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Master's thesis in Sustainable Manufacturing
Supervisor: Østbø, Niels Peter
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Declaration of originality

The author hereby declare that I am the sole author and composer of my thesis and that no other sources or learning aids, other than those listed, have been used. Furthermore, I declare that I have acknowledged the work of others by providing detailed references of said work.

Acknowledgments

This master thesis is submitted as the final product of the Master of Science program in Sustainable Manufacturing at the Department of Manufacturing and Civil Engineering at the Norwegian University of Science and Technology (NTNU).

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I would also like to thank representatives from the companies that were able to attend meetings and interviews, as of the NDA their names will not be mentioned but thought of in the best manner.

I would also like to thank my fellow classmates for two wonderful years, it has not been easy with covid restrictions and being an international class. We have made through the pandemic and online classes; I could not have done it without you

Summary

Global climate change caused by greenhouse gases in the atmosphere already has widespread effects on the environment; higher temperatures, rise in sea levels and more extreme weather effects all life on earth. Environmental scientists all over the world agree that we must reduce emission of greenhouse gases (GHG) to reduce climate change.

One way to reduce emissions is by isolating homes which again lowers the energy usage in both industrial buildings and private homes. Wood fiber insulation is a safe and renewable alternative to many synthetic insulation options currently on the market. Wood is also a natural carbon sink. Hunton Fiber is leading in wood-based insulation in the northern countries.

The binders that keep the wood fiber together are currently made of non-renewable polymers such as Polyethylene (PE) and Polypropylene (PP), which is a widely used synthetic polymer with highly suitable mechanical properties. However, does not open for biodegradability of the wood fiber without harm from microplastic.

This study will seek to answer the following research questions (RQ):

- RQ1: What are the strengths and weaknesses of the alternative binder solutions compared to binders used today? What material is found applicable to replace the original binder?
- RQ2: Is it justified to work for a renewable binder to work for high degrees of bio compostable insulation? What changes need to be made to implement the alternative binder?

The case company, Hunton Fiber, the main focus is biodegradability for their insulation. However, there is currently no renewable insulation on the market. The interest in finding a new more renewable binder-solution was therefore high. Earlier research and the literature review conducted in this study showed promising results for Polyvinyl alcohol (PVA) as a main polymer agent because of its mechanical properties, biodegradability, and water dissolvability. However, the case study confirmed the already thought of properties that PVA without modifications could not be suited as a binder. Further research showed interest in crosslinkers in the PVA solution such as HMMM, Glyoxal, and Xylan. The research confirmed that the PVA solution when mixed with these crosslinkers showed more higher suitability and crosslinking of these materials is possible.

The research confirmed increasing suitability if crosslinkers were to be added and confirmed possibility of these crosslinking agents. PVA was tested through the PDSA methodology on

wood fiber to confirm lack of elastic properties and high binder content and production methods, only to confirm the insights received in interviews and literature. Nevertheless, the wood fiber was tested for water dissolvability and confirmed full dissolve of the PVA on the wood fiber in less than 4 hours in a water bath. This could change if the PVA were to be crosslinked with HMMM, Glyoxal, or Xylan in further research.

The alternative binder was compared with both the original binder and the supplier addressed binder with respect to the requirements list given by the case company. It discussed both benefits and drawbacks of the most important requirements of the binder. However, with the lack of testing on the crosslinkers, it is seen that the original binder is still the reliable solution. Crosslinking of PVA should slow the dissolvement of PVA in contact with water, while holding properties like biodegradability as all crosslinkers is tested for degradability under certain conditions. Opening for biodegradability in wood fiber insulation will also open for usage of EOL-product in agricultural manners as compost in fields or likewise products. The research opens further engineering of the PVA with crosslinkers in respect to the requirements list is needed.

Sammendrag

Globale klimaendringer fra drivhusgasser i atmosfæren har gitt en drastisk endring i klimaet; høyere temperaturer, økninger i havnivået og mer ekstremvær er bare noe av endringene vi ser om dagen. Klimaforskere verden over er enige at en reduksjon av klimagassene må gjøres for at fremtidige generasjoner skal kunne leve som vi gjør.

En måte å endre energiforbruk og deretter klimagasser fra dette er ved godt isolerte hjem og med dette er trefiber isolasjon et godt fornybart alternativ over syntetiske materialer, hvor Hunton Fiber er den ledende aktøren i trefiber isolasjon i Norden. Trefiber isolasjon er et trygt og fornybart alternativ, hvor tre fungerer som en oppfanger for co2 ekvivalenter. Bindemiddelene brukt i dagens markeder er ofte laget av syntetiske polymerer. Bindemiddelet benyttet I trefiber isolasjon er en blanding av de syntetiske polymerene polyethylene (PE) og Polypropylen (PP) som holder høye mekaniske egenskaper, men hindrer nedbrytbarhet av trefiber uten avfall av mikroplastikk. Hunton fiber har utviklet stor interesse for nedbrytbare og lave utslipp for deres produkter. Problemer kommer fra deres benyttede bindemiddel, hvor dette er laget av syntetiske polymerer, som ikke kan brytes ned. Derfor var det av forfatteren og Hunton Fiber sin interesse å se på nedbrytbare bindemidler.

Denne oppgaven forsøker å besvare disse spørsmålene:

1. Hva er styrken og svakhetene i det alternative bindemiddelet over dagens bindemiddel? Hvilket materiale er funnet til å erstatte dagens løsning?

2. Er det rettferdiggjort å jobbe mot et nedbrytbart bindemiddel? Hvilken endring trengs for å implementere bindemiddelet?

Tidligere forskning og litteratur gjennomgangen viste stor interesse for Polyvinyl alkohol (PVA) som et hoved polymer i et bindemiddel, på grunn av sine mekaniske egenskaper, å muligheter for bryte ned i kontakt med vann og bakterier. Studiet bekreftet at PVA uten modifikasjoner ikke er egnet som bindemiddel i trefiber isolasjon. Videre forskning utviklet interesse i krysslinkere som hexa(methylmethoxy)melamine (HMMM), Glyoxal, og Xylan. Studiet bekreftet at disse

krysslinkerne ville øke ønskede kvalifikasjoner i bindemiddelet og bekreftet muligheter for å krysslinke disse materialene i PVA. PVA var testet igjennom PDSA metoden på trefiber isolasjon for å bekrefte manglende elasitet og for høyt forbruk av bindemiddel, samt produksjons metoder, for å vitenskapelig bekrefte innsikten funnet i litteraturen gjennomgått I denne studien og intervjuer. Nedbrytbarheten av PVA på trefiber ble testet i kontakt med vann og bekreftet at polymeret ble oppløst på under 4 timer. Det kan tenkes at dette vil endre seg når PVA er krysslinket med HMMM, Glyoxal, og Xylan.

Det alternative bindemiddelet var sammenlignet med det originale bindemiddelet og et bindemiddel fra en leverandør med respekt for kvalifikasjons listen sendt fra Hunton Fiber. Uten krysslinkingen av PVA, var det funnet at det originale bindemiddelet er den beste løsningen per nå. Krysslinking av PVA må senke tiden PVA bruker på å brytes ned i kontakt med fukt under lagring, mens mekaniske egenskaper og mulighet for nedbrytbarhet beholdes. Siden alle krysslinkere er nedbrytbare eller oppløsende materialer under visse klimaer. Åpning av nedbrytbar trefiber isolasjon vil også åpne for å bruke trefiber isolasjon i slutten av livet som kompost. Studiet åpner for videre modifikasjon av PVA med gitte materialer med respekt for kvalifikasjons listen gitt av Hunton Fiber.

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1 Introduction

The introduction will introduce the motivation behind this master's thesis research area by presenting problem statement, research objectives and questions, research scope and the structure of the report. The paper follows Bostad (2016) for structural reference of the paper.

1.1 Problem statement

Environmental awareness is increasing, where becoming sustainable is crucial, is it important to find solutions that could lower emissions and becoming net-zero to hopefully lower the environmental changes form global warming. Wood fiber insulation is a step in the right direction, where it almost only uses renewable resources, except the binder. Wood fiber insulation is a composite insulation product (Norsk standard, 2015) In Germany is 7% of total insulation consumption bio based, whereas 51% of this comes from wood fiber insulation (Schulte, Lewandowski, Pude, 2021).

Except the binder, whereas this paper focus on replacing the binder to a renewable binder in wood fiber insulation to make it biodegradable, as polymers create a threat to diverse animal populations. They have a direct impact on marine ecosystems and are believed to be responsible for the death of a very large number of birds and wildlife in general by ingestion or strangulation. Polymers found in the ocean have a considerable effect on marine life, and if ingested cause intestinal blockages in small fish or suffocation of other marine animals (Jayasenkara, Harding, Bowater, and Loneergan, 2005).

Solutions to many environmental problems already exists around us in nature. The challenge is to find them and use them in an applicable manner. The author has already conducted a literature review on the topic, the author will work further on this in the thesis. Also including how to produce the possible new binder. Looking at alternative binders in wood fiber insulation to make the material bio compostable could concluded that the impacts of building materials could be significantly improved when state of the art production technologies and eco-efficient materials with high recycling or compostable potentials are used (Tetty, Doodo, Gustavsson, 2014).

Insulation comes in a variety of varied materials, such as rock wool, glass wool, cellulose fiber, expanded polystyrene (EPS), foam glass, and wood fiber. Producing wood fiber insulation in Norway is beneficial as of large areas of forest and nature, making transportations of wood for production relative short. Additionally, the high rates of renewable energy used in the industry in Norway. Northern countries are known for their export of wood to other countries and large industry using mainly wood for construction, furniture etc.

1.2 Research objectives and questions

The overall objective of this thesis is to compare alternative green binders for wood fiber insulation against today's solution using non-renewable polymers. The applicable binders will be discussed in a case study and evaluated. The evaluation of alternative binders will make it possible for interested companies to choose alternative binders in their products, to lower greenhouse gasses (GHG)-Emissions and biodegradability.

The objectives can be divided into more specific objectives:

1. Identify applicable binders for wood fiber insulation through available literature.
2. Analyze mechanical properties, functionality, availability, and cost for applicable binder through the case study and literature.
3. Compare today's synthetic polymer binder vs. more sustainable binders

To accomplish the objectives, two research questions (RQ) are defined to guide the research:

Research questions:

RQ1: What are the strengths and weaknesses of the alternative binder solutions compared to binders used today? What material is found applicable to replace the original binder?

Replacing synthetic polymers in various products has been tried multiple times before, as main component and binder etc. Feedback from scientific articles and interviews comes in lack of structural and mechanical properties, availability and cost to mention some. Therefore, to make the possible solution applicable for the case company – Hunton Fiber, needs the author to discuss and defend these findings. Strengths of applicable binder should be higher than weaknesses to open for replacing today's solution.

RQ2: Is it justified to work for a renewable binder to work for high degrees of bio compostable insulation? What changes is needed to be done to implement the alternative binder?

Environmental awareness is increasing and concerns about climate change a large interest for the public, were continuously changing our way of living to lower GHG-emissions, waste, and pollution to let the next generations live as we have. Nevertheless, some green products like wood fiber insulation, uses synthetic polymers to bind the wood fiber insulation together. This to hold the wood fiber insulation in place to hold the thermal conductivity of the wood fiber and being easily worked. Therefore, is it important to look at solution in product that can make solutions renewable, therefore is it in the interest of this thesis to look at solutions that can make wood fiber insulation renewable by opening for biodegradability for further growth of threes.

1.3 Research scope

The research scope of this study can be described by the three areas: ‘Sustainability’, ‘manufacturing’, and ‘polymers’. The contribution is illustrated in **Figure 1**.

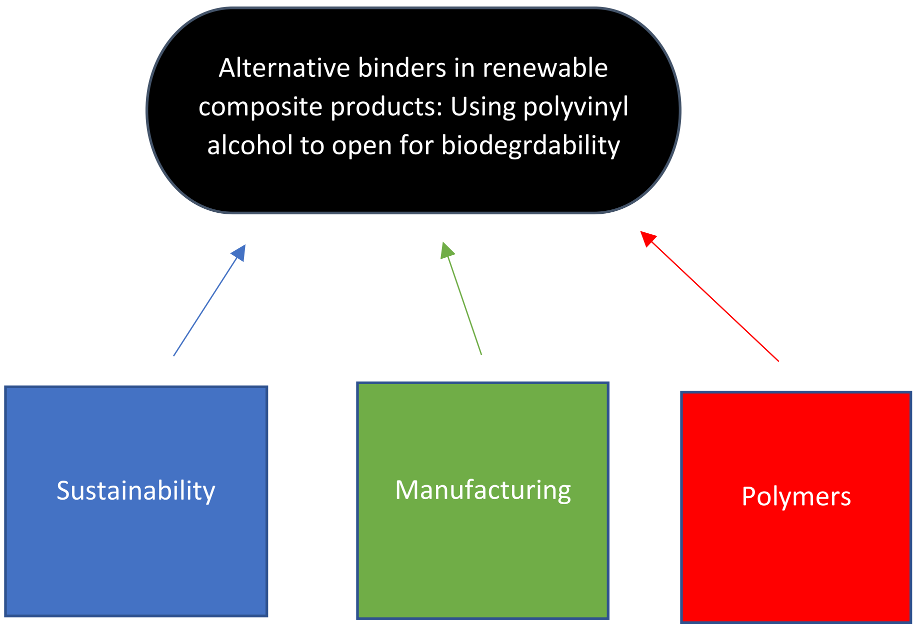


Figure 1. The three areas describing the research scope.

“Sustainability” concerns the ongoing interest for companies to become more environmentally friendly to let future generations live with the same benefits as we have with our generations. We can already see change in climate with the ongoing heatwaves around the world, droughts, forest fires, and hunger around the globe. For future generations to withhold the same standard as we have, is it needed to lower climate change from environmental impacts from products, services, and other impactful things. Hopefully contribute net-zero or positive, as wood fiber insulation already does from gate, but could become better becoming biodegradable using renewable binders and thus lowering emissions from production of crude oil and could be used as compost after EOL. Among other criteria, sustainable products must be efficient, competitive, and cost effective (Biron, 2020).

"Manufacturing" process can be defined by a specified combination or sequence of steps, or by a particular operation on a particular material or component (Varma, 2014). Manufacturing is one of the most crucial steps of this products, as the product, in its whole life follows a manufacturing process from a living tree to wood fiber insulation to End-Of-Life (EOL). Manufacturing of wood fiber insulation looks very much like manufacturing of composite materials, as wood fiber insulation is a composite material where wood fiber is the main material, and the binder and other adhesives is the reinforcement. Plywood is a typical composite wood material.

"Polymers" Polymer chemistry is adept at producing a wide range of polymeric materials tailored to a variety of applications. Unfortunately, the human eye is unable to see atoms, so the beauty of the molecular architecture of these materials often goes unnoticed (Hamerton, Howlin, Mitchell, Hall, and McNamara, 2011). A polymer is a substance composed of molecules, characterized by the multiple repetition of chemical structural units, consisting of one or more species of atoms or groups of atoms bound together to form chains of atoms.

Polymer chemistry works to make many different polymers with a wide range of mechanical properties tailored for many different products. Polymer binders are made from heavily engineered polymers tailored to reach tensile strength above 1 KPa, with low binder usage to mention some. The average synthetic polymer contains maybe one or two monomers. Monomer comes from the Greek mónos, single, and méros, part) is a compound consisting of molecules all the same, each of which can provide a structural unit of repetition in the polymer (monomer unit). The first synthetic polymer was classified colloids due to the high viscosity. Polymers of natural origin is cellulose, fibrous proteins, gutta-percha can be seen in an x-ray as crystalline structure. Polymers are used all around the world in many various applications because of great mechanical properties and cost efficiency. Binders is often made from polymers and used in many product categories. Binders is a material used to bind-together various materials. For example, is asphalt mixture made from Coarse aggregate, Fine aggregate, fine mineral filler, for example limestone flour or cement, and binders to hold all the other materials combined (Claisse, 2016). Polymer binders are often used as they are cheap, available from many producers in high quanta, easily manufactured, can withhold UV radiation and other types of weather, and does have a significant increase in mechanical properties on the product.

This master thesis is a part of sustainability project at Hunton Fiber, whereas evaluating and justifying why and if it is possible to replace today's binding solution with an alternative binder, hopefully, from an alternative and renewable material. This theoretical and experimental research will include argumentation from other fields and countries, to open for a wide argumentation throughout the thesis. Additionally, both the product development and manufacturing environment will be discussed, as these aspects are important to justify in a sustainable manner for the case company.

1.4 Report structure

The project report is set in seven chapters. The content in each chapter is briefly presented in **Table 1.**

Chapter 1 **Introduction**	Presents the problem statement, research objectives and questions, research scope and report structure (this table).
Chapter 2 **Methodology**	Present the literature review and empirical study as research methods and justifies them to show validity of results. The chapter discuss the

	theoretical section, the empirical study section, and the section discussing the structure of argumentation in the thesis.
Chapter 3 **Literature review**	Present the collection of relevant data, builds further on the project work (Steinaa, 2021). The chapter starts defining crucial properties for an alternative binder, end-of-life, and discuss the alternative binder PVOH with applicable additives and crosslinkers in a wider aspect.
Chapter 4 **Empirical study**	Present the relevant outcomes from the case study, the case company, and the outcome from performing the theoretical research and interviews for adopting PVOH as an alternative binder in wood fiber insulation.
Chapter 5 **Empirical findings and discussion through a PDSA method**	Presents the main findings from the case study and discusses the comparison between renewable and non-renewable binders upon each other.
Chapter 6 **Representing the findings**	Present the applicable binder, strengths, and weaknesses from the renewable binder in a wood fiber insulation setting. Answering the research questions. The main findings and the contribution to the research field is presented.
Chapter 7 **Conclusion**	Discusses to what degree the research has answered given research questions and fulfilled the research objectives. Suggestion for further research is given.

Table 1. Report structure of the master thesis.

2 Methodology

This master's thesis will be carried out with a theoretical and empirical part as a research-based project for Hunton Fiber.

The thesis has been carried out with a literature review based on already known topics from project work for the thesis (Steinaa, 2021) and new relevant literature. The case study and literature review affect the final solution.

