Graduation Plan

Master of Science Architecture, Urbanism & Building Sciences

Graduation Plan: All tracks

Submit your Graduation Plan to the Board of Examiners (Examencommissie-BK@tudelft.nl), Mentors and Delegate of the Board of Examiners one week before P2 at the latest.

The graduation plan consists of at least the following data/segments:

Personal information	
Name	Alexsander Alberts Coelho
Student number	5387779

Studio		
Name / Theme	Building Technology Graduation Studio – Computational Design	
Main mentor	Dr. Michela Turrin	Design Informatics
Second mentor	Prof. Dr. -Ing. Ulrich Knaack	Façade & Product Design
Argumentation of choice of the studio	Architecture is a fast evolving field and as such, the panorama where we are currently inserted is far different from the one where I first graduated from my bachelor course years ago. The design process has changed dramatically and with it, the fabrication methods and possibilities. The use of computational design is far beyond simply drawing and modelling for representation and visualization. Simulations made with Rhino, Grasshopper and their plugins (combined with lines of code from Python) are making the design process smarter and more comprehensive. And combining with additive manufacturing, a new way of constructing is developing, leaving room for high levels of customization and optimization and starting a truly high-technology era in the building industry. This breach of paradigms in the design and fabrication processes, combined with the desire for researching in innovative and sustainable materials to be applied on the building envelope, brought me to choose the Design Informatics and Façade Products chairs for my graduation studio.	

Graduation project	
Title of the graduation project	Cellulose & Lignin in Additive Manufacturing: Potential and challenges in the fabrication of structural nodes for free-form building envelope structures.
Goal	
Location:	Not Defined

The posed problem,	There is no commercial 3D printing process that uses only wood (or wood components – cellulose, lignin and hemicellulose) as feedstock. Surely there are plenty of examples of wood composites being advertised, specially in PLA matrix filaments, but frequently not reaching a 20-25 wt% proportion of natural components such as cellulose (Gauss et al., 2021). Other examples focus on the use of wood flour/powder in percentages that could reach almost 90 wt%, but combined with toxic synthetic adhesives based on formaldehydes (Kariz et al., 2016; Rosenthal et al., 2018). There are researches seeking on natural binders as replacements (Petit-Conil et al., 2011) but still, there is no option exploiting the filling properties of lignin and the reinforcement potential of cellulosic fibres. The construction industry is moving towards a sustainable future and meanwhile additive manufacturing is a safe bet to ensure an optimal fabrication process, natural materials with no petroleum-based or biodegradable polymers are lacking in the market. On the other side of the spectrum, cellulose is the most abundant natural polymer – and lignin is the second (Ebers et al., 2021). Every year, tons of wood, paper and agricultural products go to waste which could be re-processed to have cellulosic fibres extracted and upcycled into the building industry. On the same line of thought, tons of lignin are sub-utilized and burned as industrial residue from the paper industry to generate energy instead of being separated and transformed into raw material. From previous studies it is possible to say that cellulose and lignin have a potential use in the building industry as 3D printing feedstock, but further research is necessary to improve the mix and the results (Liebrand, 2018). In the design and construction of free-form structures entirely of renewable materials, customised connection nodes made of timber would demand a lengthy preparation and production through processes such as CNC and LOM (Laminated Object Manufacturing) (Gibson et al., 2021). Resulting in vast amounts of wasted material due to the subtraction fabrication technique, these would be an obstacle to a full design optimization and a sustainable construction. More adequate fabrication processes already exist, based on material extrusion (Gardner et al., 2019), which allow better control on material usage and direct reproduction from a digital model. Potentially viable materials have already been researched, such as the cellulose and lignin mixture, with acetone as binding agent, presented in *“3D printed fibre reinforced lignin”* (Liebrand,

	2018), which offers a viable opportunity for architectural applications. But there are a few gaps between material and use – mechanical properties, appearance, composition not full natural and harmless (acetone is not ideal), potential to produce façade structural elements – and material and fabrication – hot or cold extrusion and the influence of additives and binders – which require further research. These gaps are the focus of this research project.
research questions and	The main research question mentions the goals of looking into the material development, fabrication process and design intention: What are the **potential** and **challenges** of **cellulose** and **lignin** as feedstock for **additive manufacturing** processes in the fabrication of **structural nodes** for free-form structures? To support the research, and as by-products from the work to be developed in order to answer the main question, the following sub-questions were also elaborated: - Is there a natural material which could replace acetone as binding agent in the mix of cellulose and lignin presented in *"3D printed fibre reinforced lignin"* (Liebrand, 2018) without compromising the observed viscosity, homogeneity and printability characteristics of the mixture? - What is the potential of enhancing viscosity, homogeneity and printability of cellulose and lignin by incorporating natural additives to the mixture? - What is the most adequate additive manufacturing process for a material mixing cellulose & lignin? - What are the most relevant material properties of a 3D printing feedstock for structural applications? - What is the potential of enhancing the relevant properties of a material for structural applications by using synthetic and natural additives? - Can the model layering/slicing of the 3D printing process impose a challenge to the prototype geometry and structural performance?

