Future Gas Turbine Package Design Freeform wood fibre composite manufacturing

by

Yoann LE MOULEC

THESIS PRESENTED TO ÉCOLE DE TECHNOLOGIE SUPÉRIEURE
IN PARTIAL FULFILLMENT OF A MASTER'S DEGREE
WITH THESIS IN AEROSPACE ENGINEERING
M.A.Sc.

MONTREAL, FEBRUARY 23, 2023

ÉCOLE DE TECHNOLOGIE SUPÉRIEURE
UNIVERSITÉ DU QUÉBEC

BOARD OF EXAMINERS

THIS THESIS HAS BEEN EVALUATED

BY THE FOLLOWING BOARD OF EXAMINERS

M. Lucas Hof, Thesis supervisor
Department of Mechanical Engineering, École de technologie supérieure

Mrs. Nicole Demarquette, Thesis Co-Supervisor
Department of Mechanical Engineering, École de technologie supérieure

M. Éric David, Chair, Board of Examiners
Department of Mechanical Engineering, École de technologie supérieure

M. Ricardo Zednik, Member of the Jury
Department of Mechanical Engineering, École de technologie supérieure

THIS THESIS WAS PRESENTED AND DEFENDED

IN THE PRESENCE OF A BOARD OF EXAMINERS AND THE PUBLIC

ON FEBRUARY 16, 2024

AT ÉCOLE DE TECHNOLOGIE SUPÉRIEURE

ACKNOWLEDGEMENTS

Many thanks to my professors and research directors for their patience and feedback during the project. Also, this endeavor would not have been possible without the generous support of Siemens Energy who financed my research. I am also grateful to my classmates and cohort members, for their help during experiments and their advice. Thanks should also go to the librarians, research assistants, and study participants from the university, who impacted and inspired me.

Lastly, I would be remiss in not mentioning my family, especially my parents. Their belief in me has kept my spirits and motivation high during this process.

Design d’un package de turbine à gaz en matériaux composite à base de bois grace à l’impression 3D

Yoann LE MOULEC

RÉSUMÉ

Le bois est un matériau écologique et est largement utilisé sous sa forme brute, cependant il peut aussi être utilisé comme composant pour la création de matériau composite. Avec l’essor ces dernières années de l’impression 3D, les matériaux composites à base de bois peuvent être utilisés pour créer des pièces complexes en termes de géométrie qui ne peuvent être créées avec du bois sous sa forme brute. Ainsi, ce projet repense une pièce de package de turbine à gaz de Siemens et développe un matériau composite imprimable en 3D à base de polyéthylène et de bois convenant pour l’impression en 3D de cette pièce. La pièce choisie pour le projet est le conduit d’entrée d’air de combustion du package, cette pièce a été choisie pour sa géométrie complexe. Une fois que toutes les charges applicables sur la pièce ont été évaluées, un modèle 3D de la pièce est créé sur SolidWorks. Le modèle est alors utilisé pour effectuer des simulations numériques afin d’évaluer l’impact des charges en termes de pression appliquées sur la structure. Les simulations donnent une pression maximale applicable sur la structure de $20MPa$.Dans une deuxième partie, une campagne expérimentale est menée afin de créer différents filaments en matériaux composites à base de bois imprimables en 3D avec différents pourcentages de bois en termes de poids. Les filaments sont ensuite étudiés avec les techniques suivantes : analyse de calorimétrie différentielle à balayage, Analyse thermogravimétrique, mesure de l’indice de fluidité et prise de photo avec un microscope à balayage électronique. Ces techniques nous permettent alors d’avoir une idée de l’imprimabilité des filaments ainsi que leur température idéale d’impression. Après cela, différents échantillons sont imprimés en 3D afin d’évaluer les propriétés mécaniques des différents composites. Des éprouvettes de test sont imprimées afin de réaliser des tests de traction et obtenir le module de Young et la résistance maximale des éprouvettes ; et des cubes de $1x1cm$ avec un remplissage de 100% sont imprimés afin de mesurer la densité des composites. Les matériaux composites avec 10% et 20% de bois montrent une résistance maximale de respectivement $11MPa$ et $7MPa$. Enfin, une étude environnementale a été menée pour évaluer l’impact sur l’environnement de la pièce étudiée imprimée en 3D et comparer ces résultats avec l’impact sur l’environnement de la pièce actuelle utilisée par Siemens composée d’aluminium. Cette étude a montré en particulier que le matériau composite possédant 20% de bois a un impact 44% moins important en termes d’émissions de CO2 par Kg que l’aluminium.

Mots-clés: Turbine à gaz, matériaux composites, bois, fabrication additive, impression 3D

Future Gas Turbine Package Design Freeform wood fibre composite manufacturing

Yoann LE MOULEC

ABSTRACT

Wood is a sustainable material widely used as a raw material and can be used as a component for composite materials. With the rise of additive manufacturing processes and especially 3D printing, wood-based composite can be used to create complex-shaped pieces that cannot be designed out of standard wood materials. In this context, this project redesigned a Siemens gas turbine (GT) package piece into a 3D printable design and developed a wood-based 3D printable composite material from Polyethylene and wood suitable for the printing of this GT package piece into a wood-based 3D printed part. The GT combustion air inlet has been chosen for the redesign because of its complex geometry. Once all the loads that can be applied to the GT combustion air inlet have been identified, a basic 3D digital model is created. This model has been used to conduct simulations to evaluate the stress applied on the structure by the loads; the simulations give a maximum pressure of $20MPa$. In the second section, an experimental campaign is conducted to create different wood-based composite filaments with different wood % in weight. The filament is then characterized with differential scanning calorimetry analysis, thermogravimetric analysis, melt flow index measurements, and scanning electron microscope pictures. The characterizations helped to evaluate the printability of the composite and the ideal printing temperature. Afterward, tensile and density samples are printed to evaluate the mechanical properties of the different composites. A tensile test on a density sample gives a stress/strain curve that can be read to obtain the Young modulus and the maximum tensile strength of the sample, while weighting the density sample leads to the density of the printed composite. The wood-based composites with 10% and 20% wood reached respectively a maximum tensile strength of $11MPa$ and $7MPa$. A sustainability assessment has been conducted at the end of the study to evaluate the impact on the environment of a wood-based composite 3D printed GT combustion air inlet and compare the results with the impact of an aluminum-based GT combustion air inlet currently used by Siemens in their GT package. The sustainability showed, in particular, that the 20% wood-based composite has 44% less impact than aluminum per Kg regarding CO2 emissions.

Keywords: gas turbine, composite materials, wood, wood-based material, additive manufacturing, 3D printing

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

Page

LIST OF ABBREVIATIONS

ABS	Acrylonitrile Butadiene Styrene
ASA	Acrylonitrile Styrene Acrylate
CFC	Chlorofluorocarbon
CO2	Carbon Dioxide
DSC	Differential Scanning Calorimetry
ETS	École de Technologie Supérieure
FDM	Fused Deposition Modeling
GHG	Greenhouse Gas
GWP	Global Warming Potential
GT	Gas Turbine
HDPE	High Density Polyethylene
LDPE	Low Density Polyethylene
MFI	Melt Flow Index
N	Nitrogen
O3	Trioxygen
OPD	Ozone Depletion Potential
PE	Polyethylene
PLA	Polylactic Acid
PP	Polypropylene

SEM	Scanning Electron Microscope
SO2	Sulfur dioxide
TGA	Thermogravimetric Analysis
TRACI	Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts
WPC	Wood Plastic Composite