Empirical research can be qualitative, quantitative, and mixed approaches. Qualitative research approach is used to gain understanding of underlying reasons, opinions, and motivations by providing insight into the problem or helping to develop ideas and hypotheses for quantitative research. Quantitative, as can be thought of looking at qualitative research, uses numerical data that can be transformed into statistics (Sharma, 2018). The general idea with following project work and thesis follows deductive reasoning into the empirical research conducted in this thesis, which will be further explained for the reader in this chapter.

The starting systematic literature review, ref. Steinaa (2021), was building knowledge on the topic in a general manner to build applicable knowledge and to look at some solutions. Further, the literature review in this study goes deeper and picks relevant literature from how many times the literature is cited, age of article, and overall quality aspects.

2.1 Theoretical study

The theoretical study consists of a necessary literature review that builds further on knowledge given from the project work. A literature review is important to build knowledge on the field of research and to limit the chances "reinvent the wheel", after completing a literature review should the researcher have a solid foundation of knowledge in the field and a good feel of how to conduct further research on the topic (Thomas G Carpenter Library, 2022). Previous research on the topic of alternative binders suggests how the author can, in a scientific manner, implement earlier research to build on further understanding of relevant insight in alternative binders. The author used this insight to look for data that could be suitable to understand before conducting the experiment. Some of the relevant solutions in literature from the project work has been extended to this master thesis. The theoretical study will give further knowledge around possible solutions and answer RQ1 and the findings in the theoretical study will be further used in the case study as the empirical part of this study.

The problem description and research questions have formed the background for the search words used in search functions, the applied search functions from this thesis where Google Scholar, Science direct, Springer, and ORIA (NTNU) are used. The search words are presented in Table 2.

Table 2. Search words in literature search

The first set with main search words	The second set with additional search words
Wood fiber	Petrol
Binder	Sustainable
Sustainable	Biodegradable
Wood-based	Renewable
Fossil-based	Binder technology
Plant-based	Binder
	Insulation
	Energy

One of the search words was combined with the second set of search words to narrow down the scope and was combined in several ways. An example of search words used to narrow down the literature was “Wood-based renewable binder” and is shown in **Figure 1.** In the example, did the results from the search need to include the words “Plant -based”, in addition to the words “renewable”, “binder”, or both words.

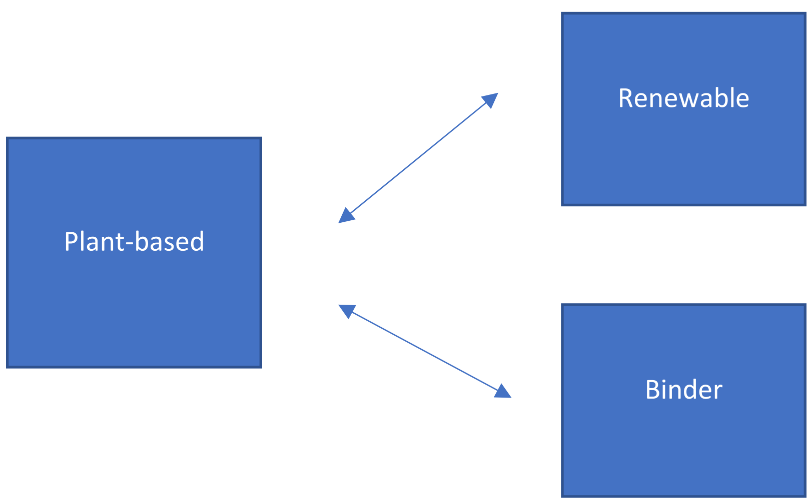


Figure 2. Example of combination of search words.

The author found many results on these search words, whereas further filtering was needed. Therefor did the author follow the same approach as the systematic literature review in the project work by Palmarini et al. (2018). In general words, started analyzing the relevant papers reading relevant titles with many citations per paper and sorting out the not applicable once. If the paper had many citations and came from a respected journal, was there higher chances for serious research. Afterwards did the author read the abstracts to look after relevance and sorting out the not applicable once, if the abstract seemed relevant, did the author start reading introduction and conclusion to find relevance for the objective. Lastly, was the applicable papers read throughout and information was taken out and discussed throughout the literature review. As the papers began to form, was it necessary to build up on more papers using sources in relevant papers.

The literature review was carried out based on previous project work and while the workshop happened, this was to build further knowledge before deciding applicable solution for further research. Conducting the literature review and the case study together, gave both meaningful insights for the literature and case study, as not applicable solution could be avoided to become a more open research. However, this could also be challenging in time consumption and adjusting information throughout the study. In addition, was new search words added as knowledge was increasing. Validity of applicable solution following every aspect was picked by data from the literature.

2.2 Empirical study

The choice of research method was a challenging class, as it is a wide problem overrunning many obstacles. Therefore, was it in the interest opening for qualitative research through a case study following the case company picking up relevant information through a literature review, interviews and lastly an experiment using the alternative binder on wood fiber. Qualitative research methods are most appropriate in situations in which little is known about a phenomenon or when attempts are being made to generate new theories or revise preexisting theories (Schonfeld and Dreyer, 2008). Since this research aims to compare solutions for alternative binders in wood fiber insulation, holding every requirement given from the case company (ref. Appendix A), is it chosen to conduct a case study. As already mentioned, does this research fit both ‘how’ and ‘why’ to be answered, as this will be given by the interviews, the workshop, and literature research. It was important to gain information about earlier takes on the project, where relevant information was discussed between the author and experts and noted down for the following work. Following the interviews with the suppliers, was some of the thought off solutions discussed, where the suppliers already had tried and made experiments with these solutions. Both the case company and the author had a large desire to test the applicable binder found in the literature. One supplier also had an applicable binder, whereas this will need further research for implementation in production line. The empirical study will therefore work further answering RQ2.

In such a complex problem as this thesis work on, will there be lack of addressing every problem with an alternative binder, since it is only performed as one case study. However, this research opens for more finings and experiments in the field and go in-depth in the objective (Noor, 2008).

2.2.1 Interviews

The interviews were held early into the project work and the thesis, to get to know the company and their products. The interviewed objects focused mostly on the binder, whereas this is an outsourced product for the case company. Thus, where both the author and Ralf Paustian in meetings with both the current supplier, supplier A and B. Under both interviews with the producers of binders where relevant information and insight gathered for further work under the study. The interview with both supplier A and B where a semi-structured interview so the author had time first to work on knowledge given from literature and the co-supervisor. Semi-Structured interviews were selected as the qualitative methodology to explore personal reflections from the suppliers, which who have quantitative knowledge and insight on the topic. Semi-structured interviews fit as a structure if there is general knowledge on the field and the interviews typically lasts around one hour (Statham, 2020). This case study will limit the information relevant for justification of choosing the alternative binder, however further research might be needed to full-scale test the binder in production. As this will open for a suggestion for replacement. The very first meeting was at Hunton with both Ralf and another representative at Hunton Fiber, much of the meeting was in general about the product and what they wanted for the thesis and the project in general. An overall agreement was set for the finished product, where "greenwashing" was not desired and should not be done and something that works with their production today was wanted, however minor changes could be done. The second interview was with the supervisor from the company, which was done to make a better understanding of the problem statement, the product in general, and what was tried before. The third meeting was with a supplier, with discussion with found solutions was discussed and drawbacks and availability was found and further discussed. Some solutions from the supplier where also presented for the case company and the author. After using the meetings for further discussing and conclusion for further research, was another supplier used to discuss alternative binder, as they had an expertise in renewable binder where its high hopes for good insights or further collaboration with the binder supplier. Where many different solutions were found, however many of these changes demanded high binder content and large changes on the production line, however it could work for the wet process line at the case company, for another product. The timeframe of interviews where approximately one hour for every meeting to open for good answers and discussion under the meeting, hence semi-structured interviews to guide the meetings in the right direction, without destroying the opportunity for discussion and meaningful insights (Wilson, 2013).

Most interviews and meeting were done over teams, as it would demand much more from the suppliers to conduct in person meetings, besides the meetings with the case company. As the solution with hybrid offices have come a large way since the pandemic and opens for efficient meetings in high solution.

2.2.2 Experiment

The empirical study of the thesis and project work were used to start an experiment at Norwegian University of Science and Technology (NTNU) in Gjøvik looking at properties and suitability for the main polymer used in the alternative binder for wood fiber insulation. The workshop was performed with chief of Advanced and Sustainable Engineering Materials Laberatory (ASEMLab) at NTNU in Gjøvik Professor Sotirios Grammatikos, who gave information how to conduct testing. There was no need to include the case company in the experiment, only sharing important insights from the experiment. As Sotirios have high knowledge in the field of polymer research, was he the obvious choice for insight in polymers and polymer processes. The main polymer was also tested in degradability in contact with water and information was noted and confirmed with insights from the suppliers and the literature.

The literature presented many reliable choices for further research, but the meetings with experts in the field of binder technology and the literature found various drawbacks in many of the found solutions. The literature had presented the main polymer and alternative crosslinkers and mixtures to work further on, where many of these was interesting to investigate further for the case company.

Parts of the justification were simplified due to the experiment forming and testing mechanical properties of Polyvinyl Alcohol (PVA) seeing the Dynamic Mechanical Testing (DMA) and tensile test from found literature to not work on too many experiments at once. Then using experts in the field from both suppliers and experts at school, gave a good argumentation for further testing. Using the first literature review to discuss possibilities and later experimenting the main polymer in the alternative

Due to the complexity of this thesis, is it found to plan an experiment following the applicable binder for wood fiber insulation, thus opening for further research in the topic.

PVA solution was tested on a bed of wood fiber to clarify in a practical manner, if crosslinkers or adhesives is needed on PVA to fully be adapted as an alternative binder in wood fiber insulation. One specimen was heated in 60 degrees Celsius over 5 hours to harden the PVA into the wood fiber. Another specimen was tested with the same amount of fiber and PVA, but where heated by an air heater with 1800-2100w for 15 minutes. The degradability with contact in water was also tested on the specimens.

Parts of the experiment were simplified due to the authors knowledge in the field of polymer testing and limitation with time sampling the wood fiber with the found binder and gain knowledge on mixture, atomic binding, and gaining access to use these testing equipment’s. However, scientific research was conducted using literature and chemistry to gain knowledge and discuss further about these tests in other experiments as production, tensile and DMA testing with crosslinkers etc. Hence also opening for further research. Evaluation of the case study was based on feedback from the meetings with suppliers, experts in the polymer field, the case company, the literature review, and lastly the own observations to keep a scientific experiment.

2.2.3 Correspondence

Throughout the thesis was much of the correspondence made through phone calls, teams-meetings, and mail, this comes from further restrictions from the Covid-19 Pandemic. Furthermore, have the pandemic showed many companies the benefits of hybrid offices, where you work both remote and on location throughout the week.

Under this thesis was much of the correspondence with suppliers, case company, and researchers were done before the experiment and in the end of the thesis due to availability of needed materials. The evaluation of the experiment was conducted both prior and after the experiment from the researchers at NTNU In Gjøvik and the case company. However, the information received under the correspondence were important to address problems and requirements for the alternative binder. Bolstad (2016) made some valuable points for correspondence over messages, where it can be both advantages and disadvantages. If the questions where to be misunderstood or insufficient, will desired information be lost. The advantages are that the receiver of the email have time to understand the question and do research before replying. As there is an NDA following this thesis, is there also time for the receiver to formulate good answers without detailing information that should not be shared. And answer when the receiver has time.

The correspondence showed great value throughout the thesis for evaluation of the alternative binder and valuable information was shared.

2.3 Structure of argumentation

The project work and literature review of this thesis starts by working further on given knowledge from the project work (ref. Steinaa, 2021), where we are briefly introduced to binders and additives, how they work, and minor discussion about applicable binders. The conducted literature review shown in this thesis works further on the applicable binder with additives and crosslinkers.

The literature review starts by introducing general information about wood fiber insulation and the importance of sustainability today to maintain the global agreement to lower emissions and pollution, to withhold further increase in global warming. Wood fiber insulation is a great choice for sustainability as the product is renewable, but the binder makes the product non-biodegradable without leaving micro plastic and other forms of harmful wastes. A desire to adopt a renewable or biodegradable binder was made. Further, were alternative binders found in the literature presented. These binders are represented in a table and was discussed from the main findings and conclusions were used to further evaluate the suitability of an alternative binder in wood fiber. For the evaluated and suitable binders, had some main polymers and some crosslinkers and adhesives drawbacks and benefits that was discussed and importance of rightful product development, production, and end-of-life (EOL) for the binder that could affect the product was evaluated. One of the main polymers materials was found highly suitable, where other crosslinkers and mixers were found interesting for further investigation. An evaluation of possible mixtures and crosslinkers, if needed, are there for explained more narrowly throughout the literature review. The further evaluation will research and discuss the mechanical properties, bonding properties, and suitability for production. The binder were compared to both the original binder and the supplier presented binder.

The empirical study presents the case company and the case study. The findings are presented and discussed, and meaningful insights are explained. One of main polymer materials is found suitable through the literature review and are explained thoroughly with information about some suitable mixers and crosslinkers. Both strengths and weaknesses are discussed further in the study with insights from the suppliers and experts.

3 Literature review

The author has conducted a systematic literature review on alternative binders in wood fiber insulation as a project work for this thesis, and the point of this literature review is to build on the knowledge given by the systematic literature review. The author recommends reading the literature review by Steinaa (2021) before further reading of this thesis to fully understand the insights, problems, justification, and evaluation given in this thesis.

Energy usage and associated climate change continue to increase globally. More than 80% of global primary energy-use is based on fossil fuels that emit around two-thirds of the world's greenhouse gas (GHG) emissions (Tetty et al. 2014). The envelope of a building and its external walls directly influences thermal and environmental performance of a building, through its weight the envelope's initial embodied energy, life cycle energy consumption, life cycle cost and the uses comfort. Whereas wall can represent up to 15% of the overall environmental impacts of a building over 60-year life cycle (Silvestre, Brito, and Pinheiro, 2011).

Advanced environmental properties include fuel and feedstock energy, special aspects of gas warming potential, ozone depletion potential, photo-oxidant creation potential, acidification potential, eutrophication potential, dust/particulate matter, and ecotoxicity potential. Compared to usual fossil polymers, natural-sourced plastics bring benefits and possibly drawbacks (Brion, 2020).

To lower the usage of wood, fossil fueled stoves, energy to mention a few are insulation used to maintain temperature inside and block out could weather, insulation is also used to block out noise pollution. The building sector also accounts for over 40% of all total primary energy usage, and will share around 54% in 2050 (Schulte, Lewandowski, Pude, 2021). The building sector also stands for approximately 40% of all man-made waste (Silvestre, Brito, and Pinheiro, 2011).

Expectation of highly insulated houses are expected to increase, with the EU directive of nearly "Zero-Energy buildings" by 2020 (European Union, 2010). Whereas insulation will be a critical aspect to reach these standards. Tetty et al. (2014) also mention that wood-based materials in buildings consistently resulted in significant reduction in most of the considered environmental burdens. This shows promising results for the wood fiber insulation, whereas the focus in this thesis is to replace the binder with alternative solutions to reduce emissions and make the wood fiber insulation biodegradable or recyclable, but highly preferred to become biodegradable. Wood adhesives are mainly prepared from polymers derived from petroleum-based resources (Norström, Fogelströma, Nordqvist, 2015), thus not making the wood fiber insulation entirely biodegradable.

PLA is often considered for replacement of polyester binder in insulation (Murphy and Norton, 2008), whereas problems making the bio compostable rise, as Polylactic Acid (PLA) only becomes compostable in industrial composting under special conditions. Murphy and Norton (2008) saw reduction in flame retardants using natural materials over normal insulation (glass fiber insulation). As this also lower the environmental impacts from production of insulation as manufacturing of flame retardants are energy intensive. Anyhow, using flame retardant in insulation is important to keep chances of fire or further increasing the potential of fire in insulation low, whereas Norsk Standard (2015) has set the standard to E-class for wood fiber insulation which is not a high, however not to be exceeded.

End-of-life (EOL) scenarios

Various insulation materials have problems becoming 100% renewable and gaining the best EOL scenario, as the binder, the flame retardant, and lastly by using inorganic materials are all materials that cannot make the material biodegradable or applicable for recycling (Silvestre, Pude, Pinheiro, 2011). Looking at PVA as a biodegradable binder will gradually dissolve with moisture (Tan, Ching, Gan, and Rozali, 2015), thus will need small openings to release moisture into the wood fiber insulation in the wall. Whether that will benefit for the insulation is not thought of in this thesis. When the wood fiber insulation is at EOL, can it be used as fertilizer in agriculture to mention some opinions of waste handling. As this study works further on solutions found in the SLR, is it thought of to work further on the PVA based binder.

Mechanical properties

In wood fiber insulation are various mechanical properties as thermal conductivity, density profiles, and tensile some crucial properties in insulation. A material can be considered as a thermal insulator if its conductivity is lower than 0.07 W/m-K, but according to ASTM C208-12 standard is the maximum range for thermal conductivity between 0.055-0.072 W/m-K, depending on the use of insulation boards, for example roof insulation board, wall sheeting, ceiling tiles, and panels (Segovia, Blanchet, Auclair, Essoua, 2020). Holding the thermal conductivity using the alternative binder over the original binder, is therefore needed. The alternative binder would not be applicable if the alternative binder where to drastically decrease thermal conductivity. Insulation needs to be usable over time, whereas lifetime expectancy is set to 60 years. Norsk Standard (2015) sets standard for compressibility of wood fiber insulation over time, that shall not excide less than or equal to 5 or belove between CP1 and CP5.

PVA has very poor performance in fire and in wet condition, as the material dissolves in water. Mechanical performance of PVA adhesive deteriorates with increasing temperature and loses its bonding resistance capacity at over 70 °C. These mechanical performances do not affect the suitability for the binder, as there will never reach above 70 °C in a wall nor become humid enough to break down the binder. Whether flame retardant will be added is for further discussion. The poor performance of PVA at elevated temperatures stems from the fact that PVA is a thermoplastic polymer, which reaches Tg (glass transition temperature) at relatively low temperatures (Kaboorani and Riedl, 2011). However, crosslinking PVA with another suitable crosslinker could fix these setbacks from lack of beneficial mechanical properties.

