystals (CNC). In addition to these, nanocellulose can be produced from bacterial cellulose referring to bacterial nanocellulose (BC). Bacterial nanocellulose is distinguished by its non-existent hierarchical fibrous structure that is produced naturally by bacteria. Due to this, bacterial cellulose is hard to produce in larger scale compared to the other nanocellulose types. (Associate professor, Appendix 2) Nanofibrils can be manufactured by using mechanical methods, such as grinding, homogenization and microfluidization. In the mechanical treatment, microfibrils of the fibre cell wall are separated resulting in a viscous gel form consisting of individual nano-scale fibrils (Kangas 2014). The manufacturing process of nanofibrils consumes large amount of mechanical energy and can be expensive. To address this, chemical and enzymatic pre-treatments were developed to facilitate the fibrillation process and to decrease the energy consumption. These pre-treatment methods have enabled production of nanofibrils in larger quantities and opened more opportunities to develop production techniques. On the contrary, nanocrystals are manufactured by using completely different methods. Nanocrystals are manufactured through acidic hydrolysis, for example sulphuric hydrolysis, which solution contains higher amount of acid than water. The manufacturing of nanofibrils can be questioned by evaluating its green chemistry. The reaction solution is challenging to be recycled, since nanocrystals and the solution have to be purified. Furthermore, the manufacturing of nanocrystals becomes more expensive than nanofibrils due to the purification operations and constricted recycling possibilities. Recently, this area has called attention of researches to discover alternative methods for nanocrystal preparation. An example of a research that used gaseous acid instead of liquid gas to manufacture nanocrystals, gaseous acid was easier to purify and recycle at the end. (Associate professor, Appendix 2)

In general, nanocellulose is characterized by its unique strength and surface properties that can be exploited in various applications. In Finland, there is a small industrial scale production of nanocellulose. At least, UPM produces nanocellulose under the name GrowDex that is mainly used in biomedical applications, for example a nanocellulose-based hydrogel for cell culture. (Business development director, Appendix 2) Additionally, the company has launched a wound care product that utilizes aseptic properties of nanocellulose. (Associate professor and Vice president research, Appendix 2) Stora Enso produces microfibrillated cellulose and uses mainly in its own products. The company uses microfibrillated cellulose to reduce square weight in its paperboard products. This implies less grams per square of chemical pulp required in the product. Addition of microfibrillated cellulose enhances the strength properties of the material and reduces the weight of end-product. (Business development director, Appendix 2) In addition to large companies, a small company named Betulium uses part of potato waste to produce nanocellulose. In Finland, most of the nanocellulose producing mills are at the pilot stage. It can be stated that nanocellulose market is currently at the critical stage and its market is expected to grow within a few years. At present, most advanced markets for nanocellulose are in Japan, where many companies produce nanocellulose in industrial scale, and there are actual commercial products using nanocellulose like hygiene products. In Sweden, nanocellulose has been produced from alga and used as a structural material in batteries. In addition, nanocellulose has also been used as a membrane in water purification. (Associate professor, Appendix 2) Expanded knowledge on nanocellulose properties has enabled demonstration of these applications. By understanding how to break down the material chemically, mechanically and enzymatically has expanded the opportunities of nanocellulose. (Vice president research, Appendix 2)

3.4.2 Biocomposites

Replacement of fossil materials with renewables have generated a new business segment of **biocomposites**. Among domestic companies, Stora Enso launched a wood-based biocomposite called DuraSense in the early 2018. The product is a combination of wood fibres, polymers and additives moulded into a granule form and can be used in various applications from injection moulded products to industrial and automotive components. Stora Enso and a plastic household products manufacturing company Orthex have introduced kitchen products made from a biocomposite produced at the Stora Enso's Hylte mill in Sweden. Originally, Hylte mill produced thermo-mechanical pulp-based newsprint and recycled fibre. The company's biocomposite are manufactured from chemical and chemi-thermochemical pulp (CTMP) using existing machine and equipment at Hylte mill. (Stora Enso, 2018 and 2019) Other companies, like Metsä Group has also collaborated with small SME companies, such as Aqvacomp to produce biocomposite. Currently, there is a small-scale production of biocomposite at the company's Rauma mill (Development manager and Customer service and sustainability manager, Appendix 2).

3.4.3 Biofuels

The development of **biofuels** has derived from the need for alternatives to fossil-based energy sources. Some differences occur in countries' motives to develop biofuels, but climate positiveness and national protectionism are expected to confront at some point. The biofuel field has faced numerous developments regarding the raw materials and manufacturing technologies. In terms of biofuels and their generations, first- and second-generation biofuels are referred to raw materials. First-generation biofuels are produced from food crops like sugars and edible vegetable oils, while second-generation biofuels are mainly lignocellulosic based. Common products of first- and second-generation biofuels are methyl esters or biodiesel and bioethanol. Among biofuel manufacturing companies in Finland, UPM produces so called second generation advanced biofuels which raw materials are on a more sustainable basis. The sources for these are sought from non-edible raw materials, for example used cooking oil. Otherwise, the company produces renewable biofuels using tall oil as a raw material, and as for manufacturing technology, the company has developed a **hydrogen treatment process**. The hydrogen treatment process is related to the process in the oil refining sulphur removal units. In the process, chemical reactions occur in a high temperature and pressure with the help of catalysts producing pure hydrocarbons that are led to the distillation unit of traditional oil refining. Unlike traditional oil refining process, the volume of oxygen in the processing of biological raw material is much higher, which implies the present of water in all state through reaction of hydrogen and oxygen in the hydrogen treatment. In addition to this, carbon monoxide and carbon dioxide are produced during the process. The presence of these compounds sets stricter requirements for the choice of material and process routes. In the manufacturing of biofuels, raw material plays a huge role in the environmental impacts, particularly in CO_2 emissions. Nearly 80 % of decrease in CO_2 emissions can be achieved with the current process compared to the fossil fuels. This is explained by biobased energy sources used in the production process, except the hydrogen used in the hydrogen treatment that is manufactured from natural gas. This is the only factor increasing the CO_2 load. (Production director, Appendix 2)

There has been a constant process development in the field of biofuels. Particularly, the process development of methyl esters has been brisk, where the spin-off of oxygen removal and isomerization-catalysts have been introduced. Furthermore, the development of hydrotreated vegetable oil (HVO) technologies has taken a great leap during ten years regarding the implementation of ideas to running production plants. The UPM BioVerno refinery can be considered as a national innovation. It is claimed to be the first refinery in the country that produces renewable fuel from 100 % wood-based raw material. The production capacity of the refinery is about 100,000 tonnes per year, and the following refinery with the capacity of 500,000 tonnes is currently under the process of investigating. The aim is to seek for growth with the construction of the new refinery. In future, climate change and sustainability issues will drive the development of biofuels. In addition to these main drivers, urbanization and megatrends will be present bringing about changes in transport and consumer behaviour. In fact, consumers want more sustainable solutions for the climate. As an example, biofuels are sold to petrochemical industry for raw materials of biobased plastics. Additionally, a lighter hydrocarbon component naphtha is sold beside renewable diesel as a component for petrol. The main customers for biofuels are fuel distributors, big oil companies, plastic manufacturing petrol-chemical industries. Currently, the demand of biofuels exceeds the supply. In Scandinavian countries, there are already 40 million tonnes of demand for biofuels, and therefore, the projects in this field are forward looking. Possible challenge might emerge in the availability of sustainable raw material. Alternative energy forms are needed besides renewable biofuels. Not all fossil-based energies are replaceable with biofuels. Biofuels and renewable materials can provide CO_2 neutral solutions using biomass raw material efficiently. With the efficient use of biomass, carbon is bound to the circulation. Otherwise, carbon sinks or other alternatives are needed to bind carbon to the carbon cycle or to the long-term circulation. (Production director, Appendix 2)

3.4.4 Biochemicals

Biochemicals have been developed for long time. In the case of wood-based chemicals, the development of biochemicals has probably originated from the exploitation of lignin that has been researched in the 1920s, 1950s and during the oil crisis of 1970s and at the present. Technological development of biochemicals has been a combination of numerous factors. Biochemicals have probably faced before some technological challenges leading to the decelerate of the development. Besides, the profitability of the development of biochemicals has depended on the competitiveness of oil-based chemicals. As the climate challenges have emerged more during the last decades, alternatives for renewables are more in demand. These apart from process and cost efficiency are the driving factors for the development of biochemicals. The current state of biochemical refinery is at the stage of development and piloting. At least, UPM is planning to build a biorefinery in Germany that would produce renewable monoethylene glycol (MEG) and monopropylene glycol (MPG) as well as lignin. MEG and MPG are already commercialized products that have been used to replace fossils. The application range for these chemicals covers the industries of packaging, textile, cosmetics and pharmaceuticals, for instance. Lignin, on the other hand, is a versatile substance that is already produced in industrial scale with LignoBoost technology. Manufacturing technologies of biochemicals can be either mechanical, chemical or biological. The LignoBoost technology is an exception, since it is based on conventional technology on extraction of lignin from black liquor and it is integrated to the pulping process. Biochemical business is quite young compared to biofuels that are already commercialized and perceived in the EU standards. The standard chemical regulations (REACH) and environmental regulations are applied to chemicals despite of the raw materials. In the case of biochemicals, the origin and supply chain of wood raw material should be transparent. The aim is to maximize the number of certified wood (verified chain of custody) that ensures the wood material to originate from sustainability managed forests. In general, the biobased business faces challenges in the phase of development where technological, environmental and economical side as well as regulation are driving the development. The environmental impacts of biochemicals are observed using eco-design and life-cycle analysis based which technological and economical sides are optimized. In the field of biochemicals, more effort is needed for marketing. The biobased is not the solution alone, but the marketing and regulation should confront at some point. (Senior manager, Appendix 2)

3.4.5 Wood-based textiles

There is an increasing demand for textile and hygienic products due to global population growth and improved standard of living. Most of the modern textiles are made from cotton or oil-based materials. There has been an ongoing debate about availability of cotton and environmental concerns of oil-based textiles. (Sajn 2019) The land used for the cultivation of cotton can be instead used to grow food crops. As the demand for arable land area for food production increases, the production capacity of cotton is gradually approaching its stagnation point. A growing demand of textile fibres and stagnating production capacity of cotton have created so-called cellulose gap. It means about one third of the textile fibre demand should be cellulose based by 2030. (Hämmerle 2011) This has excited both large and small corporations to develop new technologies for textile fibre production that outperform the current technologies in sustainability, safety and feasibility. Current technologies used in the production of semisynthetic textile fibres like viscose and lyocell are not on the greenest verge, although they consist of cellulose fibres. These textile fibres use dissolving pulp as raw material which is normally treated with toxic and water polluting chemicals. (Rose and Palkovits 2011) Alternative methods have been developed to produce more sustainable textile fibres. As an example, **cellulose carbamate** technology is a potential method for replacing dissolving cellulose-based textile fibres. Cellulose carbamate is produced from cellulose and urea through a solvent-free synthesis process. The benefits of technology are less harmful and inexpensive chemicals. (Harlin 2019) Other developed technologies produce textile fibres from virgin pulp or recycled fibre in sustainable manner (Business development director, Appendix 2). These have created tremendous opportunities for textile industries who strive to reduce use of oil-based non-renewable resource or to substitute cotton that consumes large quantity of water, chemicals and energy. Currently, the aim is to introduce more environmentally friendly textile production methods as to expand the range of raw materials to agricultural and other cellulose-based waste. (Pensupa et al. 2017; Torres-Martínez et al. 2019)

3.5 Review of innovative start-up companies in the Finnish forest industry

According to the Finnish Venture Capital Association, start-up is a young and innovative company that typically aims for a rapid international growth through a scalable business (FVCA 2019a). In order to grow, start-up at the early stage of growth company needs an ecosystem in which to launch and build its business. This ecosystem encompasses partnerships between entrepreneurs, investors, venture capitalists, business accelerators and organisations among many other parties. Investors and venture capitalists have a major role in scaling up the business. However, the success of a business derives from an innovative idea and potential of the idea is acknowledged by external parties who contribute to the promotion of business growth. There are around 4,000 to 5,000 start-up companies operating each year in Finland among which the most promising ones are boosted. (FVCA 2019b) According to the statistics of Venture Capital, Finnish start-ups ranked to the top among the most venture capital investment received European start-ups, and the number of foreign investors of the total invested has been fifteenfold compared to 2010. (FVCA 2019a) This indicates how the Finnish start-up scene has developed rapidly in a short time period, while gaining more recognition internationally. The Finnish start-up scene has been well-known for its success in gaming and software field from the 1990s. Later, the Finnish start-up scene has attracted attention of other sectors such as the biobased sector. The Finnish start-ups and companies started to recognized opportunities in developing innovative solutions for the biobased circular economy. This boosted the Finnish start-ups and companies to focus on the sustainable use of natural resources to create high-value business. This chapter reviews some of the most significant start-ups and their innovations that are based on the use of the Finnish biomass or forest-based fibre.