	- What are the limitations of the printing angle in terms of material and object geometry?
design assignment in which these result.	The "Wood Without Trees" is an ongoing research line which resulted in the master thesis from Thomas Liebrand, graduated from this faculty in the Building Technology track in 2018. The research being planned here has as its start point the findings published by Thomas and aims at improving the material mix developed and investigating the potential and challenges of applying it to fabricate a façade component with structural functions. Therefore, this project is divided into two main parts – one more investigative and exploratory and another one focus on prototyping, as described below: **Exploration** After the literature review phase, by using its findings and the previous research conclusions, the main focus of the practical framework is the material development through experimentation and evaluation of the results. This is a continuous and spiral process of exploration, analysis and conclusions that lead to further explorations until acceptable results are achieved, allowing to move on to the next step of the process – fabrication exploration – which might as well involve a few iterations with the material composition to adjust its characteristics according to the 3D printer settings. Until this stage of the research, the design assignment is mainly the development of a new material for additive manufacturing based on cellulose and lignin. With material and fabrication processes defined, samples can be produced and relevant mechanical testing executed to document the findings. **Design & Prototyping** With material and fabrication process defined and mechanical properties tested and documented, the product design phase can move forward. The assignment of this part of the research is the design of a structural node for a free-form structure, which will be a case study to evaluate the potential of the material and fabrication studied above focused on this application. The outcome of this design assignment is an improved mix for a cellulose & lignin feedstock for additive manufacturing and an analysis of its potential for structural applications

	on façade elements based on the relevant mechanical properties achieved and the case study developed.

Process

Method description

The use of cellulose and lignin as feedstock for additive manufacturing processes is a promising and relatively new field. The use of cellulose in such fabrication methods has been around for a few years already, mostly as fibre reinforcement for petroleum-based and bio-based polymers and in tissue engineering applications. Lignin on the hand, has been mostly used as a filler in wood composites and as a residual component of lignocellulosic fibres. As a combined feedstock for additive manufacturing, cellulose and lignin has not been thoroughly researched and one of the most prominent works is from Thomas Liebrand, a graduate from TU Delft, whose master thesis research originated this work.

This research topic is being developed in partnership with another student from the same Building Technology track, Christopher Biearch. The research questions are unique and independent, although the external networking and part of the literature studies were jointly developed. Part of the following works, to be identified below, will also be jointly executed.

With the context above in sight, this research will be divided into five main phases, combining a theoretical and a practical framework, a preparatory period and a final conclusions & findings gathering step:

0. *Preparation*
1. *Literature Review*
2. *Material Exploration*
3. *Printability Exploration*
4. *Mechanical Testing*
5. *Design & Prototyping*
6. *Conclusions*

Preparation corresponds to the initial weeks and started prior to the thesis commencement. Meetings with both mentors were arranged, the topic was presented and background information was gathered and researched to elaborate a general overview of the topic. An external network was also established, in collaboration with Christopher, to advise and support in terms of material studies and fabrication processes, with companies such as Urban Reef, Strong by Form and WASP and researchers from Saxion University, University of Stuttgart, ETH and RISE.

First main phase of the research is the *literature review*, executed through offline searches in the library of the Faculty of Architecture and Built Environment from TU

Delft, and online, through search engines such as Google Scholar, Scopus, ResearchGate and SpringerLink. From the first one, books on additive manufacturing and wood were consulted to compose the foundation knowledge on material and fabrication. From the second one, scientific papers, articles, reports and proceedings from conferences revealing the most recent developments on the topic were collected, due to the contemporary and innovative nature of the topic. The literature review covers a board spectrum from the material components, sourcing, mixing and finalises with the fabrication process. It was divided according to the following sections:

- *Wood* – overview, sourcing, panorama
- *Cellulose* – overview, properties, sourcing, use in AM, pros & cons
- *Lignin* – overview, properties, sourcing, use in AM, pros & cons
- *Additive Manufacturing* – overview, use of bio-based materials, use of wood, use of cellulose & lignin
- *Additive Manufacturing Mix* – current research status, binders, alternative binders, additives

The practical framework shall be carried on in partnership with Christopher and follows with the *material exploration & testing* phase. It starts from the findings of the research from Thomas Liebrand, with the reproduction in laboratory of the four mixes described in his thesis as the ones with the highest potential for use in the additive manufacturing fabrication of architectural elements. These will be the base for potential improvements such as altering the proportions of the components, combining additives to the mix and replacing the chemical binder acetone with bio-based alternatives.