Binder content

Various green binders, with various outcomes have been discussed in literature. While the normal approaches for wood fiber insulation is approximately 3% binder content. This is used to maintain the thermal conductivity received from the wood fiber. Various research in literature showed usage of around 10-20% binder or adhesive in the wood fiber insulation. Segovia, Blanchet, Auclair et al. (2020) tried an adhesive as a binder using crude glycerol and citric acid between 14-20% adhesive, only showing a decrease in thermal conductivity. Nevertheless, this was already thought of as it's the wood fiber that holds most of the thermal conductivity. Thus, lowering amount of wood fiber can be thought to lower the degrees of thermal conductivity in the wood fiber matt. PVA binder have been showing high usage of binder content as a binder, however, this is not showed using crosslinkers and adhesives into the PVA.

Alternative binding solutions

Many articles include alternative binding solutions for wood fiber insulation and other renewable materials. Wimmers, Klick and Taqckaberry et al. (2019) are one of the examples whereas alternative binders were tested in wood fiber insulation without showing promising results, whereas results of 13 produced insulation boards were only 5 where stable and even less were great, using fungi as alternative binder in the insulation. Many typical problems occur using alternative binders, where some problems come with high degrees of binder compared to binder used now, low quality, lack of function, high cost to mention a few.

Some companies have also started using alternative binders, where you can replace up to 50% synthetic binding material. Nevertheless, is it still needed to use around 50% synthetic binder in the wood fiber. Where this is not an applicable solution if you could not mix this with another beneficial non-toxic binder as PLA or adopting it as a crosslinker. Further research on this is needed.

Alternative binding solutions in wood fiber insulation needs to maintain properties like bond strength, water resistance, and thermal conductivity over a timeframe of 60 years lifetime. An applicable solution also needs to withhold sustainable aspects as social, economic, and environmental standards, whereas these aspects already hold is the last aspect environmentally friendly the focus in this thesis. The Alternative solution needs to be biodegradable or could be recycled to be feasible for the industry.

PLA is also showing mechanical properties benefitable for wood fiber insulation but having problems to compose without industrial decomposition. Thus, the same for usage of Linear low-density Polyethylene (LLPD) from waste or recycled material was showing great results of structural integrity and lowering Greenhouse gasses (GHG)-emissions but is making the wood fiber insulation not biodegradable.

Interesting alternative binders for wood fiber insulation could be Xylan mixed with polyvinyl alcohol (PVA) and Glyoxal or hexamethoxymethylmelamine (HMMM). PVA is most known for biodegrading in contact with water, and most people use them daily in their dishwashing machine. PVA is also great as it does not react good with other fluids, only water has high dissolving properties. Microstructure analysis results showed that the microcapsule shell had a polymer cross-linked HMMM structure as skeleton. All microcapsule samples had an initial decomposition temperature higher than 200 °C (Su, Xie, Wang, and Gao, 2021), could fields for agricultural reach these temperatures being exposed to summer heat, or is it needed to be used in other countries with a warmer climate. Further research in this field is needed. It is said that some vegetable products as corn, cucumber, melon, pumpkin, etc. can grow in temperatures above 50 and below 0 degrees Celsius (Open Whether, 2017). This means that wood fiber insulation waste with PVA and HMMM crosslinker can biodegrade with various degrees of temperature, as Norway has over periods. Reaching 200 degrees Celsius can be challenging without external heat source or being set in plant houses used to reach high temperatures around plants for better growing in colder climates.

Xylan mixed with poly (vinyl alcohol) or poly (vinyl amine), and crosslinkers, such as glyoxal or hexa(methoxymethyl) melamine, the xylan dispersions demonstrate promising results, whereas xylan alone cannot be used because of poor bonding properties (Norström, Fogelströma, Nordqvist 2015). Another alternative biodegradable binder is PVA mixed with starch, with adjusted mechanical properties from crosslinkers showed excellent results as an adhesive (Tang and Alvi, 2011), however if it can be suitable for wood fiber insulation are further research needed.

Starch and PVA have potential as binders, as the crystallinity of the fibers affect degradation and its amorphous regions in its structure (Afzal, Azam, Ahmad, Khaliq, Shahzad, 2021), as Tang and Alvi (2011) is HMMM a great crosslinker for applicable binders, such as starch with

Polyvinyl alcohol (PVA) improves mechanical properties for starch-based materials. Showing starch-glycerol without PVA has a tensile strength of 1.8 MPa and elongation at break of 113% at 50% relative humidity (RH), whereas including 9.1 wt% of PVA shows a tensile strength of 4 MPa and 150% increase. It is mentioned that PVOH is susceptible to biological degradation, however showing slow biodegrading (Tang and Alvi, 2011) which is applicable for long-term biodegrading in wood fiber insulation. Nevertheless, PVA alone shows high degradation times, is adding starch a booster for biodegrading to PVA (Tang and Alvi, 2011).

Poly (vinyl alcohol) (PVA) is a non-toxic material that present no adverse effects to biological systems and has become highly attractive for various applications. Due to PVA's water solubility, is it an applicable material for biodegrading wood fiber insulation (Tan, Ching, Han, and Rozali, 2015). PVA also is a well-known hydrophilic polymer matrix, with high mechanical strength and good polarity with low pH affinity. It is semi-crystalline in nature with excellent thermal and chemical stabilities (Khutia, Joshi, And Bhattacharya, 2015). PVA is a synthetic polymer to the presence of a hydroxyl group in its repeating unit, which makes it cross-linkable by means of its interconnected hydrogen bonding (Patra, Salerno, and Cernik, 2017). Opening for the already though of crosslinking with HMMM. These are all important properties to be applicable as a replacement for the original binder.

PVA comes in packages in form of granulates and can be stored around 5 years if stored in dry areas in room temperature. This is a crucial state, as the canulates can melt tighter if exposed to moisture.

Production of binder

Looking at the case company´s newly developed production site at Skjerven in Norway, is it important to acknowledge demand of high-quality products produced by high-end manufacturing plants as Skjerven has. As the rapid advancements of manufacturing plants, is there often very low fraction of defects from production, often lower than 0.01% measured in parts per million (Pearn and Wu, 2007). Or could be thought of as insulation boards per million square meter (m^2) or other relevant numbers. Thus, will the applicable binder be capable to be processed over large batches, without large defects due to process capability of the alternative binder. However, this could be seen in today's production due to poor mixture of the binder and the wood fiber. Probability of acceptance in products is an often-used terminology in quality engineering, whereas the desired probability often is set as 0.95 or 95% change of the products being accepted. This mean that the PVA based binder needs to be reliable in large batch continues production. This is called acceptable quality level (AQL), the AQL presents the poorest point process average the consumer could accept as wood fiber insulation. The index remains the most popular one because it provides quantitative measures of process yield and upper bound on product fraction of defectives (Pearn and Wu, 2007). Acceptance sampling plans are needed tools for quality assurance applications when the new binder is addressed to the wood fiber insulation, as quality and lower waste is needed. Quality assurance applications for wood fiber insulation are needed, expressly if the case company will adapt the alternative binder. Hence finding good quality plans is needed. Wood fiber insulation is from time to time found to not have sufficient mixture between the binder and the wood fiber, hence making portions of the wood fiber fall off the matt. PVA's need for wet process could lower the chances of this, as it is easier to evenly distribute wet binder, than it is to with dry fiber in a mixture over wood fiber. Kirsch, Ostendorf, and Euring (2018) found improvements in using hot steam and air in production of wood fiber insulation boards. If PVA could lower the demand for moisture and be applicable under production only using hot steam over wet production, when crosslinked with

Glyoxal and HMMM. It is not only applicable to look at EOL of the product with the binder, to guarantee a suitable and sustainable binder is it also important to acknowledge production of the binder as an impactful stage of the product. The cost of adhesives and binders to wood fiber products accounts for large part of the production cost (Kaboorani and Riedl, 2011). Anthony, Sharara, Runge, and Anex (2017) compared production of the applicable binder PVA to a non-renewable binder, PVA is a non-toxic and low cost widely used binder from before (Chabert, Dunstan, and Franks, 2008). Where neither of the synthetic or the PVA based binder holds the lower GHG emissions throughout the lifetime, as PVA is a more complex polymer to produce. However, larger energy demand could be defended in places that uses high percentage of renewable energy into their mixture, as Norway has.

Possibilities for fire inside the production facility because of flash heating and further heating processes is it important to think that the alternative binder should not contribute to flammability in wood fiber. Preferably would it be in the interest to use lower heat when processing the wood fiber insulation.

4 Empirical study

This chapter presents the empirical study of the master's thesis. A case study is conducted through interviews, workshop, and mail correspondence with the case company, Hunton Trefiber. However, the author also includes relevant data making the empirical study a mixed research method. This chapter presents the case company and the execution of the workshop.

4.1.1 Case company

This thesis will collaborate with the wood fiber insulation manufacturing company Hunton Fiber AS in Gjøvik, Innlandet. Hunton Fiber As is Northern Europa's leading producer of materials for buildings based on tree and tree fiber. They started producing cardboard by own wood mass in 1889 and have developing products for the building industry ever since. Main part of this thesis work will be conducted at their new fabric at Skjerven. This thesis, in collaboration with Hunton, will include expertise from Fiber Visions and company X who have high knowledge in the field of binders and adhesives, specially used in products of wood like coffins, paper, cardboard etc.

4.1.2 Desire for biodegradable products

As mentioned in the literature review, Hunton Fiber wants their products to be completely biodegradable or open for recycling, both opportunities open for a further development in the usage of their products. If further life after insulation is possible, for both their products and products in the future would give Hunton a competitive advantage. Their current solutions cannot completely degrade because of their PE/PP Bico binder, that makes up for approximately 3.5% of the total product.

Alternative binder for wood fiber insulation started with the desire for the product to become fully green and renewable, where you could remove the insulation from the wall and let it biodegrade without waste such as micro plastic. However, developing new solutions nor products is a high investment for companies. Many aspects of product- or service development is needed to be understood and accepted in a high competition market.

4.1.3 Product development

Developing new products and further develop exiting products are a for important step for companies in today's market, thus maintaining competitiveness against up-and-coming companies and large well-funded organizations. There is always a certain risk with product development, including both cost, resources, and loss of reputation. Although different risks being involved in new products, is there various factors the developer, in this case the author and case company can use to minimalize the risks involved in producing and pursuit the desire for a renewable binder. Ozer (2015) talks about factors to acknowledge to minimalize these risks. The factors mentioned is task-related factors, decision maker-related factors, elicitation-related factors, and aggregation-related factors. More about these will be further discussed now following Ozer (2015) structure of product development.

Task complexity is an important factor in justification for product development evaluation, as replacing binder in wood fiber insulation with a renewable materials is a complex task that includes sustainability aspects as cost, social and environmental, Implementation in production line, mechanical properties, end-of-life (EOL), binder content (as of benefits from raw material), lifetime, and lastly availability. Thinking of all these aspects is it clear that task complexity of assignment is high and justification of this needs to be high with insignificant risk. Environmentally sustainable product innovation has a higher degree of complexity than regular innovation because it also incorporates environmental issues (Melander, 2020). Usage of decision aids is beneficial.

Task Importance, the case company has already reached net-zero climate emissions when the wood fiber reaches the gate. Nevertheless, the binder is still non-renewable and blocks for possibilities with biodegradation of end-products. Thus, opening for renewal binder is in the interest of the company and further climate plans, if the product reaches applicable properties.

Decision makers at Hunton have set similar importance and interest in workable solutions for an applicable binder.

Information scarcity, throughout the thesis and before having it been discussed with both the case company and suppliers for reliable solutions for the binder. Whereas, the supplier had different solutions, but non fell inside the applicable binder selection for the company but will be further discussed throughout the empirical study. Discussion about possible solutions found in the literature was discussed with the case company, suppliers, and other experts in field.

Task instructions was given throughout the thesis, where instructions were given from the case company and the supervisor. As the workable solutions came closer to an ending was it given instructions on how to conduct testing of applicable binder for the production. Instructions were given over email, meetings, and messages.

Decision maker-related factors were picked by a broad specter of diverse expertise in the field of polymers, wood-material, chemistry, and other relevant experts in the field. Over the discussion for applicable binders were multiple people and suppliers from other countries included.

4.1.4 Previous research and understanding about renewable binders in wood fiber insulation

Previous and current research on alternative renewable binders for various materials have shown results as low tensile strength, high binder content, lack of available material, non-biodegradable, and high cost. Under a meeting with a supplier of binders for wood fiber insulation, were some of the applicable binders from research mentioned. The representative followed us throughout the meeting with interesting insight about solutions they have tried for their binders. This insight gives further knowledge that applicable research mentioned very little of and will be used in the thought of new binder types.

4.1.5 Adaptation of new binder

Large engineering projects are high-stakes games characterized by substantial irreversible commitments, skewed reward structures in case of success, and high probabilities of failure (Miller and Lessard, 2001). The research conducting possibilities of altnerative binders in wood fiber insulation, due to its complexity, does also have sufficient chances of failure. Nevertheless, where Hunton and the author interested in experimenting with HMMM and Glyoxal crosslinked PVA to open for biodegradability, and other applicable savings as power consumption, binder content, and a decrement in emissions.

Applicable alternative binder can be implemented into production at Hunton in Skjerven, Norway. Where implementation of binder is conducted under one of the last steps in production. The binder is added into the wood fiber mass and is being evenly distributed into the wood fiber from a mixer, where a heater melts the binder into the wood fiber. However, Changes in production could be needed if the crosslinking agents could not change the need for wet production to be evenly distributed around the wood fiber. Or hence the given results from Kirsch, Ostendorf, and Euring (2018) could show higher promising results and could lower the demand for binder content, however if this could work on PVA based binders needs further research.

4.2 Production line

Hunton Fiber uses a continues flow production, where the production starts up with cutting down trees and making woodchips and ends as wood fiber insulation. Further in this sub-chapter will the author present the production of wood fiber insulation, so the reader could visualize the adjustments needed to replace today’s binder.

The process starts at Skjerven in Norway with wood fibers being dropped off into the fabric, where a sorting system sorts the wood fiber into suitable sizes. In picture 1, 2, and 3 can you see the drop off sight, the filtration of wood fiber chips and an not applicable seizes gets filtred out as seen in picture 2.

1

Picture 1, 2, and 3. Here are the drop off site for the wood fiber chips, whereas the first picture (left) is showing the bunker, second picture is showing out-filtered wood fiber chips, and third picture is showing a suitable piece for production.

After the sorting in the wood fiber chips outside the factory is the chips transported to a on a belt to a refinery and an electric bowl that dries the wood fiber chips in hot air around 180 degrees Celsius, from a 7 MW heating oven. Under this process is also the wood fiber chips sent through a grinder, to make the wood fiber smaller.

After the drying and further grinding is the wood fiber sent to the processing line, where adjectives like flame retardant wax and other additives are added. The Bico(PE/PP)-fiber is introduced and mixed with the wood fiber. Pictures under shows the Bico-fiber in dry form added to the spinner and is sent to the grinded wood fiber, where a further mixing to evenly distributed the dry Bico-fiber into the grinded wood fiber before further heating to melt the Bico-fiber into the wood fiber.

2

Picture 4 and 5. Picture 4 shows the dry state of the Bico-fiber added into a spinner to resolve the packed binder. **Picture 5** shows the mixer where the resolved Bico-fiber is added into the grinded wood fiber before heating to melt the Bico-fiber into the wood fiber.

After the Bico-fiber is evenly disturbed into the wood fiber, then the wood fiber is sent for further heating where the Bico-fiber is tried smelted into the wood fiber. As the last production step, is the wood fiber sent further for cutting into standard sizes for packaging and manual inspection of end-product. In the manual inspection is it looked for spots with non-melted Bico-fiber and places where the wood fiber insulation is not fulfilled, as can be seen in **picture 6.**

After that the approved wood fiber is sent for packaging that is handled from a KUKA robotic manipulator and placed on wood Euro pallets and sent for wrapping by a machine that applies plastic wrap around sizeable packages. This conducts the final stage of production of wood fiber insulation.

4.3 Case Study

A case study is conducted with Hunton, hear by case company, to theoretically test the applicable binders from suppliers or the PVA binder with applicable adhesives or crosslinkers. To gain the best knowledge about possibilities was the head of R&D in the case company with knowledge on binders from company X and Y was interviewed because of their high knowledge in the field. Both meeting is included in the appendix. The case company has over a time been invested in changing the binder type in wood fiber insulation and new products that is under development. Hunton was in talks with their supplier for a renewable binder, and under the thesis was it also meetings with a possible new supplier who had developed a binder. The suppliers had multiple diverse solution for a binder with less emissions and some renewable binders, that could bio-degrade. Solutions are addressed earlier in both the literature review and the empirical study. Both solutions are applicable with various downsides and side effects. The documentation and explanation of the workshop will not only discuss the content of these binders, but the outcomes of utilizing these binders in production and products to open for implementation and further research on the topic for the case company. The aim of the workshop is to evaluate, justify, and compare binder solutions to the already used binder in wood fiber insulation, and to support the selection process of applicable binder for the case company.

The case study focuses on both sustainability, comparison of applicable binders, and implementation in the production line. As the implementation of the renewable binder in wood fiber insulation only is a desire at given time, but not a selected and locked way forward. Given binders contain various side effects, setbacks, and other impacts that is necessary to evaluate and address for the case company. Comparison between alternative binder, supplier found binder, and bi-co PE/PP binder will be compared in the end.

Most applicable binder and bi-co binder will be further addressed now, whereas information from case company, suppliers, and literature will be used. The found applicable binders will be further explained and presented in the appendix (?), which was followed in the case study.

4.3.1 Binder materials

Throughout the whole literature review and the empirical study was their mentioned various binders with lack of mechanical properties or other relevant aspects. As there is no significant better solution, is it chosen to work a comparison between binders in this thesis. Were the original binder, applicable binder from supplier, and PVA-based binder will be compared in a scientific manner.

4.3.2 Original Binder

The binder used in today's solution is made from a mixture of Polyethylene and Polypropylene, which are both synthetic binders.