First biobased innovations have not emerged until the past five or six years, when these innovations have moved into the commercial operation. The key sectors for biobased innovations are packaging, textiles and other fibres, health care and cosmetics, interiors and design. Regarding the textiles, **Spinnova** is one of the start-ups that focuses on the production of sustainable cellulose-based textiles. Spinnova is one of VTT's spin-offs founded in the early 2015. Beginning from the idea on spinning wood fibre into textile fibre, the innovation of Spinnova is based on the technology that uses less chemicals and a little amount of water in the process. Contrary to the conventional viscose process that produces textile fibres by dissolving pulp in a toxic chemical containing solution, textile fibres in Spinnova's technology are produced from cellulose unit with no dissolving and harmful chemicals. (Business development director, Appendix 2) Currently, the technology uses pulp fibre from FSC certified wood, but is also applicable to other agricultural and biowaste-based cellulose. The technology has been scaled up from small pilot scale to industrial scale in December 2018, where the new pilot line has a maximum capacity of 100-400 t/a. In the future, the company aims at scaling of sustainable fibre production into big commercial volumes. (Spinnova 2018)

Another spin-off of VTT founded after Spinnova is **Paptic**. The company started its business from materials for replacing plastic bags but aims to cover the whole area of flexible packaging materials. The company selected plastic bags as the first product applications due to the enhanced pressure targeted at them from the EU directive on banning single-use plastics. Paptic uses cellulose fibres from certified wood as raw material in its products that are characterized by three main arguments: renewable, reusable, recyclable. While traditional paper bags are easily unusable once being wetted, Paptic's materials can be used several times and put to the recycling process of paperboard after use making it a reusable fibre. Subsequently, **Infinited Fiber Company** was founded in 2016. The company produces cotton-like fibres either from recycled textiles or uses dissolving pulp as raw material. (Business development director, Appendix 2) The company uses technology developed in VTT that is based on the separation of fibre from material and conversion of the material into a liquid and eventually into a new fibre. (Infinited Fiber Company) The focus has been on the use of recycled textiles, but other wood-based fibres or agrological side streams can also be used in the manufacturing process. The technology has advantage in applicability to existing pulp and viscose manufacturing mills. Currently, the company can produce thousands kilos of materials in VTT's pilot plant located in Bioruukki and is aiming to scale up the production. The company has received millions of euros in investments and intends to scale up the production to half mill scale in Valkeakoski in the next year. (Business development director, Appendix 2)

Among packaging companies, **Sulapac** produces wood-based packages with a new concept. The company combines wood-based fibre or chip with biobased binding material, and even if the material ends up in the ocean, it degrades without generating microplastics. Same applies to Paptic whose products do not release microplastics into the environment. (Business development director, Appendix 2) Plastic bags and plastic products in the oceans as well as microplastics in the environment are the current drivers for biobased materials (Business development director, Appendix 2). Sulapac focuses on microplastic-free and compostable alternatives for traditional plastic products. The first application of the company was cosmetic packages, but the company has expanded its scope to other consumer goods, particularly to short lifetime products but no single use like hairbrush or clothing hanger. In 2018, Sulapac and Stora Enso launched a demo for drinking straws that are based on Sulapac's biocomposite material. Straws are one of the dozens items found most in the ocean causing adverse effects on the ecosystem. Therefore, there has been a growing need for their replacement. Besides Sulapac, **Dolea straws** also provides sustainable alternative to traditional plastic straws. Dolea is a young start-up company founded in 2019 which innovation is a plastic-free straw using a water-based dispersion barrier board of Kotkamills, and technology based of the earlier developed innovation of Her Majesty's Drinking Box Ltd. (Dolea straw; Kotkamills 2019) Both Dolea's and Sulapac's straws are biodegradable and recyclable. Sulapac's straws are advantageous for being marine biodegradable and Dolea straws for being printability. (Dolea straw; Sulapac 2019) (Business development director, Appendix 2)

Regarding the wood-based packaging products with new features, Kotkamills launched a plastic-free solution for consumer packaging and food service boards, such as single-use cup with no plastic barrier. The change can be considered as minor, since the barrier coated single-use plastic cup has existed before, but the thin plastic coating on it can be replaced with other barrier solutions. Other companies, such as Pyroll and Huhtamäki, have also this type of solutions. A certain degree of confusion has emerged regarding biodegradability of the products. In some fully biobased products, biobased plastics of Rapid Alert System for Chemicals (RAS-CHEM) may have been used that, however, are not biodegradable. At least, fully biodegradable packaging products are found in the product range of Huhtamäki and Pyroll, even though it is not sure, if biobased plastics are used in the products. Regarding the packaging products, **Jospak** provides innovative packaging solution for food industry. The company was founded in 2014 and its innovation is a cardboard tray covered with a plastic film that is easily removable. Thus, the cardboard and plastic film are easy to separate and recyclable in their own system. Besides Jospak, Pyroll has the same type of solution. Instead, **Woodly** produces plastic-like transparent food packaging film from wood-based polymers. Company's first application was salad package that Järvikylä uses as a peripheral film on their salad jars. Woodly and Sulapac have advantage in their innovation, since both companies can process their materials in existing plastic processing equipment. In the case of Sulapac, the basic injection moulding used in moulding cosmetic containers before, can flexibly shift to use materials of Sulapac as well as other types of biomaterials in its old process. Same applies to products of Woodly. Instead, there are a few companies like Paptic, which manufacturing process requires rebuild of existing paper machine. Nevertheless, old paper machine is exploitable in Paptic's process. From the perspective of paper manufacturer, this rebuild of an existing paper machine can be considered as a shift to a new type of paper-like material, since there is overcapacity in some paper grades, for example printing paper. (Business development director, Appendix 2)

There are small and large companies which operation is based on partial substitution. **Aqvacomp** is one of the companies that produces biocomposites by using cellulose fibre as reinforcement. The production is carried out in a cooperation with Metsä Group's mill where they use 55-60 % cellulose fibre as reinforcement in their product and thus uses less plastics compared to traditional plastic materials. Additionally, Stora Enso produces biocomposites by combining biobased plastics from RAS-CHEM's polyethene and polypropylene and 35-55 % of wood fibre or chips. These products can be either fully biobased or oil-based plastic composite with up to 55 % wood fibre. Even though biocomposites are manufactured by using synthetic plastic, they can have a significant contribution to the reduction of plastic use. Furthermore, these biocomposites can be recycled at some scale with synthetic plastics due to the enhanced integration of fibres into the plastic component through reprocessing of materials. This creates a great potential for a separate recycling cycle of biocomposites, in case the utilization volume increases. Biocomposites endure recycling at least seven times and its properties can be improved by adding slightly virgin material. (Business development director, Appendix 2)

In the beginning of 2019, the Finnish funding agency for research and technology, Business Finland launched a program called Bio and Circular Finland that aims to promote Finnish bio and circular based solutions to global markets. (Business Finland) The program has a budget of 150 million euros for innovation research and development funding of which half of the budget is funded by Business Finland and the other half by companies and research institutions. Research areas of the program are plastic replacement or recycling, textiles, packages and construction materials. On the building materials' side, **Lumir** has created a biobased solution for acoustics that is based on the use of cellulose fibre. The company's product is a biofibre-based spray that can be injected even on curved surface. It forms a six- or eight-millimetres thick layer that can be integrated with any colour. In addition, no emissions are released from the product, since it is fully biobased. Besides Lumir, **Woodio** provides wood-based solution for interior design. Woodio uses wood material technology in its products that are waterproof wood composites consisting of wood chips. The company's first application was washbasins and was aiming for private and public spaces. Further products of the company are wood-based decoration tiles and bathtub, for example. (Business development director, Appendix 2)

In Finland, research has recently focused on the development of wood-based fibres. Besides Infinited Fiber Company and Spinnova, Metsä Group's innovation company Metsä Spring Ltd. together with Japanese Itochu Corporation invest approximately 40 million euros in a test plant that aims to convert cellulose fibres into textile fibres through **Ioncell** process.

Ioncell is a technology developed at Aalto University and slightly modified to meet the Metsä Group's needs. The idea behind the Ioncell process is a continuous closed loop of chemicals which are water and ionic liquid, respectively. This solvent dissolves cellulose that is converted into textile fibres by using a dry-jet wet spinning technology. (Asaadi 2019) VTT is currently researching and developing production of textile fibres, but actual innovation regarding this area has not been introduced yet. (Business development director, Appendix 2) Among the emerging research areas, nanocellulose has emerged as a distinct trend of this decade. There are currently two large companies in Finland that produces nanocellulose or microfibrillated cellulose. Besides them, **Betulium** also works in the same field. A Finnish company Betulium founded in 2013 started its business from the production of microfibrillated or nanofibrillated cellulose from agricultural side streams, but today also from wood-based materials. The company provides its products mainly to chemical industries for replacing synthetic additives. (Business development director, Appendix 2)

Regarding slightly special application, **Onbone** provides innovative wood-based solution for orthopaedic, traumatological and occupational therapeutic needs. A Finnish company Onbone provides light weighted and mouldable cast and splinting materials that are manufactured from wood and biodegradable plastic. Contrary to traditional mineral based cast, Onbone's cast can be remoulded using heat without having to break the cast. (Business development director, Appendix 2) Another special application field is health care where **Montisera** and its subsidiary have focused their business on. Montisera is a Finnish development company founded in 2012 and its subsidiaries **Montinutra** and **Montipharma** were founded afterwards. (Montisera 2019) The company and its subsidiaries extract bioactive compounds from wood-based material streams that have hygienic or disease preventive effects (Business development director, Appendix 2). The company has patented hot water galactoglucomannan extracts that Montinutra uses in food and techno-chemical applications, and Montipharma in medical applications for treatment of urologic symptoms and dependency disorders. Currently, Montinutra has a small-scale production but aims to invest in industrial scale production, whereas Montipharma is heading to clinical development phases. (Kolster 2019) With the similar theme, **Repolar** extracts antimicrobial or active ingredients from spruce resin using its patented technology. Repolar product range covers from salves to lotions of wound and skin care which are widely used in Finnish hospitals and health centres. In addition to domestic trade, the company has also export trade in Europe. (Business development director, Appendix 2)

The start-ups and their innovations presented so far represent the young Finnish companies that have potential to a rapid international growth. Besides these successful start-up companies, there are start-up companies whose growth has been relatively slow, or in some cases, their business has been put into halt. Start-up business involves numerous uncertainties that often appear in scaling-up of a business. In the start-up field of biomaterial and process technique, the most challenging part is probably build-up of the first large-scale production plant. As previously stated, solutions of Sulapac and Woodly are innovative due to their applicability and flexibility. Both companies can verify the applicability of their products first without having to build their own production plant. In the case of Paptic, the company started its operation in 2015 and aims to launch the first full-scale production plant in 2020. Thus, it takes five years for the company to put the first industrial scale production into operation. (Business development director, Appendix 2) The gap between piloting and first industrial scale is often called the valley of death that refers to the life period of a start-up before generating revenue. It is typical for start-ups to seek for external funding, since funding appears as a major challenge along with the build-up of the first industrial scale. Possible funding sources for start-ups are investment companies, angel investors, crowdfunding and public funding. There have been various programs and projects for Finnish start-ups which are funded by public agencies. Among these, *Wood from Finland* was an export program funded by Finpro – *Finnish Trade Promotion Organisation* that aimed to boost the turnover and export of Finnish sawn timber to China. Additionally, a research collaboration project *Cellulose from Finland* funded by Tekes – *Finnish Funding Agency for Technology and Innovation* focused on finding new and innovative cellulose-based product solutions. Afterwards, Finpro launched an export program called *Innovative Bioproducts* that is currently directed by Business Finland after uniting of Finpro and Tekes. Contrary to previous programs that are more industry-specific, the purpose in the *Innovative Bioproducts* program is to gather all new start-ups whose business is based on the use of biomass raw material and support the growth of these start-ups in both domestic and foreign markets. This program also comprises start-ups that use forest-based raw materials like extractives from berries or bark. Furthermore, VTT Technical Research Centre of Finland and Aalto University has established an eight-year research program FinnCERES that is funded by the Academy of Finland. FinnCERES focuses on research and development of novel lignocellulose-based materials and their properties which can be utilized in novel solutions, for example in electronics or optical applications. (Business development director, Appendix 2)