LIST OF SYMBOLS AND UNITS OF MEASUREMENTS

D_{10}	Density of the 10% wood composite made out of fine wood
D_{20}	Density of the 20% wood composite made out of fine wood
D_{alu}	Density of 6061-T6 ALUMINUM
S	Surface needed to build the geometry out of aluminum sheets
V	Volume of the SolidWork model of the GT combustion air inlet
w	Thickness of the aluminum sheets
W_{alu}	Weight of the aluminum-based GT combustion air inlet
$W_{wood10\%}$	Weight of the GT combustion air inlet made out of 10% wood composite
$W_{wood20\%}$	Weight of the GT combustion air inlet made out of 20% wood composite

INTRODUCTION

Over the past decades, environmental degradation, climate change, and limited resources have grown in research priorities. Thus, the area of sustainable material is also a hot research topic, and decarbonization is a central point of effort. Decarbonization is the process of diminishing or even eliminating, carbon dioxide (CO2) and other greenhouse gas (GHG) emissions resulting from human activity. Concomitantly, the industrial sector accounts for 30% of global GHG emissions and 37% of energy consumption, according to the World Economic Forum. Key materials in this sector are iron/steel and cement/concrete, representing each around 8% of global industrial process CO2 emissions according to the International General Agency. Hence, the decarbonization of industry and its equipment, especially in the energy business and using sustainable materials, is an essential step to meet the climate targets as defined by the United Nations "2030 Agenda for Sustainable Development" To reach these GHG cuts goals, different sustainable material ideas have been developed during the last decades, such as bio-sourced materials, recycled materials, and renewable materials. In this goal of sustainable material, composite material is promising due to the possibility of using sustainable material as a filler in standard material matrices. The duality of mechanical properties and sustainability would significantly advance industries. Therefore, any industries would benefit from composite materials created out of sustainable materials, especially the construction, aerospace, and even energy industries. Therefore, **Siemens Energy** is currently trying to improve its environmental impact by using raw wood products and wood-based composite material for his projects. This thesis is about one Siemens Energy project in particular, a project based on redesigning a gas turbine package.

A **gas turbine**, also known as a combustion turbine, is a type of internal combustion engine widely used in various applications for its efficiency and versatility. Gas turbines operate on the principle of converting energy from fuel into mechanical energy through a continuous combustion process. Gas turbines are commonly used in various industries and applications, including aviation (jet engines), power generation (electricity production), and marine propulsion (ships and submarines), just to give some examples. Siemens Energy uses gas turbines to provide a power generation station to isolated structures and industries. To work correctly and deliver a power generation, this gas turbine must be protected from the environment. Therefore, Siemens Energy developed a **gas turbine package** composed of three main parts that protect the turbine against the environment and ensure a ventilation system; this package made by Siemens was made out of metal. Thus, the package is heavy and costly in terms of carbon emissions. This is why Siemens has adopted the idea of redesigning this package out of wood material and wood-based composites.

Most parts of the gas turbine package are straight-shaped and can be made out of raw materials such as engineered wood. Engineered wood is a good candidate for the project developed in this work because of the sustainable nature of wood and its good mechanical properties. However, one central part of the gas turbine package, **the air filter and ducts system**, has a lot of complex-shaped pieces that cannot be redesigned out of engineered wood. This is the main reason why **additive manufacturing** has been chosen as a main process for the project.

Additive manufacturing covers many processes, such as Material Jetting, Binder Jetting, Material Extrusion, Powder Bed Fusion, or Sheet Lamination. Material extrusion is widely used for prototyping and, more recently, for mass manufacturing (Audi company is a great example). However, 3D printing composite material, especially wood-based composites, is still challenging. Therefore, material Extrusion, widely called **3D printing**, has been chosen for the current project for its capacity to create structures with composite materials and increasing availability in industries. The design flexibility and reduced waste aspect of 3D printing make it the perfect candidate for the Air filter part of the gas turbine package. In fact, it is possible to create pellets or filaments of Wood-based composite and directly 3D print the wood-based composite into the shape of the piece needed.

Objective of the work

The main objective of the project presented in this work is to conduct a feasibility study about using wood-based material and 3D printing to re-create parts of the air filter system of the Siemens gas turbine package. The feasibility study must prove that focused parts can be redesigned and manufactured sustainably out of wood-based materials while keeping all its functionality.

Completed Work and structure

Composite material made out of wood and polylactic acid (PLA) is already widely spread but cannot be used for long-term parts in industries due to the fragile nature of PLA. Thus, polypropylene (PP), polyethylene (PE), or resins are reasonable choices. To fulfill all the requirements of the gas turbine package presented in the **Chapter 1**, PP and PE are the only candidates left. However, to understand the feasibility of the Siemens research project and the reality of wood-based composites, a bibliography review is presented in **Chapter 2**. The bibliography review explores what has already been developed around additive manufacturing with wood and wood-composite material and the statement of the art around 3D printing with wood-based material.

The project's foundation is the design study presented in **Chapter 3**. Since 3D printing allows a vast range of shapes, redesigning the focused pieces of the gas turbine could be a thesis. Therefore, this chapter proposes a straightforward redesign of the pieces based on the previous steel model to show the possibilities and improve the printability of the pieces. Then, a numerical simulation analysis is led to find the mechanical properties the composite material needs to achieve the package requirements presented in the first chapter.

The project's core is presented in **Chapter 4**. This chapter is about creating a wood-based composite material that fulfills the mechanical properties requirements found in the design study part of the project. This chapter presents the composite material composition, explains the choice of the composite components, and presents all the experimental aspects of the project. The project's experimental aspect contains the experiments' plans to ensure the reproducibility of the experiments and the results of the experiments.

Lastly, this thesis is concluded by the **Chapter 6** presenting an environmental statement of the project developed in this work and a conclusion. The last chapter is written to serve as a validation for the environmental aspect of the project, while the conclusion synthesizes all the observations made during the project. Moreover, most of the work done in this thesis is done to ensure solid basics for a more significant project about 3D printing designs and wood-based composites for additive manufacturing.

CHAPTER 1

PACKAGE PRESENTATION

Gas turbines, as presented in the introduction, are very efficient as power generators. Thus, gas turbines are a convenient way to provide electricity to isolated areas, such as boats or industries located in difficult access areas. Therefore, a gas turbine used as a power generator is not destined to move during its lifespan except for the initial transport. This is why it is possible to design a complete static package that protects the turbine against the environment during its utilization. However, protection against the environment is not the only goal of a gas turbine package. The actual in-use package made by Siemens Energy also provides air circulation, noise regulation, and even a fire suppression system. A gas turbine in itself is a very complex structure and will be referred to in this thesis as **the core**; the core is then the main machine that provides power generation. The package is placed around the core and, as explained before, is used to protect the core.

To give an idea of the structure of a gas turbine package, Figure 1.1 presents the design of the basic package made out of metal by Siemens. This package is the one currently in use to protect the gas turbines.