Polyethylene (PE) is a commonly used plastic material that consists of a long chain of carbon atoms with two hydrogen atoms attached to each carbon atom (Ash, 2016). PE is polymer with amorphous crystalline structure. PE is a thermoplastic monomer which can be recycled, however it can be a thermoset if modified, like crosslinking the polyethylene.

Hydrocarbon ethylene ($C2H4$) is gas at ambient temperature and pressure, If the ethylene gas is reacted under appropriate conditions, it will transform to PE, which is a solid polymeric material (Callister, William, Rethwisch, David, 2013) Polyethylene consists of both low-density (LDPE) branched and high-density (HDPE) linear chains. HDPE is more expensive. HDPE uses often in hard products like chairs, barrels etc. and LDPE is often used in wrapping like food packaging and plastic bags. LDPE is also elastic, while HDPE is hard and brittle.

Polyethylene looks like this:

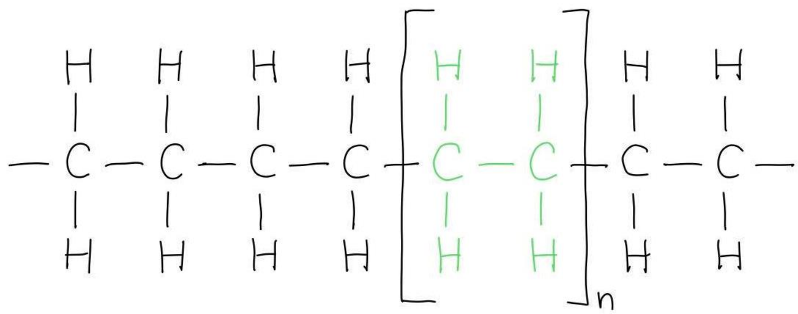


Figure 3. Polyethylene chemical structure.

HDPE has a low amount of branching whereas LDPE has a high degree of branching, ref **Figure 4.** There are many variations in the branching, density, molecular weight, and crystallinity. Its mechanical properties vary as per the type and extent of the branching.

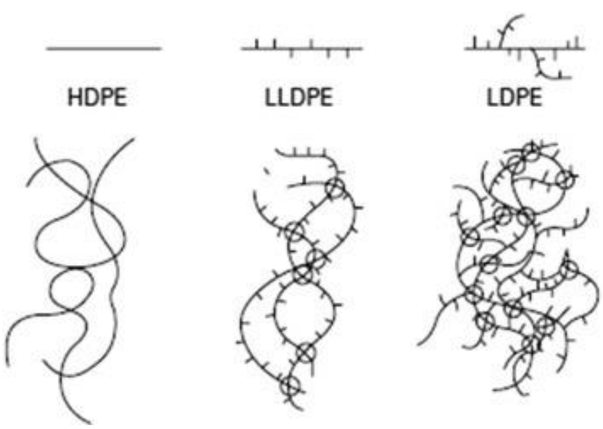


Figure 4. Branching in various versions of polyethylene (Malkan, 2017).

Polypropylene (PP) is a commercially important polymer, as it is used in many different products due to its low cost and good mechanical properties. PP is also a thermoplastic, which means it can be recycled. PP and PE have many of the same mechanical properties. However, polypropylene differs in the following respects: lower density, service temperature is higher which means that the plastic does not melt before 170 °C, it is harder, and more rigid, more resistant to environmental stress cracking, and more susceptible to oxidation and chemical attack (Koerner and Koerner, 2018). PP is produced via chain-growth polymerization from the monomer propylene. Polypropylene is resistant to many polar liquids such as alcohols, organic acids, esters, and ketones. Aliphatic, aromatic, and halogenated hydrocarbons will swell polypropylene (Sastri, 2022).

Polypropylene looks like this:

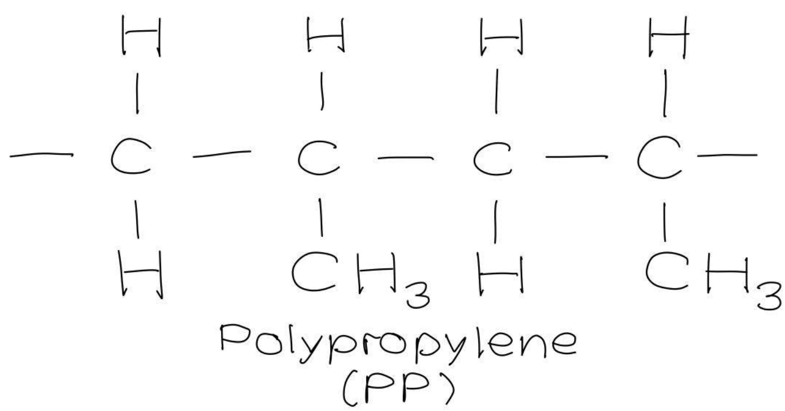


Figure 5. Polypropylene chemical structure.

PP is the plastic with the lowest density between 0.895 and 0.92 g/cm^3. While young’s modulus often differs between 1300 and 1800 N/mm^2. PP is often also used in plastic products like chair etc, because of the high similarity of PE in mechanical properties.

4.3.3 Alterative binders’ main polymer

PVA crosslinked with HMMM and Glyoxal is the alternative binder thought of in this thesis, to replace the bico PE/PP-binder. PVA (Molecular Weight (Mw) = 89,000–98,000 and 99% Hydrolyzed) is one of the most important commercial polymers. PVA have a crystalline melting point at 210 °C. PVA film are known to have high tensile strength and high impact strength, high tensile modulus, and excellent resistance to alkali, oil, and solvents. However, high impact strength and resistance to alkali and oil is not needed for an alternative binder. As a matter of fact, there is an endless stream with materials that is both mixed and/or crosslinked with PVA.

Polyvinyl alcohol (PVA) is a vinyl polymer joined by only carbon–carbon linkages. The linkage is the same as those of plastics such as polyethylene, polypropylene, and polystyrene, and of water-soluble polymers such as polyacrylamide and polyacrylic acid. Among the vinyl polymers produced industrially, PVA is the only one known to be mineralized by microorganisms. PVA is water soluble and biodegradable; hence it is used to make water-soluble and biodegradable carriers, which may be useful in the manufacture of delivery systems for chemicals such as fertilizers, pesticides, and herbicides (Kumar and Doble, 2005).

PVA can be used the same way as PE/PP through fibers, as it also is a thermoplastic material, but however difficult to process through injection molding as there is a quite narrow window of temperature where PVA is hot enough to melt, but cool enough to not start thermal degradation.

Unlike most polymers, is PVA not prepared by polymerization of the corresponding monomer, since the monomer, vinyl alcohol, is thermodynamically unstable with respect to its tautomerization to acetaldehyde. PVA is prepared by hydrolysis of polyvinyl acetate or sometimes other vinyl ester-derived polymers with formate or chloroacetate groups instead of acetate. Large number of hydroxyl groups on PVA attracts water molecules and are responsible for high degree of swelling in the binder, thus could affect the product or binder in general for wood fiber. Dissolvement of PVA in water is affected by hydrolysis, molecular weight, particle size, and crystallinity. PVA can be bought in small bags, super bags, cubic containers etc. and can be saved in super bags as granulates in room temperatures up to 5 years (Sekisui, 2005).

Thermosets cannot be recycled or remelted, as thermoplastics can. PVA is a polymer with a carbon backbone that is not liable to hydrolysis. It requires an oxidation process for its biodegradation. PVA biodegradability can occur by microorganisms in addition to enzymes through an oxidation or photo-oxidation process (Ibrahim, El-Wassefy, and Farahat, 2017).

Polyvinyl alcohol appears as odorless white to cream-colored granules or powder. PVA has a chain length which is long and crossing, some crosslinkers including poly (acrylic acid), dimethyl carbonate, cellulose nanocrystals, lignin, reduced graphene oxide, boric acid, and glutaraldehyde (Li and Xu et al. 2021) have been used, same with hexa(methylmethoxy)melamine (HMMM) and Glyoxal. However, it was found weak linking in the Hydrogen (H) bonds between some of the crosslinkers, that could affect mechanical properties. Hydrogen bonds are recognized as the most important specific molecular interactions in biological recognition processes. H-bonds are formed between an electronegative atom and a hydrogen atom bonded to a second electronegative atom. The strength of the hydrogen bond depends on the electronegativity of the atoms; hydrogen bonds as very strong (e.g., [F…H…F]−), strong (e.g., Osingle bond H…O double bond C), or weak (e.g., C single bond H…O) depending on the bond energy, which ranges from 40 to <4 kcal mol−1 (Mcleod and Rosei, 2011). PhyAc molecules contribute to the non-bonded energy (e.g., the H-bonding with PVA). How the HMMM crosslinker works is not checked and will need further research.

PVA looks like this:

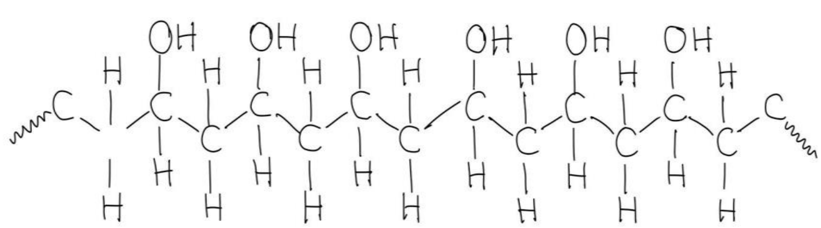


Figure 6. Chemical structure of polyvinyl alcohol (PVA).

PVA is a synthetic polymer of great industrial importance. PVA has been applied in wide range of fields because of properties such as water soluble and adhesive properties. Moreover, PVA is known as ecological polymer due to its biodegradability (Tian and Tagaya, 2008).

Tian and Tagaya (2008) measured stress – strain and storage- and loss modulus for PVA, which gained results like this: PVA with M w = 89,000–98,000 - 99% Hydrolyzed showed a glass tension temperature (Tg) of approx. 0.35-0.4, which is relatively low as PVA is a thermoplastic polymer who reaches Tg (glass transition temperature) at relatively low temperatures. The GPa was of 0.96 GPa for PVA alone. However, when adding adhesives or crosslinkers, or using PVA in composites, shows high increase in mechanical properties.)

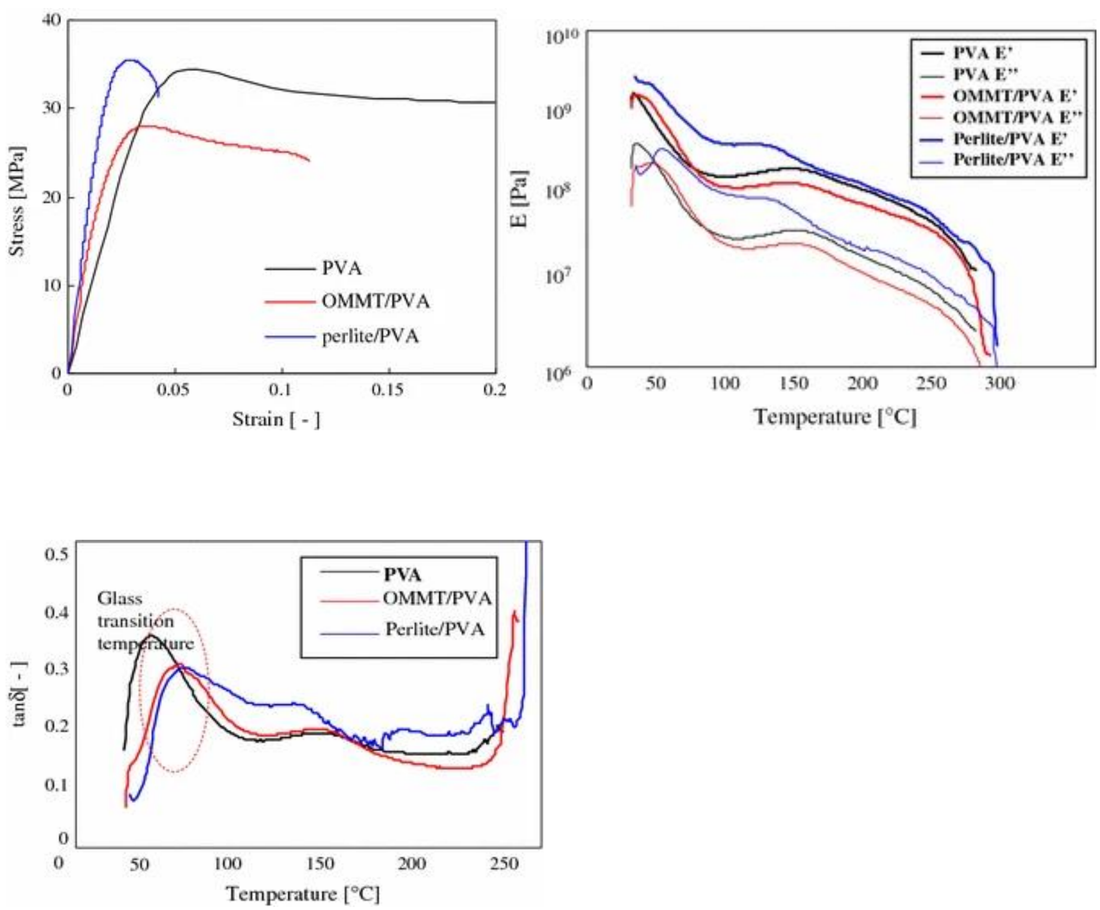


Figure 7. Stress/Strain, Loss- and storage modulus and glass transition temperature (Tg) of PVA from Tian and Tagaya (2008).

When the storage modulus is high, is it hard to break down a polymer. Storage modulus shows how much energy needed to be put into the sample to break. When an amorphous polymer is heated, the temperature at which the polymer structure turns viscous liquid or rubbery is called Glass Transition Temperature (Tg). The value of Tg depends on the mobility of the polymer chain and usually lies between 170k to 500k for most synthetic polymers. Sonker, A et al. (2021) found crosslinking results as maximum strength measured in crosslinked samples is 32.5 MPa for suberic acid crosslinked PVA which is higher than that of neat PVA (22.6MPa), which can be discussed from results found in **Figure 7,** which further shows that improvement of mechanical properties in PVA can come from addition of crosslinkers. As Li, Xu, and Wang et al. (2021) saw that the tensile strength of PVA/PhyAc composites continues to increase slowly with increasing PhyAc contents until 10 wt% while their elastic modulus shows a peak value at around 3.8 wt% of PhyAc. However, the strength and other likewise mechanical properties are only a small portion of the requirements for the binder. The crosslinker cannot destroy properties like biodegradability and / or destroy other main properties of PVA. However, the hydrophilic properties of PVA are only relevant for EOL of the binder and a form of hydrophobic agent is needed under the usage of the product to not attract moisture into walls. Preferred hydrowax or any other agent to hold these properties.

PVA and crosslinked PVA samples	Tensile strength (MPa)	Toughness (MPa)
PVA (P)	22.63 (0.5)*	40.47 (2.9)
Suberic acid CL PVA		
15% (w/w)	32.52 (0.1)	74.78 (7.6)
25% (w/w)	21.87 (2.7)	30.06 (6.5)
35% (w/w)	20.63 (2)	27.70 (3.8)
Terephthalic acid CL PVA		
15% (w/w)	10.95 (0.3)	4.69 (0.8)
25% (w/w)	8.49 (0.2)	5.11 (0.7)
35% (w/w)	6.29 (0.3)	1.33 (0.3)

*Standard error of the mean value

Figure 8. Strength of crosslinked PVA for reference by Sonker and Rothere et al. (2017)

As mentioned above and shown in **figure 8**, does crosslinking PVA with Suberic Acid and Terephthalic Acid affect both tensile strength and toughness of the material in a negative manner. Thus, is it important that the HMMM or other crosslinker does not affect the binder to below the threshold for acceptance given by Hunton, which is 1 kPA on the final product in given geometry. However, crosslinking PVA showed reduction in water uptake by less than 10% by crosslinking with Suberic Acid. Could this solve the general production requirement by using a wet line is a breach of interest following.

How to produce the PVA is another requitement to solve, as PVA comes in pulverized or wet solution. To dissolve the PVA into the mixture is it normal to put the solution into cold water and slowly heat it up while mixing the solution to gain the thermoplastic mixture. However, while the mixture is heated up, is it important to evenly disturbed the PVA into the water, wisping with your hand is not sufficient. Silverstone uses machinery that could take PVA directly into hot water for dissolving to become sticky. Cleaning of equipment after use can be done by water and heating the water up over 30 minutes.

Polyvinyl Acetate (PVA) is also an interesting polymer, but is often used as glue for wood etc., which could be beneficial for wood fiber. It even has a low degree softening temperature.

Conditions for PVA to dissolve in water is governed by hydrolysis, molecular weight, particle size, and crystallinity which is important to understand and engineer for the suitable product using PVA, as for wood fiber has some degree of moisture intact is it important for the PVA to withhold its degradation in this condition, if possible. Crosslinking reactions are one of the most used techniques to improve physical properties of polyvinyl alcohol (PVA) (Zhang, Zhu, and Edgren, 2009).

4.3.4 Applicable crosslinkers and adhesives

HMMMM and or Glyoxal was one of the thoughts of crosslinkers for PVA in wood fiber insulation, but as research has developed is it in interest to look at other beneficial crosslinkers also. Crosslinking reactions are one of the most used techniques to improve physical properties of polyvinyl alcohol (PVA). There are many various ways to crosslink PVA, PVA crosslinked with dialdehydes is one of the most commercial used ways. Crosslinking as well as modification of PVA through its hydroxyl groups can further explore new applications for this material (Zhang, Zhu, and Edgren, 2010).

As these also show advanced properties that could be beneficial to modify the binder into our requirements. These will be further discussed here.