The Finnish government provides R&D funding to various organisations including Academy of Finland, universities, research institutes and public funding agencies. The share of government R&D funding in the state budget has been decreasing from 4,3 % to 3,7 % since 2010 of which the funding for technology development has been expected to decrease. (OSF 2018) This decrease may have considerable effects on the country's competitiveness with other civilized states. As a response, many organisations aim to increase the R&D and innovation funding, which have further led to the establish of various research programs and projects. Many start-ups are pleased to take part in research projects, since they usually do not have an own research organisation like growth companies. Contrary to forest-based growth companies that usually have an own research organisation and innovation activity, for start-ups, the main energy is focused on finding markets and scaling-up of production in addition to business as usual. The innovation activity of start-ups is thus closer to the present than far future due to the current situation of start-ups (Business development director, Appendix 2). On the other hand, many of these start-ups may be involved in national or EU-wide research projects where R&D activities are more forward-looking. Nevertheless, both start-ups and growth companies are actively involved in collective research projects and programs along with research institutions and universities. (Business development director, Appendix 2)

Despite the challenges emerging in funding and scaling up of production, the outlook for start-ups in the biobased field is perceived as bright. The start-ups presented so far are examples of start-ups that have received a lot positive of attention. Many of these start-ups are expected to grow in the future as they are currently at the phase of scaling-up or are planning to scale-up. The product and technology solutions of these start-ups have proven to be profitable for worldwide adoption, since the potential for increasing the degree of processing have called interest around the world. As in Finland, other countries are also dealing with the sustainability issues. These have set challenges for materials, since EU Single-Use Plastic directive defines recycling to be the only alternative for materials and biodegradability is considered as an alternative in cases where materials are completely unmodified natural materials. Lately, there have been many conferences relating to these topics, for example *Plastic-free World* held in Germany in Summer 2019. A wide range of companies attended the conference representing new materials and technology innovations for circular economy solutions. The companies aim not only for ‘plastic-free’ but also for ‘world free of free plastics’ that refers to recycling and controlled use of free-flowing plastic waste. Plastic itself is a functional material in applications that have a long service life and do not release into environment. Otherwise, it is reasonable to evaluate usability and environmental impact of a certain application before substituting with biobased and biodegradable materials. Besides recyclability and biodegradability, compostability is another option. Regarding the treatment of future material streams, recyclability emerges as the first option following by biodegradability. (Business development director, Appendix 2) These features will be strongly involved in the development of new products and technologies, especially in packaging materials where the great faith is in fibre-based materials.

3.6 Industrial and institutional aspects on innovation and innovation process

When it comes to innovation in institutions and industries, both parties may have different approaches to innovation. In universities and research institutions, the starting point for innovation may be the study of basic phenomena. Studying the basic phenomena does not have to be related to a specific problem, but it can be based on an interesting subject to study. This kind of approach is common among electronics industry, information technology and pharmaceutical industry. Instead, it is common in the forest industry to start from the identification of a problem for which a solution is sought. (Associate professor, Appendix 2) Innovation in industries is driven more by customer demand, whereas innovation in institutes is more research driven. (Postdoctoral researcher, Appendix 2) It can be stated that innovation in institutions and universities is more focused on basic research, and in particular, on obtaining research results which tends to be more valuable than the actual creation of innovation. It is very common for institutions to collaborate with companies to drive innovation forward. Unlike companies, institutions often lack their own organisation to carry on the research to production. Therefore, the presence of companies is absolutely essential in the same way as the communication between companies and research team. (CEO, Appendix 2) It is common that institutions conduct research projects where the research subject is offered by industry representatives. The research project may be a thesis, or it could be a larger entity involving several researches (Postdoctoral researcher, Appendix 2). In addition, it is common for institutes to apply for project funding like from Academy of Finland or Business Finland. (Postdoctoral researcher, Appendix 2) The Academy of Finland provides funding to basic scientific research. Business Finland, on the other hand, provides funding for more applied research, as well does the EU, which has financial instruments for basic research in addition to applied research. In the case of applied research, industrial partners are often needed, and therefore, the research subjects and research goals have been defined more precisely. (Associate professor, Appendix 2)

The needs and scale are the distinct differences between industries and institutions. Institutions may carry out research more freely, if the subject and objectives of the research are not strictly interfaced with funding. In cases of cooperation with companies, the intention is to achieve results that meet the needs of the companies. Thus, the goal of institutions is to make technology or process researched to operate effectively on a large scale. (Postdoctoral researcher, Appendix 2) Industries, on the other hand, often carry out the large-scale production aiming at establishing business. Recently, cooperation between industries and start-ups has become more visible. At least, it is very common for start-ups to seek for industrial partner, but similarly industries have been more active in cooperating with start-ups. Industries may have created their own innovation unit to follow ideas from start-ups and help them to take their ideas to the industrial level. This has enabled industries to respond more easily to new developments and test them in practice. (Director of technical marketing and packaging services, Appendix 2) On the other hand, large industrial companies have their own innovation activity or some kind of core activity that is not public or known among outsiders. (Business development director, Appendix 2)

In the innovation activity, networking appears to be important, especially for SME companies that do not own research or laboratory facilities. In these circumstances, innovations often result from discussions and communication with customers who have a problem at hand. Meanwhile, research institutes carry out the research side, for example through the master's theses and doctoral dissertations, to provide a technical or scientific explanation of a customer's problem. This kind of network pattern is exploited among industrial companies and research institutes. Therefore, communication and networking between companies and institutions and with business agents, when it comes to marketing, are important in the innovation and development work. It is common for development work to be conducted based on the customer feedback and suggestions. The activities and outcomes based on customer feedback can be considered as one of the most important indicators, and customer satisfaction is the main objective in this. (CEO, Appendix 2)

Regarding the innovation process, SME companies have an advantage in agility. New ideas and innovations are generated effectively in a small team engaging customers in the phase of innovation creation. Contrary to large or grow companies, the agility helps SME companies to put innovation forward in test and progress, while in large companies, decision making methods and procedures are carried out differently or in some ways more slowly. Thus, the ability can be considered as a significant asset in SME companies. (CEO, Appendix 2) This kind of agile method or 'agile culture' to create innovation has emerged later in larger industrial companies. The forest industry actors have their own innovation culture and experimental culture that are supported by various group-level financing procedures. In these, people are encouraged to innovate. Contrary to long-term development processes, the innovation or experimental culture aims to achieve results within three or six months. (Sales manager, Digital lead and Account manager, Appendix 2) This type of action provides a more effective practice to evaluate potential for innovation based on which further procedures may be applied.

Although industries and institutions may have different starting points for innovation, at least trends for innovation are very similar. On the institutional side, research and innovation are influenced by funding that is further driven by trends. Fluctuating trends are constantly changing trends in the research field. At least, it has been perceived that the cycles for research trends have ran faster; the research peak is reached quickly after which it falls nearly at the same rate. (Associate professor, Appendix 2) The drivers for innovation have changed during the past ten years. In the past, the emphasis was strongly on efficiency which implied less energy, less water and less raw material with less expenses. These have subsided into environmental concern, plastic concern, microplastic pollution or plastic challenges, in general. (Vice president research, Appendix 2) From the institutional and industrial aspect, the challenges and opportunities of climate change and circular economy are the current drivers for innovation. Climate change will not change for a long time, while recyclability and biodegradability are foreseen to be the next rising trends. (Associate professor, Manager, mill services, Business development director and Vice president research, Appendix) On the institutional side, the current research focuses on these areas emphasizing especially the replacement of fossil-based materials with wood fibres. Industries have emphasized the same subjects in their activities, but also the opportunities brought by digitalisation. For industries, digitalisation is a method to reform their business operations and processes. Solutions brought by digitalisation will improve the overall usability of industrial plants. Industries have described how industries' internal processes are monitored and improved with IoT, artificial intelligence, Industrial Internet and machine vision. In the end, these are all based on the utilization of a data or Big data. Today, a large amount of data is obtained from the processes, but their utilization has appeared as a challenge. Industries have been considering how data can be used within a mill and across the mill. (Product portfolio and strategy manager, Appendix 2)

In terms of innovation, industries seem to put more weight on responsibility in their actions. (Product portfolio and strategy manager, Appendix 2) Responsibility emerges in industries' agendas in which the entire supply chain, safety, people and technical solutions are considered. Through acknowledgements of these, industries want to highlight how they operate and report on issues and how to be transparent as a whole. Safety reporting applies not only to industrial companies but also to subcontractors. OHS requirements have increased a lot over the past decades. For these, industries have adopted various management practices to show their commitment to health, safety and environment (HSE) of their people, partners and customers as well as their operational communities. Developments in these areas are monitored using various indicators. There are personnel related indicators which aim to raise awareness of operational issues among personnel and production management. (Product portfolio and strategy manager, Appendix 2) In addition, personnel indicators may be related to occupational safety and training as well as number of suggestion from personnel on safety and environmental improvements which are considered as strategic indicators. Industries or companies have their own indicators. The most common indicators among industries are efficiencies in various forms. As an example, Overall Equipment Effectiveness (OEE) is a typical indicator that provides various methods to measure manufacturing productivity. (Senior purchasing manager, Appendix 2) In addition to these, feedback from customers is an essential indicator as well as production related indicators such as Return of Investment (ROI). (Development manager and Customer service and sustainability manager, Director of technical marketing and packaging services, Appendix 2) The purpose of indicator is to serve, and therefore, industrial companies tend to stick to a specific indicator in order to evaluate the performance in meeting the objectives. (Senior purchasing manager, Appendix 2) For young companies, the use of indicators is not at the same level. They seem to focus more on evaluating customer benefit or value proposal. (Business development director, Appendix 2)

4 Key findings and discussion

4.1 Summary of key innovations and drivers

This chapter summarizes the most significant innovations emerged in the empirical study and their key drivers and main achievements. The innovations have been primarily categorized under the most appropriate theme for them to avoid overlapping. If the drivers or achievements of an innovation have not emerged clearly in the interviews, they are determined by deriving the results of the study. Drivers of innovations have been defined in following categories: ‘process and cost optimization’, ‘OHS’, ‘responsibility’, ‘technological opportunities’, ‘customer demands and market opportunities’. This categorisation allows for simple examination of drivers for innovations based on which types of drivers can be inferred. The scope of categories for drivers has been defined below which is followed by summary of the themes.

- **Process and cost optimization**: e.g. material, production or energy efficiency development
- **OHS**: occupational health and safety requirements
- **Responsibility**: e.g. environmental sustainability, regulation and policy changes
- **Technological opportunities**: e.g. digitalisation and automation, AI, overall technological development and new solutions
- **Customer demands and market opportunities**: e.g. customer demand, market demand/opportunities derived from megatrends or discrete events (e.g. urbanization, popular growth), quality improvement

The main principle in wood handling is to handle wood material in appropriate way to produce high-quality wood chips for pulping. Each process stage in wood handling are crucial factor in determining what kind of wood chips end in pulping. Because of this, improvements implemented in wood handling have aimed on supporting the yield of high-quality chips. For this, more attention has been paid to chipping technology. Available horizontal feed chipping technology has been upgraded to a more efficient and safer direction. As a result, higher chipping capacity could be achieved with the 2nd generation horizontal feed chipping technology which has later become a standard technology among wood handling plants. As capacities increased, cost-efficiency became even more important. Cost reductions were applied to storage systems. Circular storage replaced conventional oblong-shaped storages resulting in reduced storage costs per cubic chip. Afterwards, circular storages have become more common in wood handling plants. Another improvement was conducted in bark handling. Bark generated from debarking of logs have been used for energy production. According to the common principle, higher energy efficiency can be achieved with lower moisture content in the wood combustion. To maximize the energy benefit of bark, dry solid content of bark has been increased with an upgraded bark press. The function of the upgraded bark press is based on two-phase pressing that enables higher dryness. The innovations and related information have been presented in the Table 4.