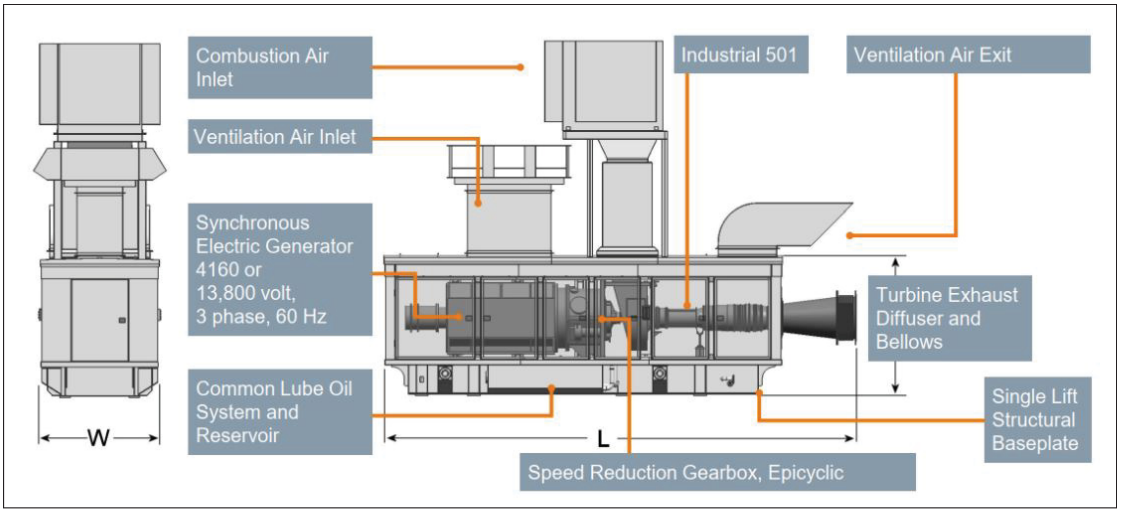


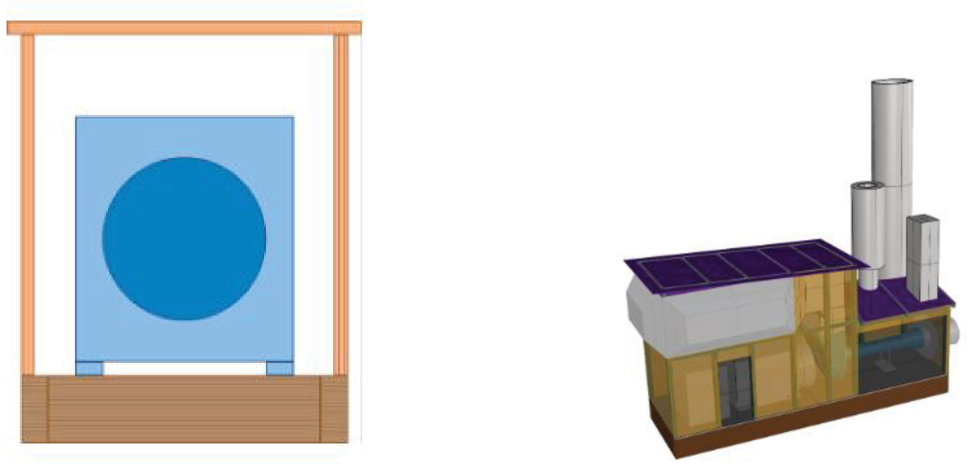
Figure 1.1 Design of gas turbine with its package made out of metal

1.1 Package structure and main components

This section shows the structure of the gas turbine package. A gas turbine package is made out of many different pieces of different shapes and sizes. However, the package can be described as having three main parts, and every part is essential to ensure the functionality of the core :

- **The Enclosure**: The baseplate is the mounting component for the core and all the systems to operate the equipment. The baseplate holds the core in place, connects the Package to the foundation, and contains all the systems (lubrication, fuel, fire and gas, controls, and generator).
- **The Baseplate** : The Baseplate acts as the primary support of the engine
- **The Inlet / Air filter system**: The air filter contains the filter elements to provide clean air to the core and ventilation system. The inlet ducting provides an inlet plenum to direct motive air into the gas turbine.

Figure 1.2 presents an example of what could look like a package made out of engineered wood for the enclosure and the baseplate. These designs are made by ARUP, which is a counseling company engaged by Siemens to realize a feasibility study on the wood-based package project.



a) Simple picture of the core being protected by the baseplate and the enclosure

b) Example of look for a potential wood-based gas turbine package design by ARUP

Figure 1.2 Wood-based gas turbine package design idea by ARUP

As explained in the introduction and shown in Figure 1.2, the baseplate and enclosure can be designed out of engineered wood, which is ideal. The use of engineered wood is ideal since engineered wood such as **Glued Laminated Timber**, **Cross Laminated Timber** or **Plywood** are very resistant materials made out of 100% wood in weight. For more information about engineered wood, any reader can consult the American Wood Council's data sheet about these materials. However, the inlet and air filter system is made out of many complex parts and cannot be crafted out of engineered wood. Therefore, composite material and 3D printing have been chosen in this project to re-design the air filter system part.

1.2 Air Filter System

The main focus of the work presented in this thesis is put on the Air filter system part. This part of the gas turbine package must be introduced in greater detail. First of all, the Air filter system is composed of three main pieces: the **Combustion Air Inlet**, the **Ventilation Air Inlet**, and the **Ventilation Air Exit** as shown in Figure 1.2. The combustion air inlet provides an inlet plenum to direct motive air into the gas turbine, which is essential to the healthy functionality of the turbine. The exit and inlet air ventilation provide fresh air to the ventilation system, which is also essential to the turbine's working process. It is important to mention that the Combustion Air Inlet is also equipped with a filter, which is not to be redesigned and will be considered in the design process.

To have a better understanding of the 3D printing challenges, the dimensions of the air filter system pieces must be introduced. Figure 1.3 is provided by Siemens Energy and presents the Air Filter dimension from the previous model of gas turbine package :

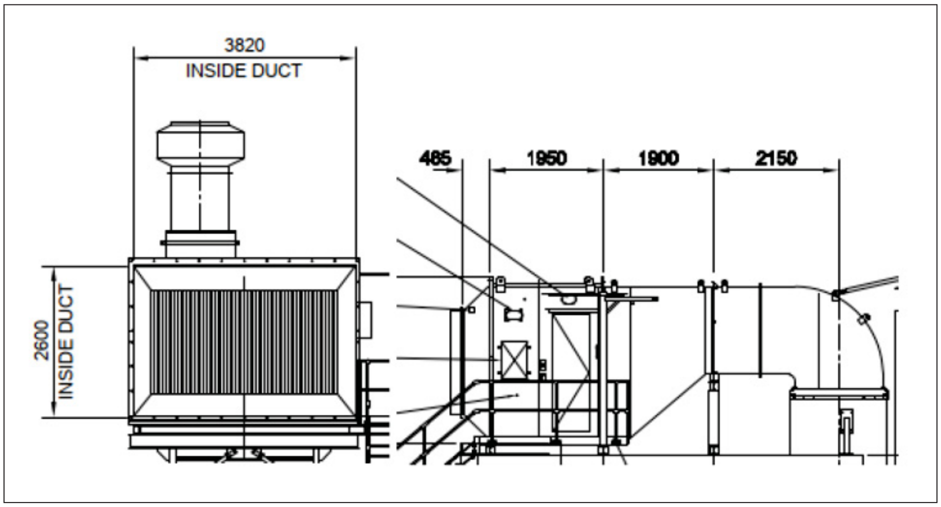


Figure 1.3 Air filter dimension from the previous model of Gas Turbine Package

The previous gas turbine model presented in Figure 1.1, gives a lot of information about dimensions and what kind of shapes must be manufactured to create the air filter system of the turbine. As seen in Figure 1.3, there are a lot of different shapes and sizes of components. Therefore, more than one material and process will be required for the whole air filter and duct system. Different processes and wood-based materials must be studied to create the air filter system of the gas turbine. During this thesis, one type of material with one process will be studied to realize a study for Siemens. The project developed in this work will be focused on the design of the Combustion Air Inlet, mainly because it is a challenging part of the Turbine package that contains a lot of complex shaped parts. Therefore, this kind of part is suitable for the Additive manufacturing process. Moreover, other projects are underway with other students on the baseplate and the enclosure.

1.3 Package specification and technical requirements

To ensure the proper functionality of the core, the package must respect some specifications and technical requirements. Only the specifications and technical requirements necessary for the air filter and duct system are mentioned in this sub-chapter. Many mechanical requirements, especially for the baseplate and enclosure, are specified but will not be mentioned here. In this sub-chapter, some specifications about transport, ventilation, Fire performance, and weather conditions will be talked about.

Transport

The package will be exposed to accelerations during transport. The lateral accelerations due to cornering and the vertical accelerations are considered to be very short-duration impulses due to rough roads. The Turbine package must handle the potential accelerations due to transport. Accelerations are considered up to $1.0g\ lateral$ and $4.0g\ vertical$.