Hexamethoxymethylmelamine (HMMM) or triazine derivative 2-N,2-N,4-N,4-N,6-N,6-N-hexakis(methoxymethyl)-1,3,5-triazine-2,4,6-triamine is a monomer of melamine resins which could also act as a crosslinker and widely used in the production of coatings and plastics, e.g. for cans, coils and automobiles (Alhelou, Seiwert, and Reemtsma, 2019). HMMM can under lab degradation or industrial decomposing transform but not mineralize under aerobic conditions, this could be trouble to degrade or dissolve the PVA if mixed. However, these conditions are not tested. HMMM is a highly water-soluble material and suspected aquatic toxity and are reportedly found in industrial wastewaters around the Netherlands. While the core structure of HMMM corresponds to melamine, it is not clear, yet, if melamine would also be a degradation product of HMMM and, thus, whether HMMM contributes to the omnipresence of melamine in the water cycle (Alhelou, Seiwert, Reemtsma, 2019).

hexa(methylmethoxy)melamine (HMMM) is often used as crosslinkers on coil sheets from polyester to prevent corrosion on steel, where between 5-30% HMMM crosslinker were used in the polyester. HMMM is also often used as a crosslinker in tire manufacturing. Dynamic mechanical analysis (DMA) showed that the glass transition temperature (Tg) and crosslink density increase with crosslinker content. Failure envelopes, normalizing the tensile data with the DSC Tg and the crosslink density, show the dependence on crosslinker content and pigmentation (Sorce and Ngo et al. (2019).

HMMM has a chemical structure as:

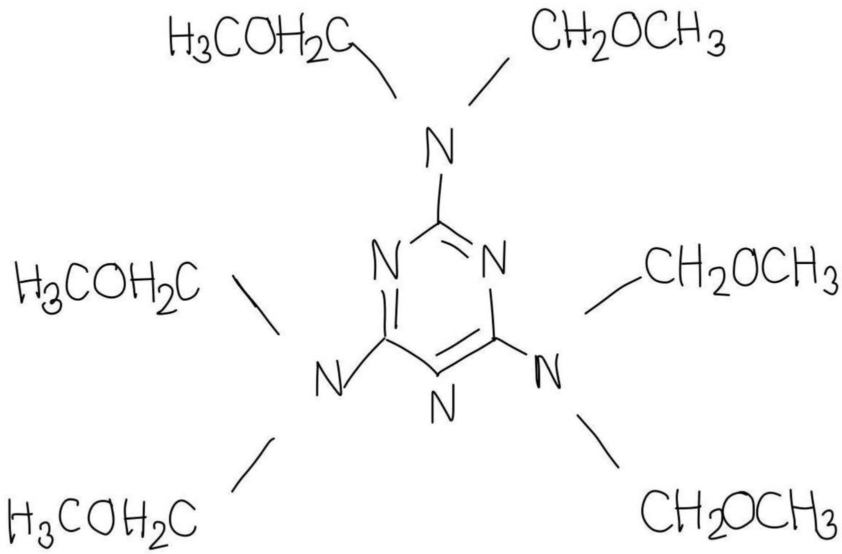


Figure 9. Chemical structure of Hexamethoxymethylmelamine (HMMM).

HMMM is seen to biodegrade in surface waters and in subsurface in bank filtration (Alhelou, Seiwert, and Reemtsma, 2019). Bank filtration is the process witch water is filtrated to become drinking water. HMMM was found to degrade by photochemical oxidation in Germany after runoff in rivers from tire were on the German autobahn and / or degraded over 53% over 18 days in aerobic activated-sludge conditions (Johannessen and Parnis, 2021). HMMM is often crosslinked with polyester. However, these crosslinkings have shown sensitivity to humidity, temperature, and chemical structure. Under DMA and tensile testing of HMMM as a crosslinker in polyester was it found that increments of HMMM content generally increased Tg and gives little variation of the storage modulus in the glassy region but increases the modulus in the rubbery region where the covalent bonds govern the behavior (Source and Ngo et al. 2019). Another reliable crosslinker for PVA could be Glyoxal and Xylan as adhesive instead of HMMM, or a combination of these.

Glyoxal

Glyoxal is a suitable crosslinker for PVA, as the hydroxyl groups of PVA react with aldehydes via formation of acetal bonds hence crosslinking could take place (Zhang, Zhu, and Edgren, 2009). Glyoxal is also recommended as a crosslinker by Sekisui (Sekisui, w.y). PVA contains secondary hydroxyl group that easily forms hydrogen bonds with starch. The crosslinking of Glyoxal on PVA showed significant results in mechanical properties, however it was not tested as a binder. There are many various blends, crosslinking of PVA with Glyoxal and other materials as starch as Gadhave, Mahanwar, and Gadekar (2019) did. Most of the alternatives are already discussed in the literature review, but as the research opens for further interest is it important to discuss this further. Where the Glyoxal was used to improve properties. Starch is great binder coming from renewable materials, however not strong enough to glue wood. Which is needed for wood fiber insulation, otherwise could starch become a binder alone. However, it could serve its purpose as an adhesive for wood obtained by mixing with another polymer, in this case PVA crosslinked with Glyoxal or would be interesting to test HMMM here also. Glyoxal at 90 ˚C reacts with the hydroxyl groups, forming a between two inter-molecular chains for intra-molecular chains.

The crosslinking between PVA with starch and Glyoxal looks like this:

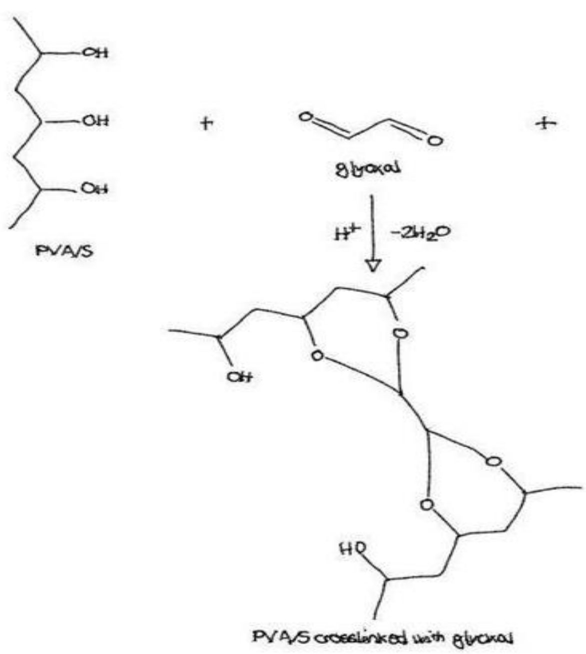


Figure 10. Crosslinking between PVA and Starch with Glyoxal.

Increasing the ratio of starch to PVA in a blend with constant concentration of glyoxal resulted in increase in the mechanical and thermal properties (Gadhave, Mahanwar, and Gadekar, 2019). Could Startch into the HMMM crosslinked PVA solve the need for higher degrees of mechanical and thermal properties, and crosslinking density could be spotted as low as 1% (Zhang, Xhu, and Edgren, 2009) it is interesting to see in further research.

Chowhury and Teoh et al. (2020) talked about suitability for crosslinkers to bind with PVA, whereas Glyoxal was crosslinked with PVA and had increasing results in water solubility and increasing mechanical properties, could this solution become relevant as an adhesive or extra crosslinker into PVA.

Xylan

Xylan is a biopolymer often extracted from outer covering of cereal, grains, and corn cobs. It has often been used as an adhesive, thickener, and additive to various plastics. Xylan is the main hemicellulosic component of hardwoods and accounts for approximately 30% of the woody cell wall (Awano, Takabe, and Fujita, 2001). It is found in terrestrial plants, and secondary cell walls of dicots and all cell walls of grass. After cellulose, are xylan the most abundant renewable biopolymer component in nature. Xylan's chain is normally linear, but occasionally it may become branched. The degree of polymerization is between 70-130. Xylan is found in significant quantities in the cell walls of hardwoods (15-30%), softwoods (7-10%), and annual plats (<30%) (Saka and Bae, 2015). Xylan with modifications have shown outstanding physical and mechanical properties. It increases their stretch and breaking resistance, and susceptibility to biodegradation (Benabid and Zouai, 2016), which is preferred when mixing with PVA to withhold the biodegrading properties. Enzymatically modified Xylan is often used in cosmetics as a thickener, stabilizer etc., in nutraceuticals as a prebiotic, and in the food industry as a digestive agent (EnXylaScope Project, 2022).

The chemical structure of Xylan:

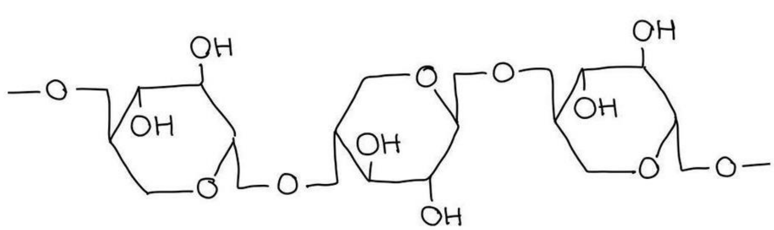


Figure 11. Chemical structure of Xylan.

Xylan have already been tried crosslinked with PVA and Borax. Witch showed high mechanical properties and interesting results in self-healing properties, actually as much as 85,8% recovery within 30 seconds of the specimens. Witch can lower the chance of plastic deformation (Ai and Li et al. 2021). However, properties like self-healing are not the highest demand for a binder in wood fiber insulation. The material was found to be freely deformable and recyclable (Ai and Li et al. 2021). If the properties came from or significantly increased from the borax in further research needed to understand. However, the results Ai and Li et al. (2021) found are of interest as it shows that Xylan can be crosslinked with PVA without trouble as already confirmed from Sekisui Specialty Chemicals (w.y) and does increase the usage of renewable materials into the binder.

4.4 Deciding environmental conditions

The global problems with micro- and nano-plastic waste found everywhere, and humans and animals are found with nano plastic inside their blood, has triggered the development of advanced biodegradable polymer materials. ISO 14040 (International standard organization, 2007) holds various standards for recycling, biodegrading, and handling of different waste materials. Thus, needing a plan whether go for biodegradability or recycling is needed. However, biodegradability opens for end of life and recycling opens for further usage, however research showing interest in using 60-year-old wood fiber is needed and cost vs. usage is needed.

The cause to decide the environmental impacts from the binder and what environmental benefits we want from the binder. It can either be biobased, biodegradable, or recyclable. A degradable polymer is a polymer which undergoes a large change in its chemical structure to break down the polymers in special environmental conditions. The major change comes from the decrease in molecular weight, this can for example come from an industrial decomposition plant, where waste is industrial decomposed over time adding bacteria, heat above 60 degrees Celsius and moisture.

Polymers in which the initial degradation results from the action of light, even if subsequent degradation processes occur via microorganisms or chemical reactions, are called photodegradable polymers. Polymer chain groups, which are sensitive to light at less than 320 nm, can be incorporated into the polymers. These light sensitive groups initiate polymer degradation when the plastic material is disposed outdoors (Jayasekara, Harding, Bowater, and Lonergan, 2005). It is in interest to see if these chain groups can be added into the original binder to degrade the polymers or add into the PVA mixture.

However, it is commonly thought of that natural polymers are biodegradable. This is not the case. Complex macromolecules, such as lignin, are relatively inert while synthetic polymers with hydrolysable functional groups, such as aliphatic polyesters are biodegradable. Lignin mixed PVA was also one interesting polymer group which could suite as an alterative binder in wood fiber insulation if the demand were for renewable and biodegradable properties.

Deciding the environmental benefit and impact from the binder where complicated, as many polymers had different drawbacks and side effects, and cannot be crosslinked. Other properties showed significant increase in pollution and waste in EOL. Hence, as the problem states, was biodegradable properties in interest, as the EOL could then be used as agricultural products as compost. Hence, extending the lifetime of the product and open for biodegradability to increase quality of the produced plant in the field.

One situation that needs further research is if the PVA-based could biodegrade under landfill conditions with wood fiber, as both heat and moisture will come naturally when the wood fiber starts to decompose in the landfills. Will it completely downgrade the thermoplastic by the exposure to heat and moisture? Will it need more heat and moisture or pure water? PVA can be both degrade in water and not.

There are multiple standards for various degrading and waste placements, ASTM D5526-18 (ASTM International, 2018) determines the anaerobic degradation under accelerated landfill conditions of plastic materials, whereas ASTM D5511-94 (ASTM International, 2018) determines anaerobic degradation under high solids digestion conditions. Both these standards need to be followed when testing the conditions.

Fiber visions also talked about lowering the environmental impact by lowering the emissions from production of PE/PP-binder. This means opening for using biobased oil, like palm oil or sunflower oil etc. Palm oil is not applicable. Instead of using crude oil. This can be done in large batches where you include 98.000 tons of palm or any other alterative oil and 2000 tons of crude oil into the mixture, or the other way around, to lower the total emissions from the binder. This practice gives the supplier for Fiber visions the opportunity to give this confirmation of lower emissions all the way from the supplier of fiber visions to Hunton or the end user, but only if every led in the supply chain has an ICC-certification. Thus, making it hard to give the certification further to users of the wood fiber insulation for Hunton. The supplier also said that PLA is tried, but as mentioned needs industrial decomposition. However, a Hamp fiber insulation manufacturer uses PLA to bind the products, however not opening for the biodegradability that hamp gives, same goes for wood fiber insulation with its non-degradable original binder.

4.5 Testing PVA as an alternative binder

Under the literature review, was it found that PVA could become a potential replacement binder in wood fiber insulation boards. Under the interviews and meetings was it mentioned some side effects from the potential binder, but for the sake of experimenting will it be tested out as a binder in wood fiber in the PDSA methodology later in the study as a part of the empirical study of this thesis.

Thinking of hazardous materials, is neither PVA nor HMMM or Glyoxal listed as comprehensive chemicals regulation is in place in Europe (REACH). Witch would make the materials not applicable for further testing and possible implementation.

5. The Plan-Do-Study-Act (PDSA) methodology for implementing the alternative binder

The PDSA methodology cycle is an iterative, four step model for improving a process. The first step is the development of a plan in which predictions of outcomes are clearly stated and tasks are assigned. It is in this phase that the who, what, when, and where of the plan is decided. This is already talked about in the product development. In the "do" phase, the plan is implemented. Data and results obtained are then analyzed in the "study" phase. Last, the plan is either adopted, adapted, or abandoned in the "act" phase based on the evaluation of the data in the prior step. The learning from one cycle should guide the cycles that follow (Christoff and Pharm, 2018). We will be following the paper of Christoff and Pharm (2018) under the PDSA of the alternative binder implementation.

5.1 Plan

The planning phase of PDSA methodology goes for what is trying to be accomplished, in this thesis are we trying to implement a renewable binder in the wood fiber insulation, that can biodegrade over time. As Christoff and Phram (2018) mentions, are it here included what, who, when.

The author needed to set goals and achievements for the research, where the overall objective, as earlier mentioned, was set to:

1. Identify applicable binders for wood fiber insulation through available literature.
2. Analyze mechanical properties, functionality, availability, and cost for applicable binder.
3. Compare today's synthetic polymer binder, supplier found binder, and alternative binder in product, production, and lifetime.

Identifying applicable binders, was under the literature review and further discussed in the empirical study with expertise in the field, found to be PVA with crosslinkers or applicable solutions from suppliers looking at biodegradability as the main objective. However, the PVA binder with crosslinkers could not be the most suitable solution for the case company, hence further research needed after the study is needed. If it is the interest to find out if it will work as a solution in wood fiber insulation.

The author also needed to identify when a change made an improvement, this however, was an important and challenging step. Not only was it needed to replace today's binder as a green alternative, will it also need to be cost efficient, easily implemented in production, and be biodegradable. This was a challenging task and therefore needed time for literature reviews and interviews with experts in the field. After some time was it in the interest of the case company to test both the PVA-based solution and the solution from the supplier.

What change can we make that will result in improvement, and in fear of repeating the main objective to many times, will this not be further discussed here.

It was decided that the author should conduct an experiment with an 5% PVA solution on wood fiber to see if PVA would degrade when applied and heated on wood fiber. It was needed to perform a risk analysis for the experiment. Risk refers to the potential for negative outcomes that participants may experience as results of working on your research or participating. Therefore, will the author now conduct a risk assessment of the experiment using PVA crosslinked HMMM in wood fiber insulation. The risk assessment will be set under Appendix D. However, the risk assessment will also include evaluation of tensile testing, DMA testing, and crosslinking of PVA with Glyoxal and HMMM, even if these experiments are not tested under this study but will lay a ground for further research.

Under planning of the alternative binder where their multiple aspects to consider from the case company, likewise the mechanical properties and biodegradability. Further will the requirements be discussed. These aspects are found discussed forward from the case company.

Product

Does not increase warm leading capability or increments in fire Haszard, tensile strength should be over 1 kPa, does not compress more than today’s solution, can be cut with known tools, does not increase in steam passage or decrease air resistance flow, form stability over time preferably lifetime, none increment for mold nor shrooms, UV stability, can handle a certain swelling or shrinkage, non-responding with plastic wrapping, does not pollute air, and lastly home decomposable. All these requirements where important for the case company. Many of these requirements are not easily tested in a theoretical manner and further research where needed. Under the testing will tensile strength and cutability will be tested at school, likewise the mixing of the alternative binder. Thermal conductivity and fire availability can be tested at the lab at the case company. Standards needed for wood fiber insulation boards are needed to be followed to become suitable as an alternative binder. Many of these standards are already mentioned above in the study.

Production demands

The alternative binder is required to hold production at same production line as original binder, with minimal changes, looking at cost and minimal waste from changing production line. The production demands are set for Health, safety, and environment at work (HSE), production cost and production line. It needs to be a dry process; wet process works for other products for the case company or steam-based production for the PVA could be of interest. The binder needed to have a lower or the same melting temperature, higher temperatures are not applicable. Does not need changes in today´s wood fiber. Does not need less convection for heating -or cooling zones. Can be cut by circle cutters in production. The wood fiber insulation must be able to be stored outside in tents when wrapped in plastic (moist, various climates etc). The binder should be able to melt around 130 degrees Celsius. Alternative binder needs to be able to be stored over some time. Non harmful toxins or emissions in production. Should not increase particulate matter at the production site. Should be able to bind dry wood fiber. The wood fiber needs to be thermomechanical refined at 170 degrees Celcius. The binder needs to handle a certain vacuum under production to align the fibers and adjust density. Both wax and flame retardant are needed as a wet solution before thermomechanical refining at 170 degrees celcius. The flame retardant is 40 dry material and 40-50% wax. The supplier informed that they'll reach the requirements for wax and flame retardant inside the binder, thus removing this addition in production. However, these functions are already implemented in production at Skjerven. The production can only go down to 13% moisture in wood fiber under production after refining.