Table 4. Innovations and key drivers of wood handling.

Innovations	Drivers	Achievements
Circular storage	Process and cost optimization	Reduced storage costs
2nd generation horizontal feed chipping	OHS	Higher chipping capacity
HQ bark press	Process optimization	Higher dry solid content, energy production

Pulp mills have been under constant pressure on environmental issues. The measures so far have been partly due to regulatory pressure, but also to the mills' own willingness to contribute to their environmental impact. According to summary of the innovations emerged in chemical pulping (Table 5), most improvements carried out at pulp mills have related somehow to resource efficiency. The aim in resource efficiency is to use all raw materials from wood consumption to water and chemical consumption as accurately and economically as possible. Since the pulping technology has remained the same, more effort has been put into the efficiency of equipment and of the entire mill. In the pulp manufacturing process, several problems have been solved simultaneously with a single equipment development. As an example, improvements in the washing efficiency of DD washers have resulted in reduced chemical, electricity and steam consumption. A single unit consists of several washing stages in which filtrates and washing fluid can be kept separate and reused in the process. Overall, the mill capacity has increased enormously over the decades. This can be explained with the improvements in recovery boiler. The modern recovery boiler or HERB uses higher steam values and preheats incoming air and water flows, which has enabled greater electricity production and greater electricity surplus for sale to electricity grid. The HERB combines several technologies and systems, such as SCR technology to remove NO_X emissions and heat recovery system to recover heat from flue gases. Another example of a process stage in the pulp production that combines several technologies is the drying line. A new type of drying system utilizes state-of-the-art technologies to improve overall operational performance as well as cost-efficiency.

Although there have been no major changes in the basic pulping technology apart from the polysulphide cooking process developed for pulp quality improvement, some individual innovations have emerged around it. These innovations are referred to new biobased products and processes derived from the utilization of side streams. A growing demand for pulp and market opportunities for biobased products have created the concept of a bioproduct mill and further a concept of a fossil-free bioproduct mill. The idea of the fossil-free bioproduct mill is to generate all of the energy needed from its own side streams eliminating the need for fossil fuels. In the bioproduct mill, a significant amount of renewable energy is produced in the recovery boiler when black liquor is combusted. The capacity of recovery boiler has reached a point where its growth is limited by the capacity of the pulp mill. Thus, increase in the boiler capacity enables the growth of pulp mill capacity. A concept of a mega pulp mill has arisen from this where reduced investment costs per tonne of pulp is driving development. The production capacity of a mega pulp mill is over million tonnes of pulp per year.

Table 5. Innovations and key drivers of chemical pulping.

Innovations	Drivers	Achievements
Polysulphide cooking	Process optimization	Improved pulp quality
DD washers	Process and cost optimization	High washing efficiency
High energy recovery boiler (HERB)	Technological opportunities	Increased energy production
EvoDry – drying system	OHS, responsibility, technological opportunities	Increased safety and operational performance, reduced operational costs
Megamill	Technological opportunities, cost optimization	Increased mill capacity, reduced investment costs per pulp ton
Bioproduct mill	Market and technological opportunities	Bioproducts, fossil-free mill

The manufacturing of mechanical pulp is very energy-intensive, and therefore, reduction in energy costs has been a major issue in the development of this area as it can be concluded in the Table 6. In the development work of mechanical pulping, energy saving solutions have been sought in the PWG process. A diamond coated surface technology Galileo was introduced in the PWG process to improve grinding. In the grinding process, a ceramic pulpstone had been used before which resulted in a greater energy waste by heating of wood and in excessive cutting of fibres. There have been two key drivers in the development of Galileo technology; increase of capacity through reducing energy consumption and replacement of the poor ceramic pulpstone. An efficient defibration was achieved by Galileo technology, which also brought significant economic benefits in terms of increased production rate and reduced energy consumption with less variability in pulp quality.

Generally, simplification or optimization of process has emerged as a distinct development trend in mechanical pulping. As an example, a conical disc refiner was introduced in the refining process, which allowed combination of two separate processes in a single unit. Significant energy savings were achieved through developments in equipment. Moreover, developments in refiner’s blades and function as well as in the capacity of motors have led to increased overall capacity in the refining process. Simplification of process has also appeared in the development of reject treatment. In the reject treatment, number of process stages and equipment have been reduced with the adoption of low consistency resulting in energy savings.

Table 6. Innovations and key drivers of mechanical pulping.

Innovations	Drivers	Achievements
Galileo technology	Process and cost optimization	Energy saving, increased production rate
Conical Disc (CD) refiner	Process and cost optimization	Energy saving
Low consistency processing	Process optimization	Energy and cost saving

Although the basic technology in recycled fibre processing has remained relatively unchanged, there have been continuous improvements in equipment efficiency. Thus, developments conducted in recycled fibre processing have aimed at minimizing operation costs. This implies lower fibre loss and lower energy and water consumption. The innovations emerged in the recycled fibre processing are shown in the Table 7. Regarding technological developments, the use of drum pulper has become more common in the OCC process, since it has been able to replace several equipment. Simplification of process has emerged in this, which has further led to improved energy efficiency. In the refining process, lower energy consumption was sought by introducing a new type of refiner that simultaneously resulted in improved refining of fibre. Lower energy consumption was also addressed in pumps. This required adoption of high consistency in the process, and adoption of centrifugal cleaning and disc filter were solutions for it. Adoption of high consistency led to the development of subsequent process stages. As an example of this has been the development of foil and basket technology in screening and fractionation. Adoption of the technology has enabled an efficient ejection of rejects from the stock. In the end, developments in this area have been mostly related to technological improvements of equipment. Low operation costs have been the main trend driving innovation in the field.

Table 7. Innovations and key drivers of recycled fibre processing.

Innovations	Drivers	Achievements
Drum pulper	Process optimization	Improved energy efficiency
OptiFiner – refiner	Process optimization	Improved refining, energy saving
Centrifugal cleaning	Process and cost optimization	Increased consistency, less pumping energy
Disc filter	Process optimization	Improved cleaning efficiency
Foil and basket technology	Process optimization	Improved removal of rejects

The manufacture of paper has been most affected by the global decline in paper demand that has forced the paper manufacturers to resort to cost-saving solutions. Based on the summary of innovations generated in the papermaking (Table 8), most developments conducted so far in the paper manufacturing have aimed at reducing production costs by reducing water, energy and chemical consumption. On the wet end of papermaking process, product costs have been reduced along with the introduction of a new mixing technology. An efficient mixing of papermaking chemicals has been achieved with the new technology resulting in significant savings in energy, chemicals and water consumption. Similar achievements have been achieved in the web forming. In the web forming section, an existing technology has been improved with small modifications that have led to increased dewatering capacity in addition to reduced energy consumption. Additionally, adoption of multilayering in the forming section can be conducted in a single headbox reducing costs of purchasing additional equipment. In addition to resource efficiency and cost savings, quality improvement has also been the focus of development. Regarding quality improvements, removal of air and gas in the papermaking process has been improved. Furthermore, a new kind of process to produce PCC has not only brought cost savings, but also provided opportunities to improve properties of paper products. Subsequent developments in the papermaking have focused on the versatile use of raw material through energy and cost saving technology. Foam forming technology is an example of a technology that has been invested in recent years due to its wide-ranging potentials.

Table 8. Innovations and key drivers of papermaking.

Innovations	Drivers	Achievements
TrumpJet Flash Mixing system	Process and cost optimization	Improved mixing of chemicals,
TrumpJet Flash Mixing reactor	Process and cost optimization	Savings in energy, chemicals and water
In-Line PCC	Process and cost optimization	Improved paper and board properties, process integration
Sleeve roll technology	Process optimization	Improved dewatering capacity, reduced energy consumption
Multilayering	Cost optimization	Savings in equipment
Deaeration system	Process optimization	Improved air and gas removal
Foam forming	Technological opportunities	Broad range of application, opportunities in cost reductions

Table 9 shows that many innovations have emerged in the paper coating and finishing. Firstly, paper coating and finishing consists of several process stages including sizing, coating, calendering, reeling and drying. Developments at each process stage have led to generation of numerous innovations. Most of these developments have been driven by the requirements for the end product. The quality requirements for the end product are high, or at least, the same quality requirements must be achieved with less raw material and energy. Thus, resource and production efficiency as well as product quality have been key drivers in this area. Regarding coating technologies, many of them were originally old technologies that have been redeveloped and reintroduced. As an example, curtain coating that was originally used for coating album paper has become later a breakthrough in paperboard and speciality paper coating due to high coverage obtained with the technology. More attention was paid to the effects of calendering on the product quality. As a result, coating surfaces and design of calenders were improved. One of the most prominent developments has been metal belt calendering through which bulkier product is achieved with less raw material. This led to increased production and opportunities to make profits.

Increased production speeds and roll sizes demanded more reliable performance from reelers. For this, a new concept for reeling was developed. A linear reeling resulted in minimized reel change time enabling continuous reeling process. Similar features were also demanded from winders. WinBelt winder was developed to meet the demands of large roll diameter and roll weight. On the other hand, Dual unwinding was developed to minimize parent roll change time at winder. Development of subsequent processes has aimed at energy and material savings. With the Aqua cooling calendering technology, the web is cooled down before calendering increasing bulk of the end product. This enabled reduction of energy and raw material consumption. In the drying section, energy savings were achieved by drying the paper web with hot air. The high intensity air dryer enabled replacement of IR dryers leading to reduced energy consumption and increased efficiency. In the paper coating and finishing, there has been a need and opportunity to develop innovations. Equipment suppliers are constantly developing new technologies and improving existing technologies. As an example, a new application method for sizing, hard nip sizing, was recently launched. The method benefits from better penetration of starch by increased nip pressure. This leads to improve strength properties of paper fibre network.

Table 9. Innovations and key drivers of paper coating and finishing.

Innovations	Drivers	Achievements
Curtain coating	Process optimization	High coverage and layering
Barrier coating	Customer demand and market opportunities	High coverage, resistance for grease, moisture and gas
Polymer coating	Process optimization	Improved calendering process
Metal belt calender	Process and cost optimization	Material savings, better surface properties
Linear reeling	Process optimization	Reeling of large diameter rolls
WinBelt -winder	Process optimization	Lower nip load
Dual unwinding	Process optimization, technological opportunities	Reduced time in roll change, increased capacity
Aqua cooling calender	Process and cost optimization	Energy and material savings
High intensity air dryer	Process and cost optimization	Energy savings
Hard nip sizing	Technological opportunities	Better penetration of size mixture

There have been similarities in the developments of paperboard and paper manufacturing. Firstly, resource efficiency and hence cost efficiency have driven the development in both areas. In the paperboard manufacturing, the aim has been to maintain product properties with less raw material. In this area, paperboard manufacturing has been successful. When considering the factors driving the development in the paperboard production, the development driving factors are very different from paper production. Contrary to paper, demand for paperboard has been steadily increasing. Increased demand for paperboard has been mainly due to the growing demand for packaging materials, particularly renewable and recyclable packaging materials to replace plastic materials. Customer and market demand have created opportunities to packaging board and other paperboard-based solutions for end-use. Requirements from customers and end-users for products have steadily increased forcing paperboard manufacturers to develop their products to meet customer and user requirements. As an example, requirements of the food industry for properties of packaging products have led to the development of ecobarrier products that provide both applicable and sustainable option for packaging solution. This has created a new business segment for paperboard industry, which has boosted the industry to expand its application range. Food industry or food service products is not the only emerging business segment. There has been a growing demand for intelligent packaging solutions, especially in logistics and storage systems, as e-commerce and commerce generally are continuously growing. Furthermore, paperboard manufacturers or converters have taken cost efficiency into account in their product development. As a result, cost efficiency solutions have been sought from packaging design. With simplified and lighten structure, the products gain more value. The paperboard manufacturing has been focused more on serving converting, and thereby, seeking solutions to provide more value to customers and end-users. The innovations emerged in this field have been presented in the Table 10.