Another essential aspect to be mentioned is the weight of the component. The whole project has as a goal to reduce the weight of the package, first to reduce the quantity of material but also to reduce the carbon emission during transport as a lighter part will cost less carbon emission to transport.

Acoustic attenuation

The enclosure of the package must ensure an acoustic attenuation in order not to disturb the environment around the functioning gas turbine. To evaluate the requirements of acoustic attenuation, two fields must be taken into account:

- Near field: Distance of 1 meter from the side of the enclosure.

- far field: Distance of 1.7 meters from the package of the turbine.

The acoustic attenuation requirements provided by Siemens are the following :

- $85dBA$ for the near field
- $59dBA$ and $69dBA$ for the standard and basic utilization for the far field.

As mentioned in this paragraph, the acoustic attenuation is mostly due to the enclosure design. However, ducts can also be designed to reduce noise from the core. Therefore, the design part of the Air filter and duct system can also take into account this aspect

Ventilation

The air into the enclosure must be ventilated during the turbine operation. An air cooling system must supply sufficient ambient air to ensure an operating temperature in the enclosure.
The actual designs presented in Figure 1.1 are considered sufficient to ensure proper ventilation for the gas turbine. As the part will be re-designed, it is essential to keep these ventilation properties of the pieces. After each re-design of each part, an air-flow analysis should be led to ensure that the new designs have enough air-flow properties to ensure proper ventilation. In this thesis, as the design aspect is kept very simple, no air flow analysis will be conducted; however, it is crucial to keep in mind that significant changes in the geometry impact the air-flow aspect of the air filter and duct system.

Fire performance

The use of wood to create structures directly related to gas turbines may not be acceptable. Using wood provides additional fire sources and can be considered less safe than the use of non-combustible material. Once the materials are chosen, measures must be taken to reduce the risks from fire as much as possible.

Here are the main fire risk considerations listed by **ARUP** (2021) that must be taken into account while using wood-based material for the package. Table 1.1 presents the risks related to the used of wood into a project related to gs turbines.

Table 1.1 Risks related to the use of wood-based material

Risks
Increased Fuel Load
Surface Flame Spread
Proximity to other structures
Fire Suppression Systems
Exposure to High Temperatures

As can be seen in the Table 1.1, the risks related to the use of wood-based materials into the current project are numerous and therefore must be taken in count later in the global Siemens project. See the full table in Table-A I-1 in the appendix for more information about these risks.

This master thesis dealt with the basic technical requirements of the package, which are the loads applied to the package. The ventilation, the acoustic attenuation, and the fire performance of the redesigned package have not been studied in this work as it is part of a coarse project and this work studies the basics of the redesigned package.

CHAPTER 2

LITERATURE REVIEW

Three main aspects will be studied in this literature review. First, the **wood-plastic composites (WPC)** in the literature will be discussed. The literature of **3D printing of wood-based materials** will be discussed in a second part, while the last part of this chapter will be focused on **material and structures sustainability assessment**. To clarify the reading of the literature review, at the end of each section is presented a table summary of the main articles mentioned in the section with their title. The articles are classed into three categories, the three main parts of the section: the wood-plastic composites (WPC), the 3D printing of wood-based materials, and the materials and structures sustainability assessment.

2.1 Wood-based composites in the literature

Wood-plastic composites are composites made with wood fibers as a filler in a polymer matrix; WPC has been mainly studied for their ecological aspect; as a matter of fact, wood-plastic composites can be manufactured entirely out of recycled materials while keeping good mechanical properties (T. Tabarsa et al., 2011). WPC up to 40% wood filling with a polypropylene matrix while using only recycled materials has been created, and the result is the creation of a usable and sustainable composite. However, increasing the wood % higher than 40% increases the hardness of the material and then reduces the mechanical and physical properties of the composite. Therefore, recent studies have tried to improve the wood percentage in weight in composites and the mechanical properties of composites. Among recent studies, some present exciting results about wood-plastic composites. Recycled High-density polyethylene (HDPE) is one way to create a wood-plastic composite using wood as a filler. (Rong Xiao et al., 2023). As shown in Figure 2.1, the composite is created out of plastic powder and wood fibers and is processed by hot molding; this results in a dense structure. The article states: "The dense structure formed by lignin decomposition and re-polymerization and the addition of plastics wastes effectively enhance the waterproof and flame retardant properties of poplar/HDPE composite."

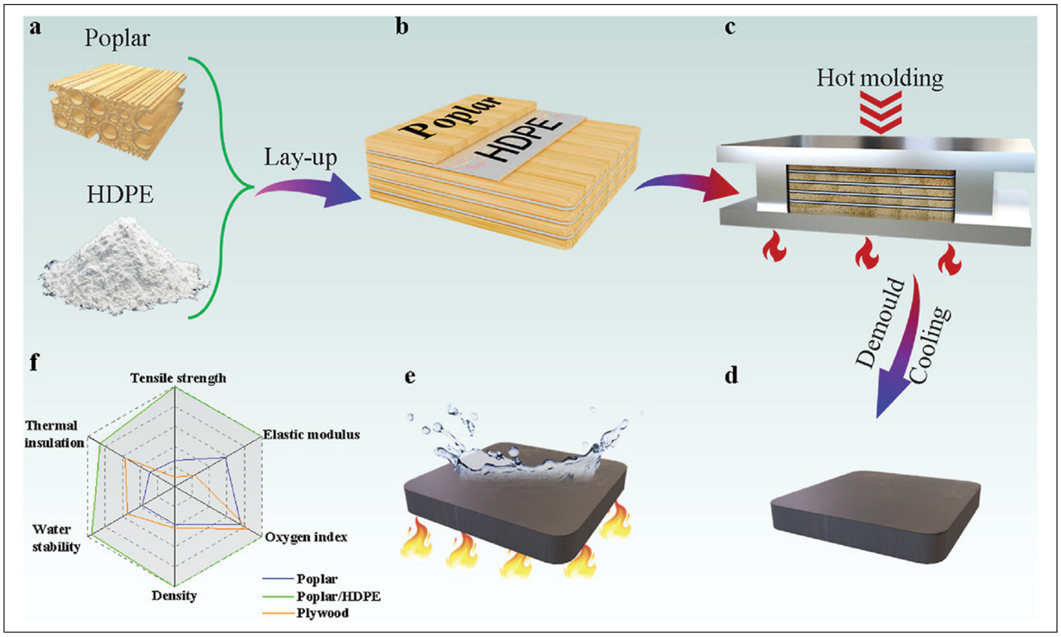


Figure 2.1 Creation process of dense WPC out of HDPE and wood (Rong Xiao et al. 2023)

Using this method and HDPE a tensile strength of $198.9 MPa$, high flame resistance properties, and low water absorption has been reached for the composite.