Environment and Economy

It was already set many demands under product and production, but environmental and economy also comes under demands. The product should be able to be recycled at Skjerven or Gjøvik, however it would be more suitable if the product could be reused or composted at home. Or as mentioned, used in an agricultural manner. The binder should be based on renewable resources. The alternative binder should not have a large increment in transportation from production-to-production site. An environmental product declaration (EPD) should be available on the alternative binder or should be made. No environmental hazards like heavy metal or dangerous components. It should be able to compete with the market, like Glava etc. The alternative binder should not increase in percentage used in wood fiber insulation, around 3 %. The availability of the binder is important, there must be multiple available distributers to decrease change of bottlenecks in production.

Under the planning phase of the alternative binder where it in interest to talk with experts in the field, whereas the case company and the author called in for open discussions and interviews with suppliers for binding solutions to see if the alternative binders where in interest or tried by stakeholders. One of the suppliers where already deep into binding solutions and the other one worked with developing alternative binders.

Both meetings are placed in the appendix for reference but will be discussed here. The author had already found many alternative solutions under the systematic literature review but had interest in finding expertise and experiments in the field for a higher scientific confirmation.

Under the first meeting with the binder supplier was there many solutions discussed, where the expertise had knowledge about drawbacks from the alternative binder.

As there are many various solutions with drawbacks and things like that, wanted the supplier to understand what our intentions on an alternative binder was. If it was to decrease emissions, recycle, becoming biodegradable and so on. This opened for discussion for better understanding the assignment, as biodegradable does not mean lower emissions.

The author and the case company explained that they wanted, with various mechanical properties, to open for biodegradability or recycling, whatever suits the most mechanical properties.

It was in interest to find or make an environmental product declaration (EDP) on the alternative binder in the wood fiber. This could be done by an in-depth life cycle assessment, which could be done as a study for other students to solve. The supplier mentioned that todays engineered Bico PE/PP solution was great in the matter of bonding, cost, and binder usage. Hence, the already discussed aspects of the original binder.

To lower emissions from production was one of the solutions from the supplier to use different kinds of oil into the mixture when producing the PE/PP-binder, thus open for certification and lower emissions on paper. This was not in the interest of the case company and the author as the final solution, as this only changes the original binder in the matter of emissions and somewhat renewable resources. However, this could be a solution for the development time or the final solution if no binder fits the requirements. The solution however could lower the emissions by minus 2 kg CO_2 per kg fiber. The solution could also implement a recycled core, but not the whole binder as polyethylene can be recycled, but polypropylene cannot be recycled.

PLA was mentioned multiple times in the literature as green binder with suitable mechanical properties for wood fiber, if some changes could be made with crosslinker or adhesives. However, the material is not biodegradable without industrial decomposition. Industrial decomposition only happens under 60 degrees Celsius, over 60 days, and certain other conditions, high moisture, and certain microbes. These conditions are not found naturally on earth. Plants who have these conditions are only found a few places around the world, and thus contribute to “green washing” if the wood fiber is not nearby the industrial decomposition-plant. Witch is already mentioned to be not applicable for this study.

Another solution was to change the binder type to another one from the supplier, this mean changing the version from 1,6 grams per km thread to 1,3 grams per km. Thus, lowering binder usage from with about 1% and opens better than the 1,6 grams dtex. However, this will also lower CO2 equivalent emissions with 2 kg per kg binder. Problems however where dtex flying around the fabric, but the new fabric at Skjerven is suitable for this since the binder “cage” is locked. This solution will open for biodegradability, thus not applicable at given time. Supplier was working on PP which is biodegradable, the PP turns to wax and oxygen, afterwards will the binder biodegradable over 1-2 years. Open for a timeline for biodegrading is not possible at given time but is further in research and could fit agricultural products. The product will not be included into the comparison, due to the lifetime and the development of the binder.

Polyethylene (PE) needs bacteria and light and would degrade after a while (compares to a sweatshirt). The supplier hasn’t worked with lignin based and little with PVA, often problem with melting point occur (150-200 degrees). Polyester however is a renewable binder that immediately starts to biodegrade, uses sun and bacteria to biodegrade. Almost all the material, approximately 85% of the binder biodegrades. Polyester binder fibers have degraded after three years. PVA is applicable as a binder but is not worked on that much from the supplier’s side. Same goes for Lignin-based binder. Crosslinking PVA with hexakis(methoxymethyl)melamine (HMMM) or glyoxal is possible. PLA and PBA removes around 25% of carbon footprint but needs to add 5x more additives for same mechanical properties, higher cost than already used binder. Polyester and polypropylene mixed binder, whereas development on biodegradable polypropylene being worked on. Goes from plastic to wax, afterwards degrades the wax.

As the meeting with the supplier gave meaningful insights for further production, where it in interest to open for further research on biodegradable binders and research on PVA crosslinked with HMMM and Glyoxal. Witch was already discussed and now confirmed by experts in the field that it could work.

Supplier for biodegradable products.

Keeping in mind the information received from the first supplier, found the case company another suitable supplier, which could give meaningful insight for the case company and maybe open for a collaboration. The supplier informed about achieving high yearly capacity in production, so availability wouldn't be a problem. Also achieving density on 50 kg per cubic meter. The supplier already uses their binder in products with different mechanical properties in paper towels and coffins to mention some. Problems were discussed as the binder needs a wet process and the wood fiber insulation uses a dry process for production. This problem was already addressed for the PVA-based binder. The alternative binder from the supplier could be formed into the wood fiber from 90 degrees celcius but would show best effect around 150-170 degrees celcius. The product starts biodegrading when exposed heat, moisture, and microbes, same as the other supplier talked about. Common knowledge. The higher the temperature, the faster the process. In an agricultural manner, if the product is exposed to dirt and maggots will the bio downgrading start immediately. Home decomposability is a standard at the supplier, thus opening for thought of EOL for wood fiber insulation. The supplier also mentioned that compostable and down gradable is two different things and should not be compared. The binder is as biodegradable as wood fiber. Under the discussion was it said that it could be tested with help at the fabric for both the supplier and the case company, with help from SINTEF and Innovasjon Norge to mention some.

Under meetings with expertise from NTNU from where various interesting insights given. It was however said to be smart to test the PVA alone before it would be tried inside wood fiber. It was therefore invested in buying in PVA in both liquid and pulverized versions to determine the dynamic mechanical properties of PVA following the BS ISO 6721-11:2012 standard (BSI Standards Publication, 2014). However, many research articles had already discussed pure 5% PVA in both tensile strength and DMA testing. Therefore, was it only in interest, under this study, to look at dissolvement of PVA on wood fiber in contact with water and time used to dissolve in various productions types.

The material that was bought in for testing was 5% Polyvinyl Alcohol Solution, 3.8L - The Curated Chemical Collection from Innovating Science and PVA 2488L Powder Polyvinyl Alcohol (500g) from Eastchem with Alcoholysis degree of 88%, polymerization degree of 2400, and Molecular weight of 105600 (g/mol).

5.2 Do

Under the Do-Phase of the PDSA methodology is it meant by carrying out the plan and documenting relevant data that could identify success, problems, or unexpected outcomes. Most of the applicable information here can be directly picked by the literature review and what is going to be found when the author conducts the experiment with testing wood fiber insulation with PVA crosslinked with HMMM and Glyoxal as an alternative binder. However, HMMM and Glyoxal was not obtained under this study and only pure PVA will be tested but could give interesting insights for further confirmation.

All these requirements removed many applicable binder suggestions. Many of the already thought of binder types were removed due to high percentage of binder content in their respectful tested fields, high cost, low availability, or non-applicable mechanical properties. The requirements made it hard to compete with the original binder used in the wood fiber insulation. Therefore, was it in interest to remove or think less of some of the requirements to open for biodegradability in the wood fiber. Under the literature review (ref, Steinaa, 2021) where many alterative binders thought off. There most applicable binder where PVA mixed with some crosslinkers to adjust mechanical properties showed promising results. The author had interest in trying mixing PVA and crosslinking it with HMMM and Glyoxal, witch alone showed promising results and could combined show great results in wood materials. However, experiments where needed testing if the binder could be used, binder content, crosslinking mixture, mechanical properties, and biodegradability or recyclability.

First is it in the need to get PVA and HMMM for testing the binding capability of the material combined with wood fiber chips. Multiple tests with different measures of binder content will be needed, for example 2,5%, 3%, 3,5%, 4% is applicable. It is here needed to analyze and see if the already thought of properties from the literature review and the meeting was applied to the wood fiber insulation. Properties that needed to show in the wood fiber is thermal conductivity, tensile strength, flame retardant, biodegradability, binding force, and heating time for binding wood fiber with the alternative binder. Finding data for melding point of binder is needed, and then making intervals for samples like each 5 degrees Celsius between 170-200 to find the optimal condition for the wood fiber insulation.

Both Tensile testing of wood fiber insulation and the HMMM crosslinked PVA can be tested under a DMA analyzer to find Tg and MPa from a ZwickRoell Tensile tester placed at NTNU in Gjøvik, however was the tensile tester out for service. And will not further worker under the experiment.

If the alternative binder applied on the wood fiber looked like it would hold together the wood fiber, without high usage of binder is further testing needed. The case company could under their research and development (R&D)- department, test the five samples minimum or preferably more for various mechanical properties as thermal conductivity, tensile strength, flame retardant, and compression. Other testing types, before full-scale test in production line, could be tested at NTNU in Gjøvik or with SINTEF at Raufoss. For biodegradability is it in the interest to test the biodegrading of the wood fiber in agricultural, dirt, and industrial decomposition and witch EOL-timeline that comes from the various binder percentage mixtures. Research and offers on how to implement the binder could be discussed under this stage, to see if the alternative binder would suite the wood fiber. The supplier also informed that they could not go further down than the original binder in content but is close to 3,5% with between 3,3 - 3,6% binder content. The solution could also fit recycled wood material with a sourer solution than today's applicable one. The conclusion for this meeting shows promising results, but as of today fits more the wet production for Hunton than the dry solution which manufactures the wood fiber insulation. Further research on binder in wood fiber insulation is needed. Keeping these insights from the suppliers, where it in interest to look further at the alternative binder with experts in chemistry, polymers, processes, and the suppliers once more.

It was decided that meeting with further experts where in the interest of the case company and the author. There was conducted a meeting with experts in polymers, processes, and chemistry, which includes Prof. Sotirios Grammatikos and Angela Daniela La Rosa (Phd.) at the University of science and technology (NTNU) at Gjøvik to further discuss the alternative binder and other possible solutions.

Under the meeting where discussion about PVA as a binder discussed and meaningful insights was given. Both Sotirios and Daniela would be helpful with polymer chemistry and testing at the lab for the alternative binder. The physical and mechanical testing of polymers is a vital part of the product development and production process for the binder.

It was important to test the binder material alone before including it in the wood fiber for further testing. Various types of testing like a dynamic mechanical test (DMA) to see how the material behaves, viscosity of the polymer, Compression, PS – testing with thermal properties, TPA, how the PVA expands, thermal conductivity and a comparison between the original and alternative binder is in interest of the project but will be conducted after this study.

Both testing PVA alone and PVA crosslinked with HMMM and Glyoxal, and other composite materials is in interest for the case company. Whereas standards are making at least 5 coupons are made from Bico, wood fiber, PVA with HMMM, PVA and other suitable composite materials.

Sotirios would like to put in effort and develop a proper solution with Hunton at in ASEMLab-NTNU.

To fully understand the Polyvinyl Alcohol (PVA) properties on wood fibers was it conducted a scientific experiment with six specimens of wood fibers. This to understand and show the evenly distribution of the PVA onto the wood fiber, as were discussed in the theoretical- and empirical research. The PVA used in this experiment was 5% liquid PVA from Innovating Science made from water, PVA, and Sodium Benzoate. To test the wood fiber, where tree specimens on both production methods tested, as this is a normal number of specimens to test in standards like BS ISO 6721-11:2012 (BSI Standards Publication, 2012). The specimens were made with 50ml, 100ml, and 150ml of 5% liquid PVA onto them. However, the specimens with both 50ml and 100ml did not completely cover the wood fibers and 150ml specimens were worked further in the study. All specimens were made with 25 grams of wood fiber and 150ml of the heated 5% liquid PVA slime with water to 90 °C, it was poured upon the fiber when the liquid PVA showed approximately 50 °C. The overflow of water will vaporize in the heating process of the specimens. One specimen was heated with 60 °C over 5 hours and later left in room temperature for over 48 hours. The other specimen was heated by a heated airflow of 1800-2100W on the PVA covered wood fiber for approximately 15 minutes and left in room temperature for over 48 hours.

Specimens	**Drying**	**Curing**
Oven Heated x3 with 50ml increase for every specimen.	Oven – 60 °C for 5 hours.	Over 48 hours in room temperature.
Air dried x3 with 50ml increase for every specimen.	Air dryer 1800-2100 W – heat for approx. 15 min.	Over 48 hours in room temperature.

Table 3. Specimens to test curing and dissolvement of PVA onto wood fiber.

Immediately was it shown that the air heated wood fiber dried the PVA better and laid a form on layer upon the wood fiber, thus protecting the inner fiber better than the oven heated specimen. This, however, is already a simplified process of production system at the case company. To test degradability of the specimens in contact with water, was the specimens placed in water for 48 hours. The specimens will then be inspected to see which dissolved fastest and how much of the polymer was gone, through eyesight (clumps or loose fibers). Both clear forms that hold the wood fiber will be filled with water, to easily inspect the specimens. The 50ml and 100ml specimens was not further tested here either, as 150ml was the only one to evenly distribute around the wood fiber.

After curing for more than 48 hours in room temperature was the specimens fine and hard. The specimens were noted down which was the air heated and the oven heated specimen, the specimens were then placed into a bath with water enough to cover the whole fire-resistant container and held a temperature of 30 °C.

3

Picture 6. Specimens after heating and 48 hours curing. The Oven heated specimen showed the highest similarity to the original wood fiber insulation.

The PVA did loosen up right after contact with water and was completely dissolved in less than 4 hours in the water bath, as already mentioned.

4

Picture 6 and 7. Difference between 15 minutes of contact with water and 3 hours and 54 minutes. The water temprature did drop from 30 to 20 °C under the experiment.

Rightfully, as already thought of, did the PVA dissolve in water, even if the PVA was mixed and hardened onto the wood fiber.

5

Picture 8. Picture of the wood fiber in PVA taken out of the bath.

As seen in picture 8, is it clear that the PVA has completely dissolved in the water and the wood fiber is only floating around in the water.

5.3 Study

Studying the obtained insights and information from the testing. If the binder works applicable with the wood fiber insulation, is it in the interest to analyze given data and compare it versus the original binder. If the plan is working around testing the binder, or not. Is it proceeded to step – Act, where decisions around the binder will be set and insights shared.

To acknowledge the alternative binder thought of to be suitable in wood fiber, was the requirements list sent to the author. The given insights from the main polymer used in the binder and the original binder will now be compared vs. the requirements set in this list. Many of the requirements are set non-discussable as these are found in standards for insulation products. The requirements are found in the appendix, as already discussed. Many of the requirements could be engineered with different crosslinkers and adhesives into the PVA, as mentioned, but could not be concluded in this thesis.

As we saw in the experiment with testing PVA on wood fiber, was the specimens either too hard and not flexible, or the solution would just dissolve without any work of the specimens. The need for crosslinkers and / or adhesives to find the rightful properties are needed, as PVA alone did not show sufficient results. However, the interest to used PVA and see if the specimens would go back to its standard form in contact with water. Further research in chemistry conducting the appropriate amount of crosslinking and adhesives using xylan, glyoxal, and HMMM is needed. To look for properties and possibilities for biodegradability using the crosslinking agents and possible adhesives. Xylan would solve one of the problems with the 5% PVA making the binder thicker. Glyoxal and HMMM have other possibilities in degradability and mechanical properties to mention a few.

Under the case study was it also conducted a meeting with an alternative supplier for binders. The supplier already had biodegradable binders in production and were interested in collaboration working with alternative binders in wood fiber insulation with the case company. As they already work with binders for coffins, composite material, and napkins etc. However, obstacles in lifetime and wet production where found. The production where discussed to some degree, and solutions where found and interesting to further test. The product is biodegradable, making the insulation biodegradable. Nevertheless, properties found in the binder would fit an agricultural solution, where the product is already produced in a wet process.

5.4 Act

Act means the intervention being tested is adopted, adapted, or abandoned based on the evaluation of the data in the prior phase (Christoff and Phram, 2018).