Table 10. Innovations and key drivers of paperboard manufacturing and converting.

Innovations	Drivers	Achievements
Eco-barrier	Customer demand, responsibility	Manufacturing of plastic-free paper-based applications
Intelligent packaging	Market demand	Improved logistics and information flow
Packaging design	Process and cost optimization, market opportunities	Improved packaging solutions

Developments in the chemicals and raw materials used in the forest industries have been influenced strongly by markets of forest industry products. According to the innovations summarized in the Table 11, the developments in the use of chemicals and raw materials have related to the optimization of processes, for example to improve process cleanliness and process efficiency. In the papermaking, cost savings have been sought from adoption of new processes, such as process to produce PCC, and raw materials, such as structured polymers and MFC in paperboard to reduce raw material costs. On the other hand, environmental concerns and responsibility have also reflected to the use of chemicals and raw materials in the way that more sustainable and environmentally friendly alternatives are demanded. This has led to the research and development of biobased and harmless materials for paper and paperboard manufacturing as well as adoption of neutral papermaking. In the bleaching of pulp, more environmental-friendly and cost-efficient alternatives have been developed for bleaching chemicals for decades ago. The actual progression in this area has been the efficient use of bleaching chemicals, which has led to increased resource and cost efficiency.

Table 11. Innovations and key drivers of chemicals and other raw materials.

Innovations	Drivers	Achievements
Neutral pH papermaking	Responsibility	Use of neutral adhesives
Precipitated calcium carbonate (PCC)	Customer and market demand, Process and cost optimization	Cost, process and resource efficiency
Structured polymers	Process optimization	Improved filler loading
Oxidizing biocides	Process optimization	Process cleanliness and efficiency, machine efficiency
Biobased materials in paper coating	Customer demand, responsibility	Replacement of fossil-based latex
Microfibrillated cellulose (MFC) in paperboard	Process optimization	Raw material savings
Enzymatic bleaching	Process efficiency, responsibility	Improved raw material and cost efficiency in bleaching

The development in digital technology and automation level has brought substantial changes to the whole forest industry. Firstly, the number of labours has decreased, since the automation level has increased. Secondly, digitalisation and development of digital technologies have created the forest industries opportunities to increase productivity and profitability. The table 12 summarizes examples of innovations introduced in the forest industry. Based on the Table 12, most innovations adopted are related to process monitoring and control which has enabled industries to optimize the entire process including optimization of resource use. These innovations involve collection, processing and utilization of data. Over the years, the amount of data has continued to grow, and the utilization of it has emerged as a challenge among industries. The latest innovations introduced in the forest industry have been aimed at improving process predictability, maintenance and repair and usability. In the pulp production, for instance, digital solutions are used to measure the pulp quality, and thereby, to enhance the yield of product quality and efficiency of plant. In some cases, such in Fiber Online Index, the driver for the development has been lack of information regarding pulp properties. This has induced the need for developing new measuring methods and calculation technologies. More advanced measurement technologies are related to contactless measurement and sensor measurement. Overall, technological opportunities are driving the forest industry to rely on advanced technologies and digital solutions.

Table 12. Innovations and key drivers of automation and digital technology.

Innovations	Drivers	Achievements
Process control system (PCS)	Technological opportunities	Process control and management
Manufacturing execution system (MES)	Technological opportunities	Process improvement
Data acquisition system	Technological opportunities	Monitoring of equipment condition
Non-contacting measurement	Technological opportunities	Advanced measurement
Soft sensor	Technological opportunities	Advanced measurement and process control
Fiber online index (FOX)	Technological opportunities, process and cost optimization	Real-time monitoring of pulp quality
Fiber GPS	Technological opportunities, process and cost optimization	Real-time simulation and optimization of processes
LumiKem	Cost and process optimization	Optimization of chemical use and water process control
Laser and x-ray measurement	Technological opportunities	Material and process optimization

In general, the idea behind generation of byproducts and further processes products has been creation of value added from the side steams of chemical pulping. The table 13 includes some significant products generated from pulping over two decades. Potential of lignin in various applications has been discovered decades ago, but their implementation has been impeded by lack of viable extraction and conversion technologies. In recent year, there have been a few prominent technologies of which the first associates with the extraction of lignin from black liquor and the latter with conversion of lignin into workable form for various applications, for example concrete plasticizer. Other byproducts of the pulping are methanol and sulphuric acid which both can be purified and converted into commercial products. It has been environmentally and economically viable to recover these compounds and further process for mill own use or to sell outside mill. By installing methanol and sulphuric plants on the side of pulping process, pulp mills can improve partly their self-sufficiency in energy and chemicals. Regarding cellulose-based product, a new technology called AaltoCell has been developed to produce MCC and a technology to produce dissolving pulp has been improved. The idea of the AaltoCell technology is to use much less acids in the process contributing less to environment and saving costs from further processes at the same time. The challenge in the production of dissolving pulp has been maintaining fibre quality with a continuous cooking. With modifications in the equipment components, hemicelluloses can be removed effectively through a continuous pre-hydrolysis cooking. This created opportunities in Asian markets where the demand for textile fibres is high.

Table 13. Innovations and key drivers of byproducts and further processed products of pulp.

Innovations	Drivers	Achievements
LignoBoost	Market opportunities	Extraction of lignin from black liquor
LingiOx	Responsibility, market opportunities	Workable form of lignin for various applications
Methanol purification plant	Cost optimization, responsibility	Alternative fuel, self-sufficiency
Sulphuric acid plant	Cost and process optimization, responsibility	Production of process chemicals, reduction of wastewater load
Aalto Cell – MCC technology	Responsibility, cost optimization	Reduced chemical consumption and costs
Pre-hydrolysis	Process and cost optimization	Effective removal of hemicelluloses

Environmental and sustainability issues play a crucial role in every development work conducted in the forest industry. Moreover, emergence of many innovations in the forest industry have been driven by environmental sustainability. Examples of some of these innovations have been compiled in the Table 14. The forest industry has aimed to produce its needs from its own raw materials. This applies to the energy that pulp mills in particular aim to produce in their own process from its own raw material, and thereby, reducing the use of external fuels, especially fossil fuels. Among pulp mills, the concept of fossil-free mill has become a sort of trend which has led pulp mills to adopt new energy solutions. As an example, gasification and steam explosion have been reintroduced in pulp mills. Bark biomass is used in these technologies to either to substitute fossil fuels used in lime kiln or to produce alternative energy product. Other energy solutions are related to firing of biomass. In this, sawdust and biosludge can be used. Adoption of these energy technologies have led to improved self-sufficiency and cost-efficiency of mills.

Besides energy technologies, the forest industry has taken environmental protection seriously. The industry has put effort to minimize its environmental impact on water, air and land. Pulp mills have been targeted with pressure to reduce emissions to air. Attention has been paid to NO_x emissions of recovery boilers, in particular. This had led to the development of SNCR technology, and in general, to the continuous development of this specific area. Regarding water management, adoption of ultrafiltration has led to reduced freshwater consumption at mills, and moreover, reduced energy cost in heating freshwater. Besides reduced water consumption, efforts have been made in reducing water load and improving overall efficiency of water use. Recent developments in this field have focused on combining energy production and water treatment. As an example of this, biogas can be produced from wastewater in a membrane bioreactor.

Table 14. Innovations and key drivers of energy and environmental protection.

Innovations	Drivers	Achievements
Biomass gasification	Responsibility	Energy savings, material efficiency
Steam explosion	Responsibility, process optimization	Steam production and production of pellets
Pulverized fuel firing	Responsibility, process optimization	Energy production
Biosludge firing	Responsibility, process optimization	Energy production
Membrane bioreactor (MBR)	Responsibility, process optimization	Production of biogas from wastewater
Ultrafiltration	Process optimization	Reduced freshwater and energy consumption
SCR/SNCR technology	Responsibility	Lower NO_x emissions

Wood products industry has its own market and is therefore considered separately from fibre-based industries like pulp and paper industry. Nevertheless, there are similarities in the trends that drive the development in the wood products industry. Firstly, climate change, urbanisation and population growth have contributed positively to wood products industry by creating market opportunities in construction segment. Wood products for construction have received positive response for having a long-term effect on carbon storage, and thereby, climate change mitigation. This has boosted the use of engineered wood products in wood construction, particularly in urban construction. Although there has been progress in the construction of wooden multi-storey buildings, construction is still restricted by regulations. Restrictions have also derived from legislative authority on industrial activities, which has forced the wood products industry to lean over resource-saving and cost-saving solutions.

As an example, adoption of finger joint in the manufacturing of basic wood products has brought some material savings as knot containing woods are accepted in processing. Another technical development has been non-settling log. Development of laminated log product eliminated settling of log structures increasing efficiency of log construction and its use in other large-scale constructions. Innovations of the wood products industry are presented in the Table 15.

Table 15. Innovations and key drivers of wood products industry.

Innovations	Drivers	Achievements
Engineered wood products	Market opportunities, responsibility	Enhanced position of wood in urban construction
Finger joint	Process and cost optimization	Raw material saving, improved visual appearance
Non-settling log	Process and cost optimization	Energy efficiency, expanded use of log
Urban wood construction	Market opportunities, responsibility	Wooden multi-storey building, prefabrication of elements

Table 16 compiles examples of some significant innovations in new wood-based materials and products. The development of these innovations has been greatly influenced by sustainability and environmental issues. Replacement of fossil materials, in particular plastics, has been a hot issue in recent years. This has boosted the forest industry actors to develop substitute products and materials which demand has been booming. As an example of products that address the current sustainability issues is biocomposites, biofuels and biochemicals. The idea behind these products are very similar: substitution or alternative to fossil-based materials. Current production capacity of biofuels is insufficient to meet the demand. Thus, market opportunities are driving the development of this business area, especially in terms of increasing capacity and developing scalable technologies. As with biofuels, the development of biocomposites is currently driven by market opportunities. There are partially substitutive biocomposites on the market, but the challenges have emerged in recycling of the products. Therefore, the business area of biocomposites has also been focusing on discovering new materials that would meet the criteria of both recyclability and biodegradability. Unlike biocomposites and biofuels, the business area of biochemicals is quite young and not fully established yet. There is ongoing planning on investing in a biorefinery to produce fully wood-based biochemicals. However, the challenges lie in converting technologies and in their scalability. Success in this allows the forest industry to enter the new business area and market. Regarding wood-based materials, nanocellulose has been a popular research topic for years. This can be detected in numerous publications which present a wide application range of nanocellulose. Due to the wide market potential, developments in this area are focused on scaling up of production. Another emerging research area has been textile fibres where significant advances have been made. Technologies to produce textile fibres or wood-based textile fibres sustainability have been the achievements of this decade. This has enabled the forest industry to enter the new business area which development is driving by the growing demand for textile fibres.

Table 16. Innovations and key drivers of new wood-based materials and products.