One other essential aspect of a wood-plastic composite is its percentage of wood in weight. Wood-plastic composites created with molding can contain up to 90% wood in weight (Xu, J. et al. 2021). The properties modifications of very high-filled WPC depend on the wood % contained in the composite and the temperature. Composites made out of Polypropylene and poplar wood fiber (WF) and bamboo fiber (BF) from 75% to 90% wood percentage in weight have been studied and Figure 2.2 presents results about these high filled WPC :

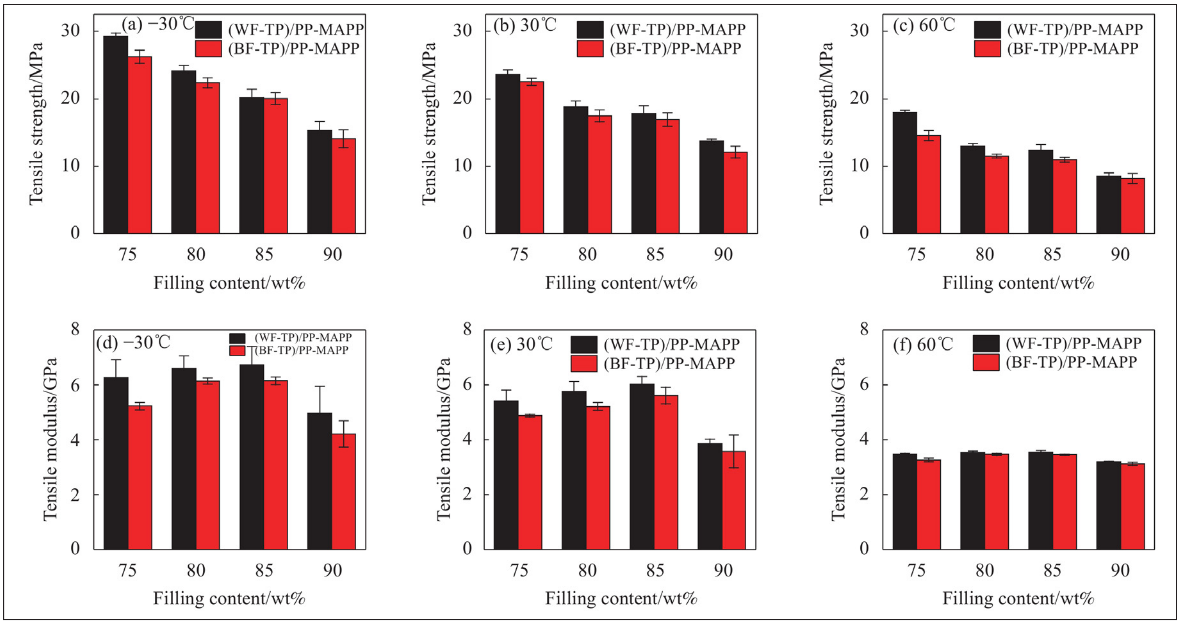
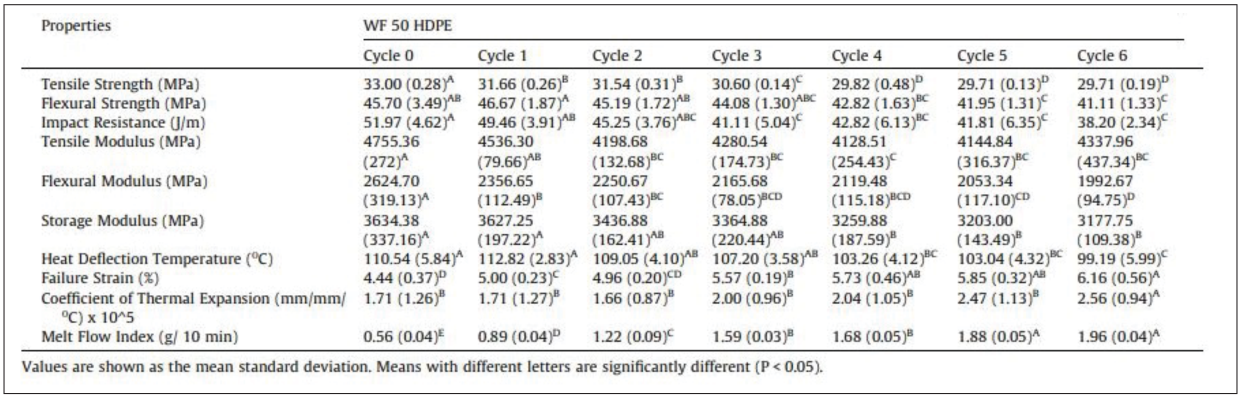


Figure 2.2 Properties of very high-filled WPC for different temperatures from Xu, J. et al. (2021)

As seen in Figure 2.2, adding more wood into the WPC reduces its mechanical properties, and water absorption of the composite is still a challenge. This is why an interesting idea to improve these composites is to use co-extrusion in order to manufacture a high-filled wood-polyethylene composite with excellent properties by changing the formula in the shell layers (Yang An. et al., 2023). The final material then shows increased mechanical resistance and water absorption properties; however, the co-extrusion process is limited in terms of the shapes of final products, and their co-extruded material can be mainly used as panels.

The previous part of the literature review has shown that Wood-plastic composites can reach high mechanical properties, water resistance, and even flame retardance properties while being durable over time using High-density polyethylene. This type of material is also sustainable; first, due to the high percentage of wood in weight it contains, some of them can reach up to 90% weight wood filling; secondly, due to the potential nature of the materials it contains that can be recycled materials. The last question about these wood-plastic composites is the recyclability of the final product. The recycled aspect of the materials used to create the composite and the final product’s recyclability are totally different; a material made out of 100% recycled materials may not necessarily be recyclable. This is why studying the recyclability of WPC composites and the effect of the recycling on the mechanical properties of the composite is a necessity (Sujal Bhattacharjee et al., 2018). The recycling of WPC is made by reprocessing the material and creating a new WPC with the remains of the previous WPC. Figure 2.3 presents the multiple reprocessings of an HPDE/poplar WPC with 50% wood weight and the mechanical properties of the WPC for each recycling cycle:



Properties	WF 50 HDPE						
	Cycle 0	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Cycle 6
Tensile Strength (MPa)	33.00 (0.28)^{A}	31.66 (0.26)^{B}	31.54 (0.31)^{B}	30.60 (0.14)^{C}	29.82 (0.48)^{D}	29.71 (0.13)^{D}	29.71 (0.19)^{D}
Flexural Strength (MPa)	45.70 (3.49)^{AB}	46.67 (1.87)^{A}	45.19 (1.72)^{AB}	44.08 (1.30)^{ABC}	42.82 (1.63)^{BC}	41.95 (1.31)^{C}	41.11 (1.33)^{C}
Impact Resistance (J/m)	51.97 (4.62)^{A}	49.46 (3.91)^{AB}	45.25 (3.76)^{ABC}	41.11 (5.04)^{C}	42.82 (6.13)^{BC}	41.81 (6.35)^{C}	38.20 (2.34)^{C}
Tensile Modulus (MPa)	4755.36 (272)^{A}	4536.30 (79.66)^{AB}	4198.68 (132.68)^{BC}	4280.54 (174.73)^{BC}	4128.51 (254.43)^{C}	4144.84 (316.37)^{BC}	4337.96 (437.34)^{BC}
Flexural Modulus (MPa)	2624.70 (319.13)^{A}	2356.65 (112.49)^{B}	2250.67 (107.43)^{BC}	2165.68 (78.05)^{BCD}	2119.48 (115.18)^{BCD}	2053.34 (117.10)^{CD}	1992.67 (94.75)^{D}
Storage Modulus (MPa)	3634.38 (337.16)^{A}	3627.25 (197.22)^{A}	3436.88 (162.41)^{AB}	3364.88 (220.44)^{AB}	3259.88 (187.59)^{B}	3203.00 (143.49)^{B}	3177.75 (109.38)^{B}
Heat Deflection Temperature (°C)	110.54 (5.84)^{A}	112.82 (2.83)^{A}	109.05 (4.10)^{AB}	107.20 (3.58)^{AB}	103.26 (4.12)^{BC}	103.04 (4.32)^{BC}	99.19 (5.99)^{C}
Failure Strain (%)	4.44 (0.37)^{D}	5.00 (0.23)^{C}	4.96 (0.20)^{CD}	5.57 (0.19)^{B}	5.73 (0.46)^{AB}	5.85 (0.32)^{AB}	6.16 (0.56)^{A}
Coefficient of Thermal Expansion (mm/mm/°C) x 10^5	1.71 (1.26)^{B}	1.71 (1.27)^{B}	1.66 (0.87)^{B}	2.00 (0.96)^{B}	2.04 (1.05)^{B}	2.47 (1.13)^{B}	2.56 (0.94)^{A}
Melt Flow Index (g/ 10 min)	0.56 (0.04)^{E}	0.89 (0.04)^{D}	1.22 (0.09)^{C}	1.59 (0.03)^{B}	1.68 (0.05)^{B}	1.88 (0.05)^{A}	1.96 (0.04)^{A}

Values are shown as the mean standard deviation. Means with different letters are significantly different ($P < 0.05$).