All the material mixes developed must have their viscosity and homogeneity manually tested. In the sequence, their printability shall also be manually tested with the help of a syringe at both room temperature and heated to a specific temperature. All results must be documented for analysis and conclusions, and the most promising ones will be selected for the following phase.

By the end of this stage, the material-related sub-questions shall be answered, pending the mechanical testing and the analysis of the relevant properties for structural applications. Additives and alternative mixtures shall be defined, and the final conclusions will be drawn once the material mechanical testing has been performed.

With the materials defined, the *printability exploration* can proceed by using a common product sample to be fabricated with the aforementioned mixes and using the robotic arm and extruders available at the Laboratory for Additive Manufacturing in Architecture – LAMA. Such work will result in further iterations with the material mix and shall result in one or more adequate material mix for further testing and prototyping. By reaching these conclusions, the fabrication-related questions can be answered, paving the way for a broader understanding of the research, now combining further knowledge in both material and fabrication and allowing for the continued work towards fabrication and prototyping.

With material and printability verified, the *mechanical testing* phase can proceed to document the properties of the materials developed and its potential for structural applications. Samples shall be fabricated using the same machinery abovementioned and tested with the collaboration of Prof. Ir. Fred Veer in the material science laboratories from the 3mE Faculty. Since this practical work will be developed by two students, with two different material applications in sight, four different tests shall be executed – bending modulus, bending strength, water absorption and shrinkage. The first two, focused on the structural potential of the material, will be thoroughly documented in this research meanwhile the other two will be documented by Christopher. Nevertheless, a summary with the complete data will be included in the research and all results will be considered to answer the research question and sub-questions.

The last practical step will be the *design & prototyping*, presenting a case study of a structural node of a free-form shell structure, to be defined at a later stage. Such node shall be fabricated using the material developed and tested and the fabrication process experimented in the previous phases. By fabricating it, challenges will be faced and its feasibility as a façade product will be analysed.

With the practical works concluded, the final step of this research will be the compilation of all work executed during the 6-month timeframe and the fully based answer to the research question described above.

Literature and general practical preference

Background

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Reflection

1. What is the relation between your graduation (project) topic, the studio topic (if applicable), your master track (A,U,BT,LA,MBE), and your master programme (MSc AUBS)?

Summarizing the research plan presented above, the core of this research proposal is innovation based on the development of a new material to be used as feedstock for additive manufacturing processes to prototype a façade element which has never been done before. Escaping from architecture, this research is purely Building Technology:

To develop a prototype and control the fabrication process of a product, which could as well be transformed into a building component of larger scale, through additive manufacturing, computational design plays a fundamental role;

To develop a new material which has been researched before but requires further engineering and improvements has material science in its core, fundamental on the understanding of the behaviour of building elements and materials.

2. What is the relevance of your graduation work in the larger social, professional and scientific framework.

Social

The first applications of wood in additive manufacturing feedstock were in the form of wood composites with low percentages of wood flour to added a polymer matrix. This evolved to the use of lignocellulosic fibres and lignin as fillers, then cellulose (micro and nano) fibres reinforcements and, finally, high percentages of wood powder combined with adhesives for the creation of a printable paste. None of the above is entirely natural and harmless to the human being and to the environment. In a reality where society thrives to be sustainable and reduce its carbon footprint, a search for a natural and renewable material is highly relevant and an important factor in the Architecture field.

Professional

Freedom and a constant search for optimization in terms of design and construction are growing concepts in architectural projects nowadays. The possibilities to be unlocked by the popularization of additive manufacturing in the construction field are numerous. 3D printing allows for a much more rational use of material, offering virtually zero waste since any support material or leftovers can be recycled into the next batch. Speed is also on its side, with printers rapidly improving and the balance between customization and standardization, also driving down related production costs.

Scientific

The scientific relevance of this research resides on its innovative aspect and one-of-a-kind material and application development. The use of wood in Architecture is not new, neither is the use of additive manufacturing on product design focused on building elements. The combination of both topics with a clear direction towards the development of a natural feedstock has been rarely approached and presents a promising field ahead.