Innovations	Drivers	Achievements
Nanocellulose	Market opportunities	Expanded application range
Biocomposites	Responsibility, market opportunities	Substitution of fossil-based materials
Biofuels	Responsibility, market opportunities	Alternative for fossil-based fuels
Hydrogen treatment process	Process optimization	Production of advanced biofuels
Biochemicals	Responsibility, market opportunities	Alternative for fossil-based chemicals
Wood-based textile fibres	Responsibility, market opportunities	Environmentally friendly method to produce textile fibres

Table 17 summarizes some Finnish wood-based start-ups and information related to their innovations. As the Table 17 implies, sustainability has been the main driver in the innovation of these start-ups. Most of these start-ups have emphasized their innovations to combat current and future sustainability issues like accumulation of plastic wastes and availability of sustainable raw materials. Among these start-ups, at least Paptic, Sulapac, Aqvacomp, Woodly and Dolea Straws have emphasized their innovation to contribute to the reduction in the accumulation of plastic waste. The idea behind product innovations of these start-ups is either to replace the share of plastics in the product completely or partially. Regardless, the purpose is to prevent the release of plastics into the environment while mitigating the environmental impact. The trend of plastic replacement has been frequent, especially in packaging products and materials. Consumer and design products appeared later on the pattern. Another emerging trend has been textile fibres. At least, Spinnova and Infinited Fiber Company have worked on developing new methods to produce or process textile fibres. Achievements have been made in the production of textile fibres from recycled fibres or wood-based fibres with energy, chemical and water saving technologies. Thus, market opportunities have opened in the textile industry. Other potential markets are found in medical and pharmaceutical industry. Among the Finnish start-ups, Onbone, Repolar and Montisera with its daughter companies are working in this area. Onbone started its business with a sustainable and ecological solution to gypsum. Instead of using impractical disposable gypsum, Onbone’s gypsum made of wood and biodegradable plastic can be moulded and reused. Montisera and Repolar are special in the regard that they use wood constituents instead of using wood fibres in their products. The idea behind the product innovations of these start-ups is to promote human and animal welfare with effective constituents of wood. All the innovations listed in the Table 17 are one way or another part of the circular bioeconomy by prioritising the use of raw materials for greater resource efficiency.

Table 17. Examples of Finnish wood-based start-ups and their innovations.

Start-up	Innovation	Drivers	Achievements
Spinnova	Wood fibre spinning technology	Sustainable textile industry	Industrial pilot scale in 2018
Paptic	Plastic replacing packaging products	Sustainable alternative to plastic films	Industrial-scale production line in 2018[1]
Infinited Fiber Company	Technology producing fibre from recycled fibre and cellulose	Sustainable and cost-efficient fashion	Production plant of 25,000 t/a in 2020-2021[2]
Sulapac	Biodegradable and microplastic-free wood-based material	Sustainable material replacing plastics	Investment of 15M€ for scale-up and internationalisation[3]
Jospak	Recyclable cardboard tray	Sustainable food industry	Third production line to commence in Spring 2020[4]
Aqvacomp	Biocomposite for plastic reinforcement	Sustainable substitute for plastics	Production capacity of 5,000 t/a in Rauma[5]
Woodly	Wood-based transparent packaging material	Ecological and sustainable packaging products	2M€ of growth funding[6]
Lumir	Wood-based acoustic products	Better acoustics with wood fibres	Winner of the Bio and Circular Economy growth path in 2019[7]
Woodio	Waterproof wood composite products	Ecological materials for bathroom products	Investment funding of 4M€ (Metsä Spring as notable investor)[8]
Betulium	Water-based cellulose materials	Replacement or supplement of synthetic organic polymers	Investment from Bang & Bonsomer Group since 2017[9]
Dolea Straws	Recyclable, biodegradable and custom printable drinking straw	Sustainable drinking straw	Honourable mention in the Bio and Circular Economy Growth Path in 2019[7]
Onbone	Wood cast product	Non-toxic and biodegradable medical products	Investment of 10M€ for international launch[10]
Montisera	Bioactive compounds	Patents, IPRs and trademarks	Two daughter companies (Montinutra and Montipharma)
Montinutra	Bioactive compounds for medical and food industry	Bioactive extracts with health benefits for food and pharma industry	Pilot-scale production facility to be built in 2020[11]
Montipharma	Bioactive compounds for pharmaceutical industry	Clinical development phases of medicine and food ingredients	Plan to enter Phase I clinical development in 2020[12]
Repolar Pharmaceuticals	Resin based health care products	Resin-based products for human and animal care	International business growth[13]

[1] Paptic. 2017. Finnish startup company Paptic is planning a paper machine investment to challenge plastic production (release).
[2] Goodnews. 2019. Infinited Fiber Company raises EUR 3.7 million (press release).
[3] Sulapac. 2019. Saving the world from plastic waste comes one step closer – Sulapac raises eur 15 million in a fully subscribed financial round (press release)

[4] Epressi. 2020. Finnish Jospak collects a million euros in funding – production capacity of ecological food-packaging trays to increase significantly (press release).
[5] Metsä Group. 2017. Metsä Group softwood pulp to be used in LG's loudspeakers (press release).
[6] Woodly. 2019. Award-winning Finnish innovation Woodly completes funding around, raising €2 million (release).
[7] UPM. 2019. UPM supported bio-based and circular economy startups at Kasvu open (release).
[8] Woodio. 2019. Metsä Spring Ltd. joins Woodio (release).
[9] Epressi. 2017. Bang & Bonsomer tekee strategisen investoinnin nanoselluloosayhtiö Betuliumiin (press release).
[10] Goodnews. 2015. Onbone to expand through EUR 10 million investment (press release).
[11] Kolster. 2019. Montisera commercialises promising bioactive compounds – Montinutra revolutionises the circular bioeconomy (press release).
[12] Montipharma. 2019. Novel solutions to tackle some of the most burning global health issues (website).
[13] Goodnews. 2015. Finnish spruce resin heals around the world (press release).

During the empirical study, interviewees were asked to name the most significant innovations emerged in the 21st century without defining the concept of innovation in advance. Most interviewees perceived innovation as an outcome of a process or technology improvement or product development and provided description of the developments in their area of expertise and examples of innovations behind the developments. Nevertheless, there were cases where sufficient information on innovations were not provided. This led to the search for additional information in the literature. It has to be reminded that the semi-structured interview method has allowed interviewees to review the interview themes and questions from their own perspective. Therefore, there might have been incoherencies between descriptions of innovations. In addition, the interviewee's background and experience have had some degree of impact on the availability and quality of the results. Those interviewees who had been involved in the development of innovation were able to provide more accurate information on innovation. This was reflected in the quantity or quality of the innovation descriptions. In the opposite case, the interviewees were able to describe better how the forest industry in a particular area has developed. Otherwise, there were deficiencies in the results regarding innovation examples, but not necessarily in developments and drivers. Nevertheless, developments and drivers are important in terms of results, but through innovation examples they could have also be inferred. In this study, quality of interviews is more essential than quantity of interviews. This clearly appeared as the problem of this study.

Regarding the concept of innovation, some interviewees also perceived innovation as small improvements in production. These improvements were mainly referred to development ideas or suggestions for improvement from employees. Rather than consider this as innovation, it is counted as a measure to indicate innovativeness or innovation activity. According to the statement of Production Director of a grown company, "innovation that cannot be transformed into commercial products and profitable industrial business does not curry much significance" (Production director, Appendix 2). Based on this statement, potential innovation or discovery which has not yet been commercialized or is still in the pilot phase cannot be considered as innovation. This applies to various innovations or discoveries emerged so far in the empirical study. However, these 'non-commercialized' innovations have been brought out due to their promising market opportunities. Successful marketing drives innovation forward, while challenges in the development phase of innovation retards the innovation process. As an example of such innovations is nanocellulose which breakthrough has been slowed down by high production costs. On the other hand, it has been claimed that the challenges of nanocellulose are rather discovering of new and innovative applications than production methods (Martikainen 2018). In addition to nanocellulose, there are many other innovations that are facing similar challenges either in the phase of development or commercialization. In the empirical study, the interviewees have been mainly focused on successful and promising innovations rather than failures.

When reviewing drivers of innovation in the forest industry, there have been more than one driver behind the creation of innovation in reality. In this study, one of the intentions was to find out the main driver behind the development of a particular innovation and other possible drivers in order of importance. Most interviewees could not name just one single driver, because they found several drivers to be equally important. When it comes to the most recurrent driver in the empirical study, **efficiency** was one of the main drivers highlighted by interviewees. This has been merged in the category of 'process and cost optimization' shown in the Tables 4-17. Efficiency plays a major role, especially in industrial production, where efficiency is often related to the cost savings. Cost savings or **cost efficiency** derives from the use and consumption of resources, such as water, energy and raw materials. In almost all industrial processes, the aim has been to maximize resource use while minimizing resource consumption. This has led to development of various technological innovations that have been adopted in industrial production. These technological innovations are often referred to improvements or developments in equipment or components, which result in slightly or considerably improved process, and improvements in existing technologies or development of completely new technologies, which implies changes in raw material use and process conditions. From the perspective of end-product, the appearance or properties of end-product can be preserved or improved over implementation of technological innovation. Speaking of outcomes, **quality improvement** has been one of the main drivers in industrial production before. Before the 21st century, developments were carried out in terms of the end-product quality even at the expense of consumption and load accumulation. Afterwards, developments have been aimed at reducing consumption and load assuming that the quality of end-product remains at least the same. All in all, quality, costs and consumption of water, energy and raw materials are the basic assumptions in the development work of industrial production.

Based on the Tables 4-17, 'responsibility' was the second repeated category after the 'process and cost optimization'. Responsibility is often reflected in companies' commitment and goals regarding forests, environment, people and society. For the forest industry actors, responsibility originates from certified forests and runs through the whole value chain. Forest certification has appeared to be essential in all kinds of business operations in the forest industry. With forest certification, forest industry actors ensure that their forest management and supply chain are sustainable. **Sustainability** as a part of responsibility has probably been one of the major drivers of innovation during the past decades along with efficiency. The motivation of companies to promote sustainability in their actions derives from their own willingness to act in accordance with sustainable development, but also from **political and regulatory pressure**. All reporting and permits, such as emission standards and environmental permits, are supervised by governmental authorities. For the environmental permit, the use of Best Available Techniques (BAT) is one of the conditions to reach the permitted emission limits. This forces companies or industrial companies to rely on more efficient technologies and clean processes, which in turn drives development of innovation. One important aspect that received little recognition in empirical study was **safety**. Generally, occupational safety and health (OHS) plays a central role in all kinds of industrial activities. In the empirical study, however, only a few interviewees raised the safety issue in the development work or development of innovation. Safety as a driver appeared only in two innovations according to the Tables 4-17. Apparently, safety appears to be more relevant to industries where stricter safety requirements often lead to improvements in equipment and machineries.

Another important factor in the development of the forest industry has been 'technological opportunities' brought mainly by digitalisation and automation. Raising the level of automation has simplified processes and increased operational reliability of machineries.

Process automation has emerged especially in paper coating and finishing as well as in wood handling where machines based on automation are being constantly developed. Meanwhile, digitalisation has had a greater impact on the forest industry. Many of the innovations in the Table 12 have been developed due to lack of detailed data on wood quality during the process or the need to optimize costs and use of resources. **Digital technology** solutions have enabled the forest industry to create value added to their operations through evaluating and identifying wood quality, and thereby, optimizing the whole wood supply chain. Thus, developments related to the process and cost optimization have involved the use of digital technologies. A combination of these has become common in the development of innovation. Another increasing trend has been integration of **intelligence** in both processes and products. This has led to development of intelligent packaging and paper products, and furthermore, exploitation of **artificial intelligence** in industrial use. In recent years, there has been intense discussion of AI and other emerging phenomena such as **IoT** and **Industrial Internet**. These phenomena have been already addressed in the development of the forest industry, but achievements in this area have been inconsistent so far. IoT solutions as drivers of innovation were brought up mainly by interviewees from industrial companies. However, only one interviewee gave examples of innovations in which IoT solutions have been utilized. Another interviewee stated that the use of IoT solutions has been at different levels among industries. In some industries, technologies have been only tested for individual processes. Few industries have succeeded in expanding the use of IoT solutions throughout the mill. In this, the challenges have arisen from the availability of large amount of data and how to use the data inside and outside the mill.

After all, innovation in the forest industry is mostly driven by **market** and **demand**. Although 'market opportunities and customer demand' appeared as the main driver mainly for new wood-based materials and products (Table 16), it has been inevitably behind the development of almost every innovation. Fluctuating trends and long-term megatrends have constantly brought about changes in global market situation and demand, which in turn affects consumer behaviour. From global sustainability megatrends, climate change was identified by most interviewees as one of the most relevant factor driving innovation in the forest industry. Adaption to climate change has pushed the forest industry towards biobased **circular economy** or **bioeconomy**, which has become a strategic mean for the forest industry to promote its **competitiveness**. Promotion of sustainability is a key objective of the bioeconomy. This has accelerated phase-out of fossils and replacement of plastics to which the forest industry is striving to address with biobased, biodegradable, recyclable and compostable alternatives. Despite the focus of innovation, innovating for sustainability has become a critical means of survival for the forest industry actors as the global competition in the changing environment has become more intense.