Figure 2.3 Physical and mechanical properties of Wood-HDPE composite after reprocessing cycles (Sujal Bhattacharjee etal., 2018)

The properties of the WPC through the recycling cycles decrease; however, even after six reprocessing cycles, the material still has decent mechanical properties and can still be used for industrial applications.

As seen in this section, wood-plastic composites are becoming more and more efficient, resistant, and sustainable among recent scientific studies. However, as explained in the introduction and Chapter 1, this project is about creating package parts using the process of 3D printing. If composites created with the molding process have excellent properties, this does not implicate that it is the case for the part created out of 3D printing.

Table 2.1 summarizes the main articles mentioned in the 3D printing of wood-based material WPC category of the literature review.

Table 2.1 Summary of the main articles mentioned in the literature review category WPC

Author	Year of publication	Title
Rong Xiao et al.	2023	Visual design of high-density polyethylene into wood plastic composite with multiple desirable features: A promising strategy for plastic waste valorization.
Tabarsa, T. et al.	2011	Manufacturing of wood-plastic composite from completely recycled materials.
Xu, J. et al.	2021	High-and low-temperature performance of ultra-highly filled polypropylene-based wood plastic composite
Yang, An. et al.	2023	Preparation of Situ Microfiber-Reinforced Co-Extruded High-Filled Wood-Plastic Composite with Excellent Mechanical, Creep Resistance, and Water Resistance Properties
Elsheikh, A. H. et al.	2022	Recent progresses in wood-plastic composites: pre-processing treatments, manufacturing techniques, recyclability, and eco-friendly assessment

2.2 3D printing of wood-based composites

Using wood-plastic composites with 3D printing is much more restrictive as the 3D-printed material has to respect melt flow properties and must not warp during the printing process. However, these requirements are not the only issue manufacturing with additive manufacturing process, and especially 3D printing brings a lot of issues and malfunctions. (V. Goodship et al., 2016). Warping, overheating, irregularities in the layers, and gaps between the infill and outline are issues that can be encountered during 3D printing.

Most of the current wood-plastic composites available for 3D printing are made out of PLA (Polylactic acid) PLA based composites for 3D printing are widely studied among article and brings interesting results (Kananathan, J. et al., 2022) (Chen, F. et al., 2022). However, as explained in the introduction, PLA could not be used in this project because of its durability properties. Indeed, PLA is a biopolymer and cannot support the 20-year lifespan expected of the gas turbine package. This is why another material must be used for the project's wood-based composite. First, 100% wood 3D-printed material would be great for sustainability. However, as shown by their article 100% wood-based composite presented in this article as "wood ink" made out of Wood flour, Cellulose nanocrystal, and Xyloglucan could not be used in this project due to the low mechanical properties of the material or the high warping properties of the printed parts as shown in the Figure 2.4 (Kam, D. et al., 2022).

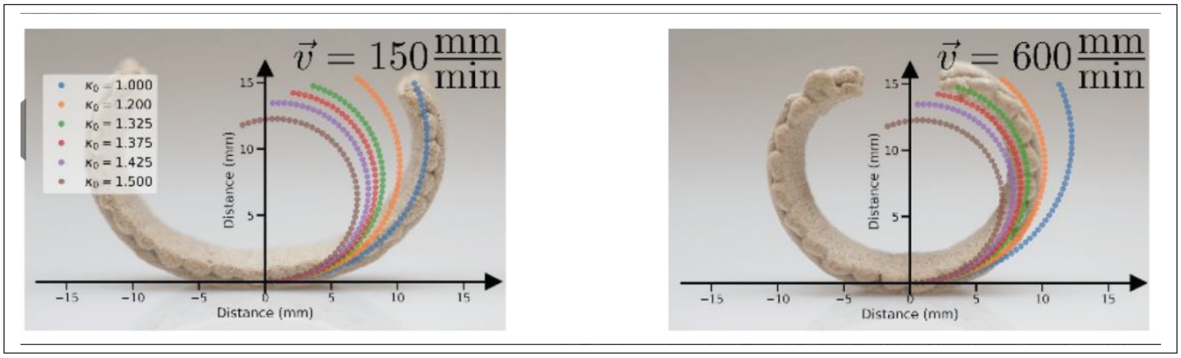


Figure 2.4 Warping of 3D printed parts made out of 100% wood "ink"

The wood "ink" is very promising in terms of sustainability but is not realistically usable for the industry at the moment.

The two best candidates for the polymer material of the composite in the current project are polyethylene (PE) and polypropylene (PP). Very few PP, PE, and wood-based composite are suitable for 3D printing in the literature. The first and only study available on the subject discusses about a 3D printable wood-based WPC with HDPE.(A. Koffi et al., 2022). The main results show the creation of a 3D printable WPC with property improvement as the wood filling augments up to 30% in weight. In fact, as the percentage of wood increases, the warping of the 3D-printed part is reduced. Figure 2.5 shows the difference in warping between virgin HDPE and WPC composites created with 10% to 30% wood infill.

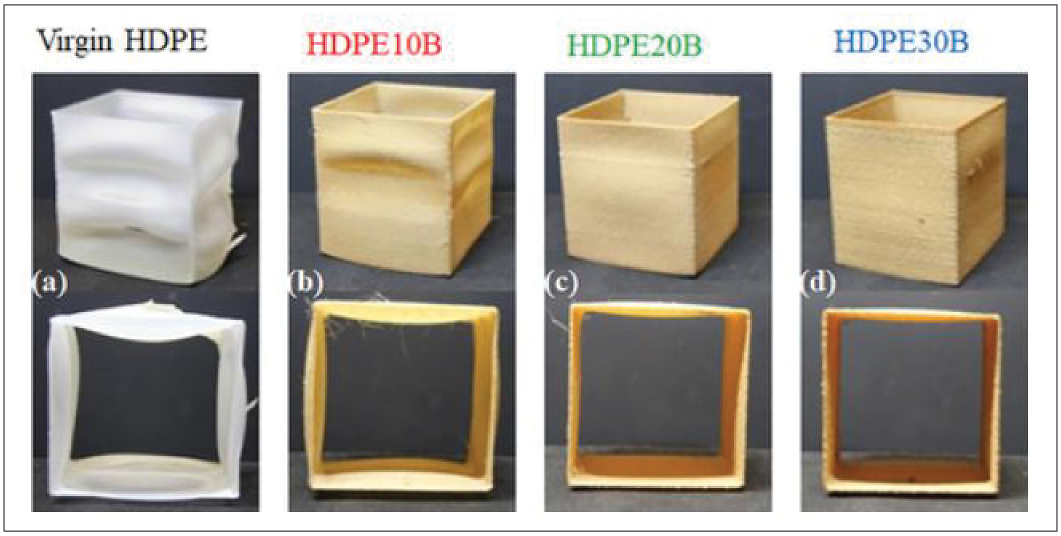


Figure 2.5 Warping of 3D-printed parts for different wood% in the composite. Koffi, A. et al. (2022). HDPEXXB representing a composite made out ouf HDPE and XX% of wood

Also the mechanical properties increase as the wood filling increase, going from 150 ± 50 Mpa to 250 ± 50 Mpa. This study is of significant importance for the current project as it shows that it is possible to 3D print wood-based composite with PE while enhancing the properties of the 3D-printed part compared to the initial raw polymer. However, the study does not talk about applications for this composite, and this is why the project developed in this work is an excellent completion to the Koffi, A. et al. study.