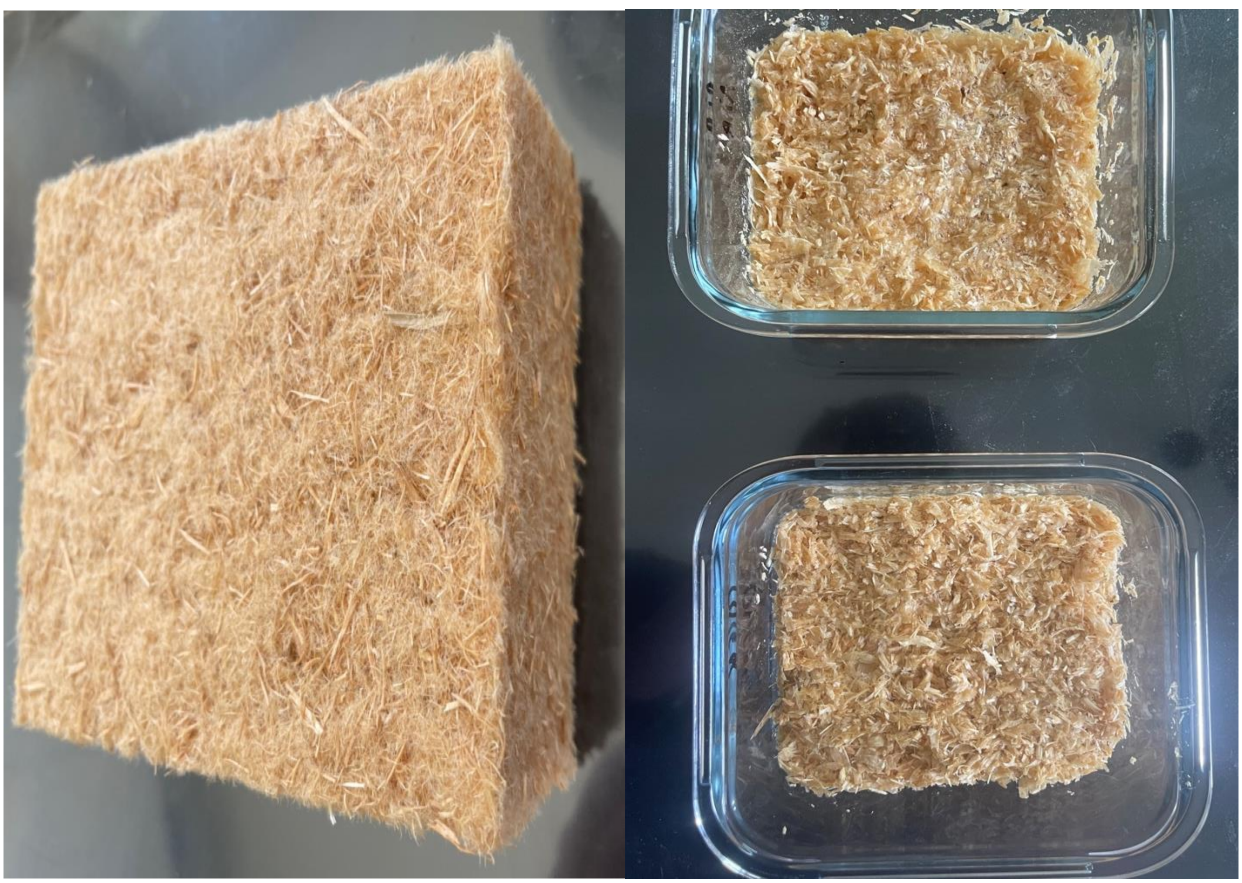
If the study and testing of the alternative binder finds to be suitable for wood fiber insulation starts the implementation of needed equipment in production. Whereas production line, as mentioned, can be expensive to replace with other solutions. However, if the alternative binder could show decreased cost in both energy and binder, could the optimization be down paid overtime. However, the new EU taxonomy will give the company better scores if the product becomes fully biodegradable, which gives better reputation and prices for loans to mentione a few. If somewhat the alternative binder should not be in interest to adopt by demands not met under testing, is It under this stage the alterative binder should be scrapped.

The author and the case company are here choosing the binder content that is suitable for the wood fiber and is holding the requirements. The other samples with various binder content will be scrapped.

In composite manufacturing, which also acts for wood fiber insulation is it needed to achieve a satisfactory distribution of the degree of cure (for thermoset resins) or degree of crystallization (for thermoplastic resins), within a reasonable processing time, avoiding resin degradation or excessive residual stresses (Aleksendrić and Carlone, 2015). Under testing of the PVA applied onto farm wood fiber, was it seen under hardening that PVA used long time in significant amounts to dry and bind the wood fiber. The wood fiber composite was hardened in an oven with 60 °C. over 6 hours and laid in room temperature the following day, without showing significant results in dryness. The sample stayed moist over a significant time. The wood fiber is normally flash dried in high temperatures; however, these environments are not easily maintained without the rightful equipment. Another sample held the same about of dry wood fiber and PVA content but were tested with a dryer to see if sufficient heated air would dry the PVA faster.

As seen in **Table 4**, does the alternative binder show promising results as a replacement. However, the need for engineered properties is further needed. The HMMM shows some of these properties. Both the experiment and earlier results of the PVA shows high mechanical properties, but high usage of binder content and some mechanical properties needs further adjustment. These adjustments can be done with HMMM crosslinking or Glyoxal as already discussed. This research has opened for further adjustments of PVA as main polymer in wood fiber insulation and discussed for further usage. The binder would also receive added thickness, strength, and self-healing properties if Xylan is added as a crosslinking agent or adhesive into the PVA.

Comparing the end results of original- and alternative binder:



Picture 9 and 10. Comparing picture of original wood fiber insulation and PVA-based wood fiber.

The comparing **picture 9 and 10,** shows the difference between the produced wood fiber insulation at the case company and the experimented. The original binder can be seen as the standard the alternative binder should work to hold; however, some changes could be done to fulfill the alternative binder. Changes in binder content would decrease the ability for wood fiber insulation to withhold the heat inside houses and become less applicable. As seen in the picture, is there only used pure wood fiber in the PVA based binder, while the original fiber is worked until thin fibers. There are no pictures of the binder given from the supplier, as the NDA prohibits this. However, there is still needed to discuss the findings here. As the product already is commercially available, have the producer already a good practice and knowledge to maintain high quality of the product. However, as PVA have problems with would only the supplier binder be produced in a wet production and lifetime was generally too low, as wood fiber insulation is thought of to have a lifetime around 60 years. However, the binder would be suitable if the binder could increase lifespan and preferably be produced in dry process. Moisture in production up to 15 percent could work in production used today. Further of the PDSA methodology states that the PVA-based binder is adapted for further changes and insights when implementing the possible crosslinkers and adhesives.

6. Representing the findings

This chapter will present a comparison between the original Bico PE/PP binder, the alternative binder, and the binder presented from a supplier. Strengths and weaknesses are presented to justify further work for an alternative binder with a background from this study. The comparison of the binders is presented in **table 4**.

The important elements of binders were discussed in both the theoretical research and further discussed with experts in the field in the empirical research. The important elements are both shown in the literature review and under shown in a document form the case company under appendix A.

Table 4. Comparing analyze of original binder, alternative binder, and binder from supplier.

Requirements	**Original binder**	**Alternative binder**	**Binder from supplier**
Mechanical strength	X	X	X
Degradability		X (under certain conditions)	X
Lifetime	X* Over 60 years (lifetime of product)	X (affected by humidity etc. Further research needed)	6+ days standard.
Biner content	X		X* Bit higher than today´s solution
Price	X (1086 USD mt) (Exportv, 2021).	X (Applicable) 5200-5500 USD per mt (Chemanalyst, 2022).	X
Production line	X	X* (wet production or further reduction)	

End-Of-Life	X* (Engineered recycling properties)	X	X* Biodegradable after some years
Contribute to dust	X	Wet solution	Wet Production
Renewable resources			X
UV-Stability	X	Further research needed	
Availability of material	X	X	X
No shrinking in contact with wrapping	X	X	X
Melting temperature	X	X* Wet solution to be applied or further research needed	X* between 60-150. 90 Full efficiencies
Cutting with known tools ("pizza cutter" for end user)	X	X	X
TVOCC mm emissions	X	X* Non-toxic material	X
Can withstand moisture, mushrooms, and fertilizer	X	X* Not pure PVA, needs further engineering	Degradability activating conditions
Form stability under various conditions	X	Further research needed	X* Used in coffins, paper, etc.
Does not demand changes in wood fiber	X	X	X
Availability of material	X	X	X
Available EPD	X	X	X
Multiple suppliers	X	X	X
Mechanical properties	X	X* Needs further engineering with	X

		adhesives or crosslinkers	
Increase in Flame ability			
Storage of materials	X	X* up to 5 years in room temperatures	X
Thermal Conductivity	X	X* Changes not found	

Note: X means somewhat applicable or some changes is needed to fulfill the requirement. For example, engineering of adhesives or crosslinkers to added binder. Or, further research is needed.*

The first part of the evaluation of the binder, covers the fundamental settings to become applicable as a binder in wood fiber insulation. These properties are needed to functionally work as a binding material in wood fiber insulation, without decreasing other properties. Here comes the usage of binder material or preferable called binder content per insulation board. This is to withhold thermal conductivity and the standard given for insulation boards, given in the literature review. The alternative binder is not found to lower thermal conductivity in wood fiber. Binder content should not exceed 5% in worst case, however today´s solution uses around 3,5% binder content. If the alternative binder and the wood fiber decreases the standard of 0.07 W/m-K, would the wood fiber insulation not be suited to be called a thermal insulator according to ASTM C208-12 standard is the maximum range for thermal conductivity between 0.055-0.072 W/m-K. The binder solution from the supplier had an increase in around 0.2-0.5% over the original binder, which is suitable and can be used. The alternative binder with the usage of pure PVA had an increase in around 10% found in literature and used 150ml 5% PVA on 25 grams of wood fiber, this however could be decreased to some degree, but 100ml were found to be too little. Nevertheless, the pure PVA solution had a too high usage of binder content. The binder should additionally not increase the need for higher temperatures when being produced. Both the PVA and the supplier found binder do not need an increase in temperatures when being produced, as both works around 100-150 °C. Additionally, the mechanical properties as tensile strength, thermal conductivity, elasticity, and other needed properties. Both alternative binders found sufficient in mechanical properties, however, the elasticity of pure PVA is poor and will need further adjustment by usage of crosslinking agents and adhesives. As the study is about opening for biodegradability or recycling, was the next thing to look for applicable materials that could biodegradable, both the alternative and supplier found binders could biodegrade. The experiment of PVA on wood fiber confirmed this, however, studies find PVA to produce non-harmful micro plastic in multiple studies. This is not an applicable solution, but research only found PVA to check of the other aspects of the requirements with some modifications. Additionally, the research shows still a biodegradable property, which is not found in any other materials found in the study. PLA however did not contribute to microplastic but is only industrial degradable. PVA could also last for many years, where the supplier binder only would last for over 6 days. Research is also ongoing in the field of biodegradability or recycling at another supplier. To implement in today´s production, would the binder need to be produced in a dry process, as the original binder and wood fiber is produced in a dry process, where moisture is flash dried early in the process. Both the PVA based binder and the binder from the supplier needs a wet process to be fully functional. The supplier said their binder could be produced and functional down to 15% moisture in the fiber. This, however, needs further research to see if it would work. PVA needs, as already thought of, crosslinking and adhesives to lower the demand for moisture in production. Additionally, as PVA is a non-harmful material, will hold the binder down to zero in TVOCC emissions. However, possible crosslinker could increase this. TVOCC emissions or harmful air mixture (VOC/TVOC) are inside rooms where people are continually living in, like homes, schools, or offices. Trotec (w.y) says VOC are substances that vapors easily in low temperatures and hides in gas form – and harms the air. They are called volatile organic compounds and is measured as total value TVOC (Total volatile organic compounds) with recommendations from the environmental ministry in each country. There are many VOC-sources inside homes etc., these are floors, paints, glue, carpets, and furniture. For example, could places in the US with wall carpets have high TVOCC values. Formaldehyde (HCHO) is a chemical backbone of many industrial products as spray coat, paint, glue, and binders in general. Many formaldehydes filled materials as wood, floors, or textiles can contaminate the air for a long time because of evaporation. Formaldehyde is classified as cancer developing emission. Even emissions higher than 0,1 mg per m3 is forbidden by law, even for small timeframes. People could be sick from VOC-loaded indoor air, this is called “sick-building-syndrome”.

Formaldehyde and TVOC emissions with high values can cause various harm as:

Formaldehyde	**TVOC**
0,05-0,125 ppm: cannot smell	< 0,2 mg/m3 no irritation or lowered wellbeing.
0,01 – 1,6 ppm: irritating nose and throat (slime) and eyes	0,2 – 3,0 mg/m3: irritation or lowered wellbeing possible in changing environments with other parameters.
2 – 3 ppm: sticking eyes, nose, and throat.	3,0 – 25 mg/m3: exposure will cause headache and other possible changes in wellbeing if exposed over time.
4 – 5 ppm: cannot stand in 30 min, reduced wellbeing, tears flowing.	>25 mg/m3 Headache. Other neurological harm beside headache is possible.
10 – 20 ppm: after a few minutes comes tears that could last for over 1 hour, short of breath, coughing, burning in throat, nose, and eyes.	
30 ppm: pneumonia and threat of life.	

Table 5. Threats found form Formaldehyde and TVOC found from Trotec (w.y).

The case company demanded zero increase in flame ability, as the wood fiber insulation needs to hold minimum of E-class of fire retardant. PVA burns, however it burns slower than regular paper and wood, and wax-based materials, but burns slower and contributes to more soot. The PVA would melt, instead of burning. The price is important to hold competitiveness in the market of insulation, the supplier given binder only had a small increase in price, but PVA approximately cost twice as the original binder, with the given increase in binder content will

PVA not withhold applicableness for the binder. However, further research could decrease the price with adhesives or crosslinker. Nevertheless, holding full biodegradable demands changes somewhat in the product. Storge of materials is not affected in this comparison, since every material has large storage time in room temperatures. Under the comparison was it found that the wood fiber insulation would per now, be most suitable using the original binder. However, the binder from the supplier is in interest if properties like lifetime can be extended. The PVA based binder have many beneficial aspects and properties but needs further adjustments and research to lower the need for binder content and other mechanical properties. This, however, is discussed further in the study to not be impossible. As these drawbacks could be easily removed if further research is done crosslinking with Glyoxal and HMMM with adhesives as Xylan. Other possible crosslinkers and adhesives are also in interest if further research finds it suitable for the binder. PVA seems to utilize most of the requirements for the biodegradable binder and is recommended to work further on. However, PVA is not a renewable material, but Xylan is a renewable biopolymer and if Xylan could decrease the need of pure PVA, would much of the binder be renewable. Pure biopolymers were found insufficient to replace the synthetic polymer in a matter of mechanical properties and binder content. Both Glyoxal and HMMM could degrade in certain conditions, HMMM could degrade in photochemical oxidation. Hence not destroying the properties of biodegradation in PVA-based binders.

Under this thesis have we tried and discussed looking at alternative binders for wood fiber insulation and possible obstacles implementing this. The author has conducted a previous project work using a systematic literature review and meetings with suppliers (Steinaa, 2021) with the case company to build an understanding of the problems and the product in general. Under the thesis have further literature been reviewed and meetings with case company and suppliers have been conducted.

To fully answer the research questions (RQ's) have various meetings, experiments, and analyzation of data been done.

RQ1: What are the strength and weaknesses of alternative binder over today's binder? What material is justified to replace the original binder? What is needed to implement the binder in production?

The strength of the alternative binder is to open for biodegrading of the renewable wood fiber that solves a large amount of waste from insulation used and opens for using it as compost after EOL. However, many obstacles are found in alternative binders, at least found in this research. Some of the solutions found in this research had more flaws to become a reliable binder, than benefits. Some of these where high binder content, not degradable or biodegradable, low performing mechanical properties, availability, and lastly price. As mentioned, further research should acknowledge PVA as a main polymer, but adhesives and crosslinking agents as Xylan, glyoxal, and HMMM could suit further research in the field, as they're already seen as suitable fits, However, engineering of these properties is not done. However, does these materials increase relevant properties, with withholding the biodegradability of materials, as these crosslinkers is found in research to degrade under certain conditions.

Drawbacks are found multiple places in the alternative binder and the possible implementation of the alternative binder. The first large drawback is the change in production equipment for the use of PVA based binder. However, this solution could be modified with the rightful adhesives and crosslinking agents as mentioned. Furthermore, changing the production line to open for higher grades of sustainability would also be in interest for helpful companies like Innvoasjon Norge and other benefits for loans etc. Certifications for ISO standards and green products will also come from making the product greener. Also, possibilities to open for new services and products is applicable, as the product then could serve multiple product groups as insulation and EOL could become compost or recycling the product using it in other wood-based products, like furniture. Nevertheless, the base binder found in this research uses to much binder content, was too hard, and did not hold the needed properties.

RQ2: Is it justified to work for a renewable binder to work for high degrees of bio compostable insulation?

Under the thesis and project where multiple aspects and EOL scenarios discussed, whether recycling or degradability was desirable. If we think that wood fiber insulation will be used for 60 years, which is the standard in today's solution. Will the most desirable be to use the wood fiber insulation as a bio compostable product, and then to be used in possible agricultural products like compost for other products. Changing the PE/PP binder to a PVA based binder with adhesives and crosslinkers as xylan, glyoxal, and HMMM could open for these properties. PVA based binder on wood fiber is tested in this thesis and confirmed to dissolve in contact with water. Xylan is a natural biopolymer often used as thickening agent with improving mechanical properties. Wood fiber insulation is sold with sustainable benefits over other competitors like glass- and rock wool, as wood fiber insulation have net positive emissions, which means the total emissions is less than the contribution from trees. The most reliable solution to wood fiber insulations binder is then to hold the sustainable benefits to even higher, working for a bio compostable solution for both the wood fiber and the binder could biodegrade under certain conditions at home or as garden waste at recycling stations. Nevertheless, does PVA contribute to non-harmful micro plastic, however PVA is the most suitable commercial polymer used today with minimal drawbacks. Under the undergoing research was there conducted interest in a supplier's solution for binding agents in wood-based products with biodegradability as a standard. The product is based of natural products, and will not contribute to micro plastic, pollution, nor any other harmful waste or toxic emissions. These products, however, was made to degrade over a certain amount of time. The degradability time, in contact with moisture, bacteria, and heat, was just above 6 days as a standard. Where this is not applicable for the lifetime of the product. Nevertheless, opening for biodegradable wood fiber insulation could open for EOL products in agricultural manners as compost for fields or likewise.

7. Conclusions

The theoretical research gave insights of changes in product or production can be a large investment for a company, necessity of justification of need to adopt products or services is needed. To answer the research questions was the research objectives conducted in a scientific manner. For the case company to further work on the solution with PVA, will the case company need to make changes in the production of wood fiber insulation. As the suppliers talked about, does PVA need a wet production process to evenly distribute around the wood fiber before hardening. Another obstacle found under this project, was the use of pure PVA to harden the wood fiber and thus becoming too stiff to not withhold further work when placing the product inside houses. Therefor is the use of crosslinking agents and adhesives like Xylan, Glyoxal, and HMMM thought of to give higher performing binder, that would decrease the usage of binder, make the wood fiber more workable for the end-user (not as hard and brittle as the pure 5% PVA did), hold the biodegradable properties whether in contact with water or other solutions, making the binder thicker, increase in mechanical properties, withhold properties to be easily formed, elastic, and competingly priced in today´s market. The supplier found solution where of large interest due to full degradability without microplastic nor other harmful waste. Nevertheless, the small lifetime in contact with humidity, bacteria, or heat would decrease the properties of wood fiber insulation and biodegrade the material over time. The need for biodegradability and possibilities for recycling was the top criteria in this case study, where PVA based binder was set to be the most suitable base binder, checking of most of the given criteria. However, the PVA will still need crosslinkers as Xylan, Glyoxal, and HMMM. PLA was in interest, however, was not worked further on due to lack of biodegradability. Nevertheless, where performing better than PVA in some properties.