4.2 Finnish forest industry development during the past 20 years

The transformation of the Finnish forest industry had already begun by the end of 1990s. At the time, the golden era of the Finnish paper industry was over as the market for printing paper reached its saturation point. This led to reduction in production capacity and relocation of production to low-income countries. Meanwhile, the Finnish forest industry sought for survival means from cost-effective solutions and emerging markets. It was not until the late 21st century that a new era of circular and bioeconomy began. As a part of the national strategy, the bioeconomy helps to achieve the Sustainable Development Goals (SDG) which include responsible production of supplies and food as well as climate actions and promotion of education (Hetemäki et al. 2017). The bioeconomy promotes sustainable use of renewable resources like forests to create added value. This has boosted the Finnish forest industry to create new products, processes and services which has subsequently led to the renewal and development of the industry. However, these changes have influenced and reflected differently the structure and operations of the forest industries. This chapter reviews the changes taken place in the forest industry by different industrial fields and themes.

It has been evident that the size of pulp mills has increased enormously during the past decades. Although there have been no major changes in the basic technologies, great development has occurred in the capacities in general. Beginning from the log handling, where automation level and adoption of improved process measurement and controls have enabled higher up-time and quality, the increase in log intake capacities have reflected through the whole wood handling including chipping capacity, storing capacity and chip screening capacity. Generally, increased mill capacities or mega size pulp mills have been the driving force for continuous increase in line capacities. As typically at pulp mills, the department of wood handling has also had a trend in utilizing side streams and secondary energy sources. Trends in external biomass treatment technologies like pulverized fuel firing and biomass gasification have provided more opportunities in the department of wood handling. Development work in the wood handling has associated with technologies improving internal use of biomass, in addition to the development of wood handling equipment. Further developments aim to implement and integrate technologies into existing pulp mill infrastructure and system to increase energy-sufficiency and cost-efficiency of the mill.

When considering the factors behind the capacity increase of pulp mills, energy in various forms and applications have actually been the most important. Perhaps the most significant development on the energy side has been the increased electricity production. There have been several technological developments involved in this, such as efficient washing equipment, but developments occurred in the recovery boiler can be considered as the key factor. First, adoption of higher steam values and pre-heating of incoming steams in the recovery boiler have allowed for greater electricity production. Greater energy production allows for a greater mill size. Greater mill size usually implies less waste heat and electricity. This has been one of the reasons for the decline in the mill's own energy consumption. As a result, the share of surplus in energy consumption and production has increased over the years, whereby more energy can be sold, and thus, lower production costs per tonne of pulp are achieved. Over 20 years, the capacity of pulp mill has become a limiting factor for the growth of the recovery boiler capacity, whereas ten years ago it was the opposite. The capacity of the recovery boiler has nearly tripled in 20 years, as well as the pulp production capacity, leading to million tonne pulp mills.

Million tonnes of pulp mills have also raised questions about the environmental impacts of pulp mills. It has not been exception that the construction of a pulp mill raises concerns about emissions to water systems, air and land. In the past, pulp mills had been accused of causing eutrophication and pollution of water systems. A major improvement in wastewater treatment and a significant reduction in wastewater load occurred in the 1990s, when biological wastewater treatment was introduced (Manager, mill services, Appendix 2). From the 1990s to the present, pulp mills' emissions to air, water and landfill have decreased significantly (Figure 23). More efficient washing equipment, recycling of filtrates, banning of landfill waste and more efficient technologies have enabled these achievements. Among all of the pulp mill emissions, NO_x emissions started to receive attention later compared to other emissions, and therefore, the reductions in NO_x emissions are smaller than in others.

For these, SCR and SCNR technologies were introduced in recovery boilers. After all, emission limits are mill-specific cases and environmental permits site-specific.

The cases gone through so far have mainly concerned chemical pulping or Kraft pulp mills. In the meantime, there has been a struggle for survival on the mechanical pulp industry. As the paper industry plunged into crisis after 2007, large investments in the mechanical pulp industry were few and far between. In terms of trends, developments in the mechanical pulp industry have been similar to those in the paper industry. Quality dominated before the 1990s after which more attention was paid to energy. Energy saving projects became more important and cost savings were sought by reducing energy consumption. Within this framework, process development was carried out in the manufacture of mechanical pulp. As a result, a new grinding technology based on diamond surface, was developed. New technology brought significant savings energy and enabled capacity growth in the CTMP process. In the meantime, capacity in the TMP has also been increased with an improved CD refiner. Along with process or equipment development, the development of blade in the TMP process has been carried on. Today, most of the mechanical pulp capacity is still in printing and writing or newsprint and in SC/LWC paper which demand has been weakening. This has been reflected in the closure of lines and capacities, especially at the end of the old lines. However, paperboard grades are growing for the most part, and therefore, major investments are targeted at this area. Another growing trend in the mechanical pulp industry has been the conversion of existing production plants to produce kraft liner, whereby CTMP can be partially used in the product. The need to develop cheaper conversion methods has driven the development forward.

As revealed in the development of the mechanical pulp industry, the paper industry has faced challenges to survive in the changing business environment. As the use of digital media has become more common, demand for paper especially for printing paper and newsprint has continued to decline. This has led to overcapacity in the paper industry, which has forced many paper machines to shut down or to be sold or to seek for means of survival. Since then, the paper industry has focused more on minor investments like cost-saving projects to cut down energy, water and chemical consumption. Thus, less large-scale investments have been conducted in the paper industry apart from conversion of existing paper machines into paperboard machines. In recent years, the forest industry has shifted gradually from paper to paperboard which demand has been steadily growing. Megatrends like globalisation, urbanisation and population growth as well as trends in e-commerce have contributed to this change. However, not all paper machines are suitable for conversion, therefore the need to develop more cost-efficient converting methods has pushed the development forwards in this area. In the meantime, the paperboard industry has focused on improving paperboard in terms of quality and cost saving. Improvements have been made in the lightness of the paperboard. Same paperboard properties have been preserved with less bulk. This has brought savings in raw material costs. Furthermore, the paperboard industry has managed to expand its application scope and enter new markets.

Trends in the paper and paperboard market have directly affected the trends in raw material for pulp grades. Tissue market has grown steadily during the past decade, therefore the market for recycled fibres has been on the DIP. Regarding the tissue market, about 4-6 new DIP lines are built globally each year. On the other hand, setup of new news lines has been very rare over the past decade. A lot of new OCC lines are built around the world every year, and their markets are about tens of lines annually. When considering developments in the recycled fibre processing, the capacities have generally increased, and specific energy consumption has decreased. Process and equipment developments have been carried out according to low operating costs, which imply lower energy and water consumption as well as lower fibre loss. Progress has been made in reject treatment where rejects could have been separated into distinct fractions. A lot of attention has been paid to this, particularly in the recovery and further processing of fractions, since pressure has been exerted mills to minimize amount of waste.

The wood products industry has a completely different market compared to the fibre-based pulp, paper and paperboard industries. As most sawn wood and wood panel products are exported, price competition on the global market has been tough for the Finnish wood products. Although the Finnish wood products are known for their good raw material quality, the final price of the wood products including labour and transportation costs may make the Finnish wood products less attractive compared to other competitors in European countries. Globalisation has greatly affected the Finnish market for wood products. It has expanded Finnish exports of wood products, for example to Asia, but also brought more competitors to the market. The wood products industry has faced many challenges during the past decades. Firstly, the recovery from the financial crisis after 2007 has led to the closure of many industries. (Loukasmäki 2015) This applies mostly to sawmill, joinery and furniture industries. Decline of traditional industries has forced the whole wood products industry to seek survival from cost savings, and therefore, the industry has focused on process improvement. Although the basic processes have remained pretty much the same, individual improvements have been carried out, for example in drying technology and wood panel adhesives. Nevertheless, the wood products industry has been criticized for the lack of innovativeness (Finnish Forest Association 2019; Finnish Woodworking Industries federation 2019). Since the forest industry is strongly associated with the bioeconomy, the development of new wood products and solutions is an important part of the bioeconomy strategy realization. Urbanisation, population growth and promotion of low carbon have driven the development of urban wood construction. One of the most significant achievements has been in urban construction which has opened up a whole new segment for the wood products industry. Another major development behind this achievement has been engineered wood products, especially CLT that has been approved in the urban construction. While the urban construction market is increasing, the wood products is struggling with wood construction legislation. The aim is to remove additional regulations that impede wood construction and thus promote low-carbon urban living.

Overall, recovery from economic difficulties and transition to the bioeconomy have driven the forest industries to shift towards new business models that focus on the production of high value-added products along with traditional forest industry products (Pätäri 2010). Pulp mills have managed to renew their image in processing valuable production side-streams into high value-added products. Nowadays, pulp mills or integrated mills are referred to biorefineries or bioproduct mills or even to forest-based bioeconomy (Hurmekoski and Hetemäki 2013; Näyhä, Pelli, and Hetemäki 2015). Renewal of the image has brought changes not only externally but also internally. Thus, it is essential to consider the changes occurred inside mill. Firstly, energy balance and material flows are considered at the whole mill level instead of departmental level leading to increased overall efficiency at mill. In terms of efficiency, mills are shifting from partial optimization to total optimization. At this point, digital technologies emerge as a key factor enabling upgrade of efficiency. Digital technologies enable introduction of advanced control, monitoring and measurement techniques. In addition, more data is obtained from raw material and processes and transferred faster from forest to mill. Beginning from the forest, the end use of the log can be optimized best for its applicability.

4.3 Prospects of innovations in the forest industry

The 2020s will be hectic and urgent for the forest industry as well as for industries of other sectors, while the EU has set itself ambitious climate change and energy targets for the year 2020 and 2030. The targets defined in the strategies of 2020 and 2030 are prerequisites for the transition towards a low-carbon economy linked to the long-term strategy of 2050. (European Commission 2011) In addition, the EC has set and updated its Bioeconomy Strategy to accelerate the deployment of sustainable circular economy maximizing its contribution to the Sustainable Development Goals (SDGs) at the same time. (European Commission 2018) These boost the transition towards a carbon-neutral bioeconomy that is both an urgent challenge and an opportunity for the forest industry. First, how the forest industry intends to adopt the Bioeconomy Strategy and will there be enough forest biomass available to meet the demands of the bioeconomy. This has raised questions about the forest use of the forest industry, and whether forests can be felled sustainably without reducing number of carbon sinks. Various quarters have had their own ways to calculate felling volumes and carbon sinks resulting in somewhat conflicting information and statistics (Business development director, Appendix 2). This has been a sensitive subject for the forest industry actors, but most of them believe that the Finnish forest use is on a sustainable basis. According to a few forest industry representatives, the Finnish forest management is in line with sustainable development allowing increase in felling volume as long as the forest use is lower than the annual growth. On the other hand, the intention is not to increase the use of forest resources, but rather to increase the financial use of forests through diversified exploitation of forest biomass.

Based on the findings of the study, trends and megatrends affecting the development and innovation of the forest industry in the near future have been summarized in the Figure 26. The transition to a biobased circular economy or, more specifically, the implementation of the Bioeconomy Strategy will keep the forest industry busy in the coming decades. One of the main goals of the Finnish Bioeconomy Strategy is to secure the competitiveness of bioeconomy sectors (MEE 2014). In order to maintain the competitiveness in the changing business environment, the Bioeconomy Strategy will inevitably force the forest industries to upgrade their business models, strategies and capabilities. In a response, the forest industries develop innovative products and services based on wood biomass, for example renewable biobased fuel for energy use and transport to curb carbon dioxide emissions accelerating climate change, biodegradable and recyclable bioplastics and biocomposites to combat plastic accumulation in environment, and sustainable textile fibres from recycled waste or wood to fill the gap in the demand of textile fibres. The aim is to utilize all components of the wood biomass such as bioactive ingredients that are used in pharmaceutical and medical applications. The development allows the forest industry to enter completely new markets while expanding its customer base to other sectors. In the meantime, it drives the creation of new companies and start-ups which play an important role in delivering new ideas and accelerating the diversification of the industry. Collaboration between different actors and stakeholders is needed to drive new innovative ideas to industrial scale and eventually to commercialization. This concerns particularly research institutes and universities whose studies tend to remain in laboratory scale. As appeared in the empirical study, representatives from growth and SME companies have expressed their frustration with potential ideas and studies that have not been taken forward. In the case of research institutes and universities, this may be partly due to a lack of proper network or partnership or simply lack of financial aid. No development or result can be achieved without financial source. At this point, legislation and politics have a great impact. They can both further and restrain the bioeconomy transition of the forest industry.