For now, in the literature review sections, only small-scale manufacturing has been discussed.

However, the studied part of the gas turbine package have more significant dimensions than the usual printer can print (cf Figure 1.3).

Table 2.2 summarizes the main articles mentioned in the "3D printing of wood-based materials" category of the literature review.

Table 2.2 Summary of the main articles mentioned in the literature review category "3D printing of wood-based materials"

Author	Year of publication	Title
Goodship, V. et al.	2016	Design and Manufacture of plastic components for multifunctionality: structural composites, injection molding, and 3D printing
Kananathan, J. et al.	2022	Comprehensive investigation and prediction model for mechanical properties of coconut wood–polylactic acid composites filaments for Fused Deposition Modeling (FDM) 3D printing
Chen, F. et al.	2022	Preparation and properties of heat-treated esterified wood flour/polylactic acid composites for FDM 3D printing.
Kam, D. et al.	2022	Wood Warping Composite by 3D Printing
Patti, A. et al.	2021	Rotational Rheology of Wood Flour Composites Based on Recycled Polyethylene
Koffi, A. et al.	2022	Extrusion-based 3D printing with high-density polyethylene Birch-fiber composites

2.3 Large scale 3D printing

Most of the 3D printing research and 3D printers are geared towards small-scale manufacturing. Large-scale additive manufacturing, in general, holds immense promise as it unlocks a multitude of possibilities. The study of 3D printing on a large scale represents a significant advancement and is being explored by the scientific community. Therefore, for the current project, large-scale 3D printing is a challenge in itself, and even if large-scale 3D printing is not part of the project, having a look into the recent studies around large-scale manufacturing serves as a validation for the project.

The majority of the progress in large-scale manufacturing is focused on building construction. Consequently, most of the research in large-scale manufacturing revolves around concrete 3D printing Sanjayan, J. G. et al., 2019) (Alhumayani, H. et al., (2020). 3D-printed concrete has a considerably lower overall environmental impact (by more than 50%) than conventional concrete. Large-scale 3D printing with polymer is less widely researched than concrete 3D printing. First of all, pure PP and PE are really difficult to use as materials for large-scale 3D printing due to the warping of the printed pieces. However, adding fillers in the PP greatly help the printability of the material for large-scale 3D printing (Winter, K. et al., 2022).

2.4 Materials sustainability assessment

The evaluation of the environmental impact of a material is critical, especially when the material created is supposed to have a better impact on the environment than its previous counterpart. An optimized way to evaluate the environmental impact of a material is to use the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) method and evaluate the impact of the material regarding more indices than only the CO2 emissions. In this context, the environmental impacts of the wood-polymer composite compared to wood pallets have been studied (Khan M. et al., 2021). Two life cycle assessment methods, attributional life cycle assessment, and consequential life cycle assessment, have been used to evaluate the two materials. As a result, the wood-polymer composite had the lowest environmental impact in depletion potential, acidification potential, eutrophication potential, global warming potential, global warming potential, and ozone depletion potential regarding the attributional cradle-to-grave life cycle assessment. In contrast, wooden pallets showed the lowest impact on global warming potential. In the consequential life cycle assessment, wood-polymer composite pallets showed the best environmental impact in all impact categories. Therefore, the results depend on the methodological approach of the life cycle assessment; however, it can still be concluded that wood-plastic composite is a better choice over plastic pallets and, in most cases, over wooden pallets.

On the other hand, end-of-life options for the composites are to investigate P. Sommerhuber et al., 2017). As mentioned in Figure 2.3, a WPC can be reprocessed into a new WPC while keeping good mechanical properties. To complete the study presented before, Figure 2.6 presents a part of the results where a virgin WPC, and a recycled WPC are compared regarding their environmental impact evaluated with the TRACI method.

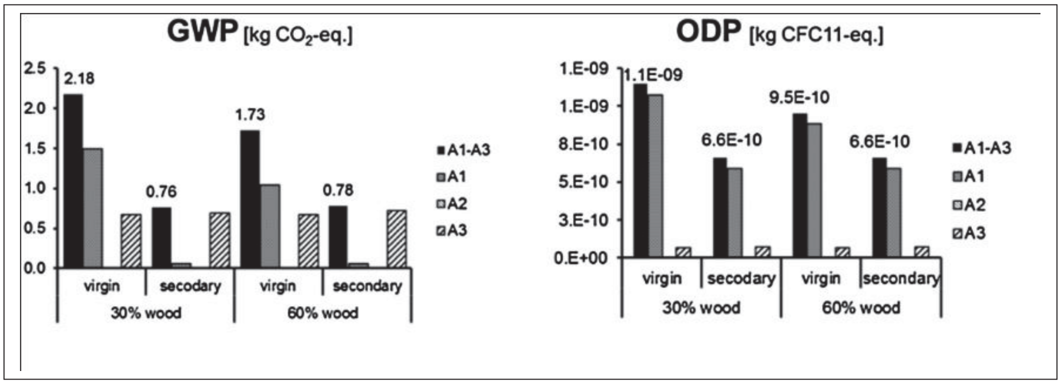
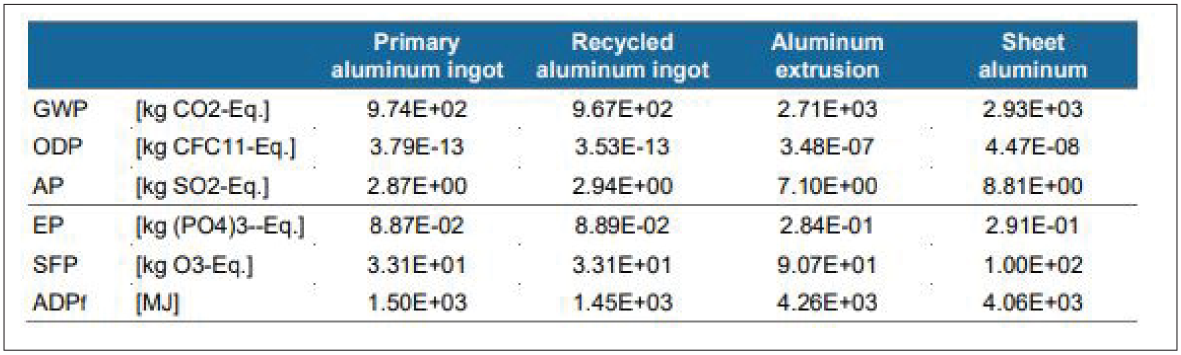


Figure 2.6 Global warming potential and Ozone depletion potential impact evaluation for a virgin and a secondary WPC

As can be seen in Figure 2.6, a secondary WPC has less impact on the environment than a virgin one. The results for the global warming portential (GWP) and the ozone depletion potential (OPD) are shown only, but the same tendency continues for the other indices.