The main findings were presented and compared in **Table 4** and further discussed in the findings of this study. The table showed that the original binder still checks of most of the boxes, where the alternative binders lack further work to hold further applicableness for the case company. However, both solutions seemed interesting for the case company and further research could give the PVA binder the properties needed to become fully suitable in today´s product and production.

Both the alternative binder and the supplier presented binder where both discussed and experimented in the empirical part of the case study. The case study contributed to find relevant and meaningful insights of both the binders and give a practical insight to better evaluate the binder information received under the empirical research. Nevertheless, the reader should acknowledge that data collection, understanding, and analysis is based on human understanding and could represent the findings poorly, if data and documents were missing or misread.

Further work should be done on the alternative binder to see if the PVA-based binder, could with adhesives and crosslinkers, be in further interest for case companies and if the binder could be used on other wood-based products like plywood. This to see if mechanical properties could be engineered in the manner to which it would be beneficial for the case company, making the wood fiber insulation biodegradable in EOL. However, there was not found a solution to make the binder both purely renewable and biodegradable with the thoughts of requirements given from the case company. Adding of these crosslinkers should not interfere with biodegradability, as research states the degradability of the respected materials.

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Appendix A: Requirements for alternative binder from Case company

		Agri	Isolasjon
Funksjonalitet sluttprodukt	Øker ikke varmeledningsevnen		X
	Ingen betydelige bidrag brann / antennelighet		X
	Strekkfasthet > 1 kPa		X
	Komprimerbarhet --> som dagens		X
	Ingen bidrag til emisjoner (TVOC mm)		X
	Kan skjæres med kjente verktøy	X	X
	Øker ikke vanndampgjennomgang		X
	Reduserer ikke luftstrømningsmotstand		X
	Formstabilitet over tid (krymp i fakket)		X
	Ingen bidrag til mugg- soppvekst	(X)	X
	Tåler en viss krymping / svelling, variasjon i rel. fuktigh. (ikke redusert styrke)		X
	Ingen vekselvirkninger med plastemballasje	X	X
	UV- stabilitet (lagring, sluttbruken)	X	X
	Densitetsprofil i platen mulig (tettere i bunnen, luftigere på toppen)	X	
	Home- compostable	X	(X)
	Etterligne kokosmatter, 1-2cm	X	
	Håndterbarhet hos gartneren (skal ikke knekke)	X	
	Kan brukes i tynne matter (folie), type Silencio Soft	X	
	Tåle mugg, sopp	X	
	Tåle gjødsling	X	
	Tåle fuktighet (vanning av planter)	X	
	Bidrar ikke til støving (finstoff)	(X)	X
Rammebetingelser prosess (HMS, produksjonsutstyr, leveranseform, håndtering, mm)	Tørr prosess, med dagens produksjonsutstyr (minst mulig endringer)	X	X
	Ikke høyere smeltetemperatur, gjerne lavere	X	X
	Krever ingen endringer på dagens trefiber	X	X
	Ikke nedsatt konveksjon (smelteovn, kjølesone)	X	X
	Kan skjæres med pizza-kniv-sagblader	X	X
	Lagring i telt (uteområder)	X	X
	Bindemiddelt må kunne lagres over en viss tid	X	X
	Ingen skadelige emisjoner i produksjonsprosessen	X	X
	Bidrar ikke til støving (filtere)	X	X
	Skal kunne binde tørr trefiber (dyrkerne skal ha kontroll på vanning selv)	X	X
Miljø	Sirkularitet, gjenbruk hos dyrkeren / resirkulering på Skjerven eller Gjøvik	X	X
	Basert på fornybare ressurser	X	X
	Akseptabel transportavstand	X	X
	Tilgjengelig dokumentasjon på miljøegenskaper /-profil	X	X
	Ingen miljøgifter (tungmetaller, farlige komponenter)	X	X
Økonomi	Konkerransedyktig ift dagens (med mindre funksjonlitet eller miljøprofil ↑)	X	X
	Ikke større %-andel tilsetning enn dagens	X	X
	Tryg / sikret tilgjengelighet (flere produksjonssteder / leverandører)	X	X

Appendix B: Meeting with supplier X

Meeting Supplier

Alternative binders wood fibre insulation / new products

Questions for supplier

- Are there any solutions for the binder/adhesive that is currently being worked on?
- Is it some solutions that have been scraped? And why?
- What are your requirements for sustainable products? Lifetime, strength etc.
- Highest working temperature for given binder?
- What is the approximately cost?
- What binder/adhesive is used today?
- Are Polyvinyl acetate (PVA), Xylan, Citric Acid-modified starch, Lingnin tried?

Questions from supplier.

- What is our ambition, biobased and / or biodegradable?
- Should calculate on EPD and what we would achieve by changing the binder (partly)

Environmental Product Declaration is an independently declaration of a product’s environmental impacts. Can be calculated with life cycle assessment (LCA). Marius has some knowledge about LCA from SimaPRO (software for LCA).

Today’s PE/PP engineered binder with regard to bonding to wood fibre have significant mechanical properties and low cost.

ICC solution

Mass balance concept, ICC certified, biobased feedstock possible, 2 pipelines into production⍰ mass balance based, can come with a negative carbon footprint⍰ one would have the certificate, and a label; lower carbon footprint⍰ comes with a price, depends on what we want to achieve and the amount one we buy. Large amounts, lower overall cost. Using this solution is cheaper than PLA and PBS as binders. Biko would be the same as today’s solution.

Maximum -2kg CO_2 per kg of fibre, depends on feedstock (applies to 100% ICC certified). Fiber can be made with recycled core, as polyethylene can be recycled, but polypropylene cannot be recycled.

PLA is marketed as biodegradable, but they are only industrial degradable (needs 60 degrees and certain other conditions, high moisture, and certain microbes, (these conditions are not found naturally on earth), in case of consumer relation they could invest in equipment doing the job. Composts as biomass, into water and soil, in around 60 days and in 60 degrees Celsius. Process This process starts with chemical hydrolysis process, followed by microbial digestion. PLA is chemically unstable but has possibilities to tailor properties.

Supplier talked to American customers, where it does not make sense to ship PLA mixed wood fibre over long distances for industrial decomposition. As this will increase greenhouse gasses and cost for end-of-life for product. There are only 4-6 industrial demolition facilities in USA. Without these stations nearby are the product greenwashed.

PL, PBS

Loose performance / function, realistically loose of 25%. Compared to fossil-based binders.

Product is already in the company. Another supplier can deliver the fibres

Higher value to product saying that everything is biobased. (Increasing cost for product?)

Lower dTex

Fibre with lower dTex, could be an option as well, for example 1,3 dTex, can supply us with that one

Spin finish is different, 1,3 opens much better than the one has today, can be an issue in the plant, “clouds of biko”). Is no problem with new production system. Applying the 1.3, instead of the one will decrease usage of binder to between around 1 % less from making the fibre thinner. Financial benefit, dust is being reduced. Products is applied with cellulose, as absorbent packaging in meet packages are. Both 1,3 and the one used today can be ICC certified with carbon net negative impact from gate. Approximately -2 KG CO2E.

Wood fibre insulation in general

Particle boards are worse than PL/PE in wood fibre insulation. Particle boards uses around 25% synthetic materials.

Natural or renewable binder cannot affect the lifetime of the wood fibre insulation. Therefore, are binders which decompose after some years mot applicable.

Gate net negative product, even with high energy usage and fossil-based binders.

Agricultural product

Degrades PBS but not the PLA. no good solution, ends as microplastics. PLA needs industrial decomposition, witch as mentioned, is not applicable before large investments and more industrial decomposition facilities are easily available.

Working on PP which is biodegradable, biotransformation transforms to a wax, and oxygen; not possible yet to define a certain time when the degradability is supposed to start. Undergoing research on this field, whereas solution could be in place between 1-2 years.

Polyetylen PE, needs bacteria and light, would be degraded after a while (compares to a sweatshirt)

Working on modifications of the standard PP/PE today.

Haven't work with lignin based and little with PVA, often problem with melting point (150-200 degrees).

Polyester is a renewable binder that immediately starts to biodegrade, uses sun and bacteria to biodegrade. Almost going away, around 85% of the binder biodegrades. Polyester binder fibres have degraded after three years.

More applicable with biodegradability than recycling in agriculture.

Renewable binder / adhesive

Enough material for industrial size use, to make bio binder / adhesive applicable.

PVA is applicable as a binder but is not worked on that much from supplier side. Same goes Lignin based binder. Crosslinking PVA with hexakis(methoxymethyl)melamine (HMMM) or glyoxal is possible.

PLA and PBA removes around 25% of carbon footprint but needs to add 5x more additives for same mechanical properties, higher cost than already used binder.

Polyester and polypropylene mixed binder, whereas development on biodegradable polypropylene being worked on. Goes from through plastic to wax. Wax degrades.

Appendix C: Meeting with Supplier Y (Norwegian)

Møte produsent Y

Informasjon om produsent

Produserer bindemiddel til kister, kompositt materiale, servietter etc.

Biochemetic - Hvordan produkter naturlig bygges opp, var starten på Organisasjonen.

Løsningene trenger våt prosess, ikke tørr som trengt for produksjon uten endringer i produksjonslinjen til Hunton nå.

Cap på 10k tonn hvert år. Utvikler en ny linje på veg som kan utvikle total produksjon opptil 20k tonn hvert år. Reststrøm from papp, mat etc. Fruktskall, eggeskall er null problem fra leverandører. Dermed er tilgjengelighet for binder null problem.

Wet porøse prosessen

Isolasjon plater i tørrprosess, densitet på 50kg per kubikk meter. Fleksible matter.

Parter om å løse tørrprosessen

Våtprossess trenger våtprosess for å sette i gang oppstart av

Gjelder kister også, med en impregnering i pappmasse

Hvete type i våt prosess

Krav for produksjon

Tørrprosess hvor midlet smeltes inn i produksjon hos Hunton

Termomekanisk raffinering ca. 170 grader i tørke

Tilsette brann hemmer i el-kjele

Bico = bikomponment plastfiber

130 grader for å smelte bico-fiber i produksjonslinja til Hunton. Jo lavere temperatur det trengs for produksjon, jo bedre for Hunton grunnet lavere energibruk. Ideelt burde alternativ binder ha mindre energikrav.

Vakuumet i slutteprosess setter fiber i form. Vakuumet Juster også fiber retning, densitet etc. Alternativ binder må kunne tåle vakuum.

Jevn fordeling av fiber igjennom hele profilen er viktig under produksjon av tre fiber isolasjon

Voks og flamme hemmer i våt løsning.

5 tonn tørrfiber i timen i kapasitet hos Hunton.

40% tørrstoff flammedemper og 40-50% voks

Bindemiddel som ligger 40% og 30% på flammedemper

Høy solidcontent

Kombo flammedemper bindemiddel med 35-40% bindemiddel

Går å blande ut binder

Dagens flammedemper som granulat, organo click har flytende, vanskelig transport

Tørrforming er mulighet, våtforming er vanskelig

Testing

Tilsette veske før eller etter raffinering

Trenger en viss restfukt når vi former plate hos Hunton.

Maks ned til 13% restfukt i ovnen hos Hunton.

Låter brukbart i produksjon, fiber vil forme seg?

Mulig testbasert produksjon?

Krav om klasse E nest laveste klassen for flamme resistens i til trefiber isolasjon. Produsent klarer dette. Løse fiber er det ønskelig med B-C klasse. Forhøye flammeklassen? Vannet skal tørkes bort, grunnet vannløsning vil dette påvirke flammedemping?

Minste tempraturen for å starte prosess, effekt med 90 grader. Maksimere prosess 150-170 grader hos Organo Click. Styrke ved 90 grader.

Nedbryting av bindemiddel starter ved utsettelse av varme, fukt og mikrober, rundt 0 grader starter det. Prosessen går raskere ved høyere temperaturer. Jord og mark vil det begynne med engang. 8 uker. Ikke nedbrytbar om det er mange år. Biobasert.

Planer for agrikultur og ønskelig rundt full bio-kompostabilitet på dette produktet.

Standard for å brytes ned over 6+ dager. Homedecompostability er en standard hos produsenten. Standarden med nedbryting av produkter etter 60 år kan bli komplisert, da utviklede løsninger starter etter ca. 1 uke, i henhold til standard.

Kompostbertbart og nedbrytbart er to forskjellige ting, som ikke skal sammenlignes.

Starter ikke prosess grunnet manglende eksponering, bindemiddel er like nedbrytbart som trefiber, påstår Organo Click.

Ingen utstyr for simulering og tester, eksterne institutter for tester. Organo click kan utføre noe av dette, grunnet deres utstyr for testing.

Krav for bindemiddel i isolasjon

Mange krav og punkter om densitet, brann, strekktest (viss motstand), emisjoner organiske komponenter BC – Vil emittere, dimisjons stabilitet (klemme plater mellom stendere), ikke for tykk, lett skjærbar, ikke sopp-/muggvekst, så høy vanndamp gjennomgang, trykkmotstand og varmelednings egenskaper kan ikke bli negativt påvirket, ikke høyere antennelighet eller energiutvikling, bindemidlet må tåle mugg/sopp og ikke bidra til mer.

Største vanskelighet, hvordan man kan gjennomføre produksjon. Ikke høy investering for noen. Bra styrke etc., men mye vann.

Kostnadsmessig er prisbilde bra om prosessen er lik.

Bindemiddelet som er tenkt over 1000 tonn hvert år for Hunton, 1-10 euro per kilo.

40% tørrhalt(?)

Dagens løsning benyttes 3-3,5%, plate er 2% bindemiddel. Mulig mindre, men produsert med kompresjon som gir bedre styrke.

Ikke stort mer, f.eks. 3,3-3,6%, kan gi samme effekt. Må testes.

Har truffet høye densitet verdier, mye mer enn det som trengs. Ikke fosfor eller aluminium som andre alternative bindemiddel bruker. Er 35% vann i bindemiddelet.

Ikke en klar løsning, men kan forskes på, legges under F&U.

Teste hypotese gjennom forskjellige støtteordninger som Innovasjon Norge.

Krav om flamme resistens, klasse E nest laveste klassen. Organo click klarer dette. Løse fiber er det ønskelig med B-C klasse. Forhøye flammeklassen? Vannet skal tørkes bort, mister flammedemping?

Bruke resirkulerte tre fibre kan fungere fint med Organo Click. Bindemiddelet kan komme med en surere løsning for dette.

Konklusjon av møte

Løsningen ser mest passende ut for våtlinjen til Hunton per nå, men videre forskning på området vil bli diskutert mellom Hunton og forfatter med produsent.

Appendix D: Risk assessment of testing

RISK ASSESSMENT (Marius Steinaa)

Unit/Institute:	NTNU in Gjøvik. Faculty of Engineering - Depertment of manufacturing and civil engineering	**Date:**	12.07.22
Responsible line manager (name):	Kenneth Kalvåg	**Revised:**	
Responsible for activities being risk assessed (name):	Kenneth Kalvåg		
Participants in the risk assement (names):			
Marius Steinaa			

Description of the activity, process, area, etc.:

The risk assessment applies student testing the alternative binder using Polyvinyl Alcohol (PVA) as a binder for wood fiber insulation(WFI). The process includes DMA and tensile testing of the specimens and preperations of these by heating and forming between plates and cutting.

Activity / process	Unwanted incident	Existing risk reducing measures	Probability (P)	Consequence (C) Evaluate the categories individualley. *Health should always be evaluated.*				Risk value (P x C)	Risk reducing measures - suggestions Measures reducing the probability of the unwanted incident happening should be prioritized.	Residual risk after measures being implemented
			(1-5)	Health (1-5)	Material values (1-5)	Environment (1-5)	Reputation (1-5)			
Mixing HMMM and PVA	*Geting mixture in eyes, Toxins, and spill on c*	*Saftey googles, mask, and experiment wear cloths*	*2*	*1*	*2*	*2*	*1*	*12*	*All students should go through HSE training (the use of hand tools and mandatory protective equipment). This should be documented.*	3 (P = 1)
Combining wood fiber with altnerative binder	Chemical reaction (fire, toxins, etc).	Fire extingser, sink, gas mask	2	2	2	2	1	14	*All students should go through HSE training (the use of hand tools and mandatory protective equipment). This should be documented.*	7
Cutting WFI with altnerative binder	Skin reaction to HMMM mixed PVA and cu	Safty gloves, HSE-course, mask	3	2	2	1	2	21	*All students should go through HSE training (the use of hand tools and mandatory protective equipment). This should be documented.*	14
DMA-testing for Material behaviour	Damage of DMA-tester	Training, supervision and HSE-training	2	1	3	2	3	18	*All students should go through HSE training (the use of hand tools and mandatory protective equipment). This should be documented.*	2
Heating the pulverized PVA	burning skin, spilling of hot polymer, and/c	Supervision, training, and HSE-course	3	2	1	1	3	21	*All students should go through HSE training (the use of hand tools and mandatory protective equipment). This should be documented.*	14
Cutting formed PVA	Cutts, destroyed cupons, damaging the sav	Glasses, HSE course, training, superviss	3	1	1	1	3	18	*All students should go through HSE training (the use of hand tools and mandatory protective equipment). This should be documented.*	12
Preperation of PVA	Buring skin, solution on eyes/cloths/skin	Lab coat, saefty glasses, thermal gloves	3	1	1	1	1	12	*All students should go through HSE training (the use of hand tools and mandatory protective equipment). This should be documented.*	8
Laying the PVA on the wood fiber bed	burning skin, spilling of hot polymer, and/or toxins from polymers		1	1	1	1	1	1	*All students should go through HSE training (the use of hand tools and mandatory protective equipment). This should be documented.*	0
Trying dessolving the wood fiber in PVA in wa	Water spill	Dry place and walking	1	1	1	1	1	1	*All students should go through HSE training (the use of hand tools and mandatory protective equipment). This should be documented.*	0

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