Figure 26. Megatrends and trends affecting innovation in the forest industry. (Nguyen 2019)

In the bioeconomy transition, the aim is to create favourable conditions for business and investment environments that support the emergence of new bioeconomy solutions (MEE 2014). Policy and other legislative measurements can be used to support and facilitate the bioeconomy markets and innovations ensuring at the same time that the raw material use is on a sustainable basis. In the empirical study, some interviewees indicated that there is still much room for improvement in the current policies and regulations governing the use of forest and natural resources, in general. There is a need to identify and remove potential barriers that may cause delaying in the market entry of novel products and technologies as well as develop tools to facilitate the bioeconomy transition. It should be ensured that there are no unnecessary policies or regulations imposed to the use of forest biomass compared to other competitors (MEE 2014). As an example, the wood products industry is struggling with unnecessary regulations that prevent the construction of higher wooden multi-storey buildings and impede urban wood construction. In the meantime, biochemicals do not have a separate support system like biofuels which could facilitate and extend their use in current applications. In these cases, different policies are applied to distinct stages of the forest-based value chain in different ways. This increases the complexity of the bioeconomy policies, which may impede the introduction of new forest-based solutions and innovations. Moreover, policies and regulations tend to pursue economic benefit over environmental benefits of which the latter is important for forest-based businesses. Thus, policy and regulatory framework for forest-based business should be developed from both an environmental and economic point of view.

The prospects of the forest industry depend on the perspective. In terms of market growth, traditional forest industry products like paper and sawn wood may give a different perspective on the future of the forest industry compared to new wood-based products. While markets for traditional forest industry products continue to stagnate or decline, the markets for new wood-based products are expected to grow. The forest industry aims to seek growth from diversified businesses while addressing global sustainability challenges. The solutions rely on new wood-based products or innovative bioproducts. Firstly, environmental sustainability challenges, such as climate change, resource scarcity and global warming, will be present in coming decades. These force societies to adopt new models to move from a linear economy to a circular economy. In the circular economy, minimum amount of waste and loss are created beside production and consumption of goods and services. This implies major change in consumer behaviour. Consumers can contribute significantly to sustainability through their choices. Therefore, it is important to increase consumers' awareness and educate them. The same applies to producers and retailers who should make their value and supply chain more transparent emphasizing the sustainability impacts on environment and economy. This can be promoted through proper communication channels and marketing approaches. More effective marketing approaches are required from the government and companies. The forest industry companies have expressed their concerns about skilled labour, especially young talent. All sectors of the forest industry are competing for skilled labour. Therefore, advocacy work and image advertising are important in order to excite people, especially young people in the industry. The forest industry companies have put effort in influencing education and thus people's thought about the industrial sector based on sustainable values and sustainable development. Education related to this area should be provided in future.

In general, the forest industry actors see the future of the industry as positive. Despite of negative impact of digitalisation and ICT on the graphic paper market and demographic developments on solid wood products market, the demand for packaging and tissue products continue to increase globally due to increasing e-commerce and consumption. With increasing consumption, there will be a great demand not only for renewable but also for recyclable materials. Renewable or biobased is not enough alone, but recyclability is required. This is distinctively reflected in plastic replacing products which demand is expected to grow. Availability of renewable resources will tighten as capacities increases. Not all current products can be replaced with forest biomass, therefore competition over raw materials, especially sustainable raw materials, will be present in the future. On the other hand, competition and development of resource use are currently and will be monitored with EU rules and certification, in the case of forest use. The forest industry companies can contribute to this by ensuring their raw materials to be procured from sustainably and responsibly managed forests. To ensure the competitiveness of forest use, the wood raw material should be as sustainability and well procured as any wood used in wood processing. In addition, the supply chain should be transparent. The goal of the forest industry companies is to have all wood used certified.

The future of the forest industry is to adapt global trends to the needs of society. Global trends or megatrends, notably digitalisation will be a major factor driving the transformation of the forest industry. A massive amount of data is already available, but the challenge arises from its utilization. Utilization of a large amount of data for in-mill and inter-mill use will play a key role in the digitalisation of the industry. Digitalisation of industries have generated majority of the current phenomena, such as IoT, Industrial Internet and machine vision. How these technologies can be utilized in mills is currently explored. Over digitalisation, state-of-art technologies can be introduced at the mills to improve the overall efficiency of mill. Information on the quality of the raw material is obtained at the early stage of chain allowing the subsequent processes to be adjected accordingly. The following trends in this area will be the introduction of AI and remote solutions as well as robotics. These have gained a lot of attention among the forest industry representatives, but the actual implementation degree of them varies depending on the fields. Apparently, the use of state-of-art technologies is more advanced at pulp mills, while in most of fields the use is still applied to a single process. Nevertheless, digital technologies will bring about major changes in the forest industries. At the same time, they can put additional pressure on the forest industry to achieve the highest cost-effectiveness.

5 Conclusions

The aim of the thesis was to provide insights into the development of the Finnish forest industry in the 21st century. In the thesis, experts in the field were interviewed regarding the development of the forest industry from various fields and themes. The interviewees were asked to give a comprehensive description of the development of their specialization and to name the most significant innovations that have enabled the developments. As revealed in the results, there has been a wide range of innovations behind the industrial development. The innovations covered developments in technology, equipment and components that have led to increased overall capacity. In addition, innovations have been related to new products and materials which have diversified the product range of the forest industry. Innovations emerged in various industries indicate what has been emphasized in the development of a particular sector. In this study, innovations were limited to process technology and product innovations. If other innovation types had been included, the number of innovations could have been much greater. Although, the scope of innovation was defined, a large number of innovations may have been overlooked due to limited scope of the study.

The results suggest that there have been several drivers behind the development of innovation. ‘Process and cost optimization’ were the most recurring drivers among the innovations emerged in the study. In this context, industries have aimed to improve the overall efficiency by optimizing cost, quality and consumption. These three have become the basic assumptions in the development work of many industries. Efficiency was found to be heavily weighted in the 21st century, whereas in the past quality was more of importance. Another major driver of innovation was ‘responsibility’. Apparently, the activities of industrial companies are driven by numerous policies and regulations that force companies to adopt more sustainable business models. On the other hand, companies want to contribute to the sustainable development on their own accord. Global sustainability issues such as climate change, resource scarcity, population growth and urbanisation have been major sources for innovating in the forest industry. This has led to the introduction of national strategies, including climate and energy strategies as well as bio- and circular economy strategies. The Finnish forest industry has been shifting towards a low-carbon bioeconomy in recent years. The Bioeconomy Strategy has emphasized creation of new businesses and innovations as prerequisites for transition to the bioeconomy. This has boosted the growth companies as well as SME and start-up companies to create new wood-based products. Especially start-ups and their innovative ideas play a significant role in diversifying the industry and advancing the Bioeconomy Strategy.

Major changes have taken place in the Finnish forest industry during the 21st century. Recovering from the financial crisis after 2007 has led to irreversible changes in the structure of the industry. Formerly reputed descending field has become a rising field. The forest industry still has a number of problems that need to be addressed. The quality of R&D and education must be ensured, as well as the adequacy of funding for these in order to maintain the industry's competitiveness. Despite many challenges to face, the future of the Finnish forest industry is believed to be in a good light. The success of the forest industry in a global business environment depends on the creation and implementation of innovative ideas that are based on the efficient use of sustainable raw material. Studying the development of the forest industry through innovations has given rise to further research. It has been previously suggested to study more closely how the processes of different corporations and methods to innovate in the forest industry have developed over the past decades. In addition, how companies examine their development through various performance indicators and how the use of these indicators has evolved over the decades. However, further research about innovations and innovating in the forest industry should be conducted as the study area provides several aspects.

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Appendices

Appendix 1. RESEARCH QUESTIONNAIRE & TEMPLATE

This questionnaire concerns the empirical part of the master's thesis regarding innovations of the bioforest industry conducted in the School of Chemical Engineering at Aalto University.

The aim of the study is to evaluate the overall development of the bioforest industry during the past 20 years by compiling the most significant process and technology innovations from different topic areas.

The thesis is prepared in cooperation with PI – Forest Products Engineers and the results are intended to be published in PI events and publications during 2019-2020.

Questions:

1) Can you briefly describe the key processes and technologies in this specific area?
2) Over the past 20 years, what have been the most significant innovations and their drivers in this area? Please select the main driver from the list below; you can also mention 2nd and/or 3rd important driver behind the innovation.
3) What have been the main achievements and their key performance indicators (KPI) in this area? Please give examples, how KPIs have developed over the past 20 years?
4) Can you still describe the overall development of this area over the past 20 years?
5) How do you see the future prospects, either growth opportunities or challenges, in this specific area?

Further information and examples of the main drivers:

- **Process and cost optimization**: e.g. material, production or energy efficiency development
- **OHS**: occupational health and safety requirements
- **Responsibility:** e.g. environmental sustainability, regulation and policy changes
- **Technological opportunities**: e.g. digitalization and automation, AI, overall technological development and new solutions
- **Customer demands and market opportunities**: e.g. customer demand, market demand/opportunities derived from megatrends or discrete events (e.g. urbanization, popular growth), quality improvement

Appendix 2. LIST OF INTERVIEWEES

Aho, T. *Senior technology manager.* Valmet Technologies Oy. 9.10.2019.

Berg, M. *Business development manager*. Kemira. 12.9.2019.

Engström, J. *Chief technology manager*. Andritz. Interview. 27.8.2019.

Havu, A. *Product portfolio and strategy manager*. Valmet. Interview. 24.9.2019.

Jortama, T. *Senior purchasing manager*. Stora Enso. 27.9.2019.

Kivioja, E. *Sales manager*. ABB. 3.9.2019.

Kontturi, E. *Associate professor*. Aalto University. 17.9.2019

Kylliäinen, P. *Project manager*. Stora Enso. 10.9.2019.

Kymäläinen, M. *Postdoctoral researcher*. Aalto University. 20.9.2019.

Liias, P. *Development manager*. Metsä Fibre. 10.9.2019

Lucander, M. *Retired research fellow*. KCL. 17.9.2019.

Luomi, S. *Senior technology manager*. Valmet Technologies Oy. 20.8.2019.

Matula, J. *CEO*. Wetend Technologies Ltd. 23.10.2019.

Mikkola, M. *Managing director*. Finnish Woodworking Industries Federation. 6.11.2019.

Niinistö, A. *Digital lead*. ABB. 3.9.2019.

Nilsson, P. *Senior manager*. UPM. 29.8.2019.

Nousiainen, J. *Production director*. UPM. 6.9.2019.

Oksanen, J. *Manager, mill services*. Stora Enso. 11.9.2019.

Palsanen, J. *Retired* director. UPM. 5.9.2019.

Pietikäinen, M. *Account manager*. ABB. 3.9.2019.

Qvintus, P. *Business development director*. Spinnova Oy. 3.9.2019.

Ruottinen, M. *Customer service and sustainability manager*. Metsä Fibre. 10.9.2019.

Torvinen, K. *Vice president research*. VTT. 3.9.2019.

Tuovinen, O. *Development manager*. Valmet Technologies Oy. 25.10.2019.

Viitikko, K. *Sustainability, R&D manager*. UPM. 30.8.2019.

Viljanmaa, M. *Senior development manager*. Valmet Technologies Oy. 20.8.2019.

Yliniemi, L. *Director of technical marketing and packaging services*. Metsä Board. 6.9.2019.