For the current project, the environmental impact of pure polymer will be needed for the calculation of the created wood-based composite. The TRACI evaluation of different pure polymers, as well as a solution for the waste handling of these polymers, has been studied (Hottle, Troy. 2015). The results of this research will be used later in Chapter 6, as well as the results of **The Aluminum Association** that gives the TRACI assessment of standard aluminum. Figure 2.8 presents the environmental impact results of "standard" aluminum:



		Primary aluminum ingot	Recycled aluminum ingot	Aluminum extrusion	Sheet aluminum
GWP	[kg CO2-Eq.]	9.74E+02	9.67E+02	2.71E+03	2.93E+03
ODP	[kg CFC11-Eq.]	3.79E-13	3.53E-13	3.48E-07	4.47E-08
AP	[kg SO2-Eq.]	2.87E+00	2.94E+00	7.10E+00	8.81E+00
EP	[kg (PO4)3--Eq.]	8.87E-02	8.89E-02	2.84E-01	2.91E-01
SFP	[kg O3-Eq.]	3.31E+01	3.31E+01	9.07E+01	1.00E+02
ADPf	[MJ]	1.50E+03	1.45E+03	4.26E+03	4.06E+03

Figure 2.7 Environmental impact assessment of aluminum according to **The Aluminum Association**

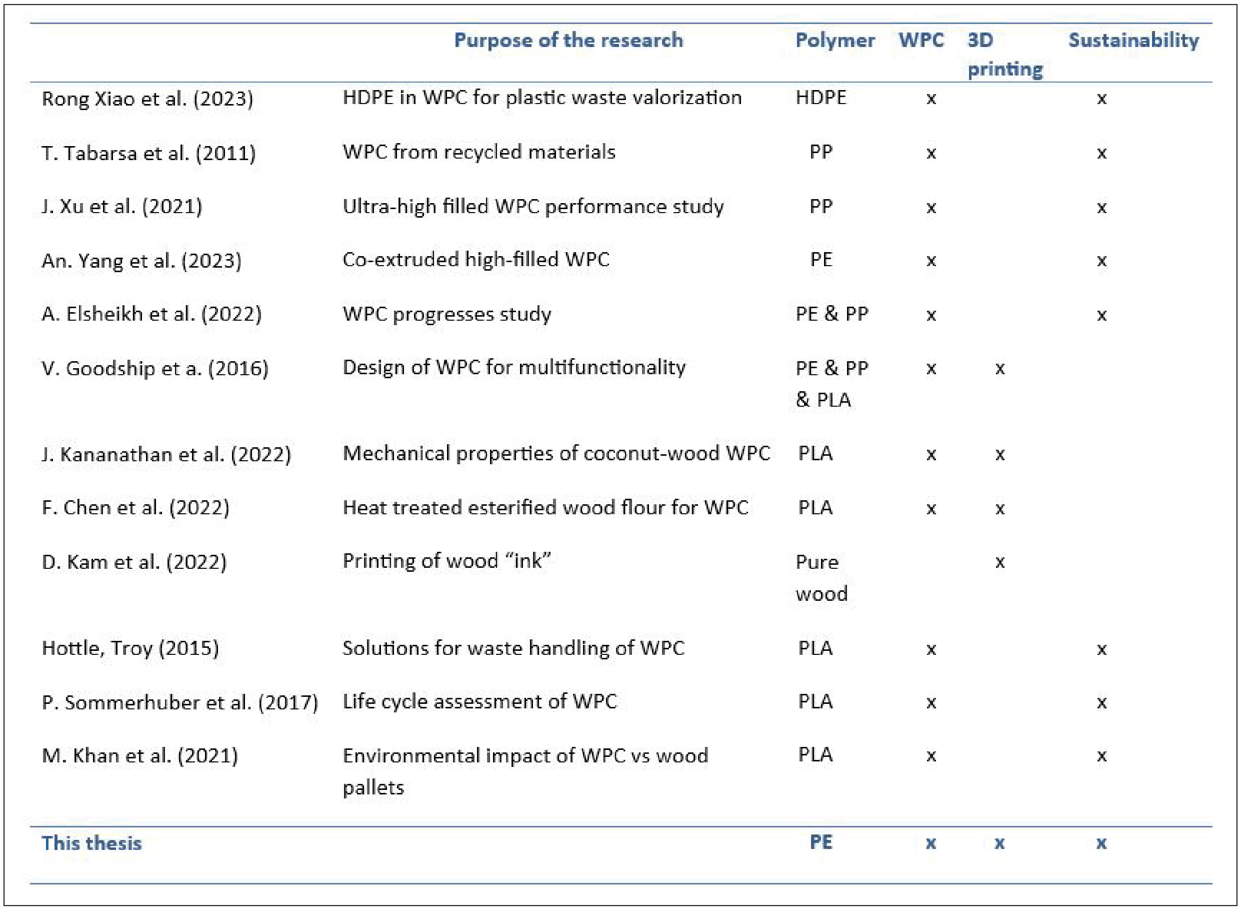
Table 2.1 summarizes the main articles mentioned in the 3D printing of wood-based "material materials and structures sustainability assessment" category of the literature review.

Table 2.3 Summary of the main articles mentioned in the literature review category "materials and structures sustainability assessment"

Author	Year of publication	Title
Hottle, Troy.	2015	Assessment and Solutions for Waste Handling of Compostable Biopolymers
The aluminum association	2022	EPD Background Report of North American Semi-Fabricated Aluminum Products for Building & Construction.
Sommerhuber, P. et al.	2017	Life cycle assessment of wood-plastic composites: analysing alternative materials and identifying an environmental sound end-of-life option.
Khan M.et al.	2021	Environmental impacts of wooden, plastic, and wood-polymer composite pallet: a life cycle assessment approach.

2.5 Conclusion

The literature review has browsed different scientific articles in various fields. To have a better understanding of the benefits of each scientific paper, Figure 2.8 presents a summary of the purpose and technologies presented in each scientific paper:



	Purpose of the research	Polymer	WPC	3D printing	Sustainability
Rong Xiao et al. (2023)	HDPE in WPC for plastic waste valorization	HDPE	x		x
T. Tabarsa et al. (2011)	WPC from recycled materials	PP	x		x
J. Xu et al. (2021)	Ultra-high filled WPC performance study	PP	x		x
An. Yang et al. (2023)	Co-extruded high-filled WPC	PE	x		x
A. Elsheikh et al. (2022)	WPC progresses study	PE & PP	x		x
V. Goodship et a. (2016)	Design of WPC for multifunctionality	PE & PP & PLA	x	x	
J. Kananathan et al. (2022)	Mechanical properties of coconut-wood WPC	PLA	x	x	
F. Chen et al. (2022)	Heat treated esterified wood flour for WPC	PLA	x	x	
D. Kam et al. (2022)	Printing of wood "ink"	Pure wood		x	
Hottle, Troy (2015)	Solutions for waste handling of WPC	PLA	x		x
P. Sommerhuber et al. (2017)	Life cycle assessment of WPC	PLA	x		x
M. Khan et al. (2021)	Environmental impact of WPC vs wood pallets	PLA	x		x
This thesis		**PE**	**x**	**x**	**x**

Figure 2.8 Summary of the research purpose and and themes of each important article of the literature review

This chapter has proven that 3D printing is widely studied among the scientific community and, therefore, is getting more and more reliable as a fabrication process. Small-scale 3D printing has made much progress in terms of technology, while large-scale 3D printing is still being developed. Large-scale 3D printing is mainly studied for the construction field at the moment with concrete. However, recent studies have tried to adapt large-scale manufacturing with other materials, such as polymer-based composites. On the other hand, wood-based composites, especially those made with an injection molding process, have been widely studied and have astonishing properties such as very high wood filling in weight percentage, excellent mechanical properties, water resistance, and even flame retardance. However, wood-based composites used for 3D printing are still in development, and only very recent studies such as Koffi, A. et al.

(2022) work present wood-based composite with PE and good properties. However, 3D printable wood-based composite applications have not been published in recent studies and, therefore, represent a significant advance in the field of composite materials and 3D printing.

CHAPTER 3

OBJECTIVES, HYPOTHESIS AND BENEFITS OF THE WORK

The last two chapters have provided many insights and knowledge on the package and what is being studied about wood-based composites and 3D printing. Considering all the information gathered, it is possible to establish pragmatic goals for the project. In addition, in this chapter, we will outline the objectives, detail the hypotheses and methodology adopted for the gas turbine package project. On the other hand, it is essential to identify and present the study's limitations. Limitations of the current project are relevant to mention as wood and 3D printing have been chosen from many materials and process possibilities. Lastly, to wrap up this chapter, the importance of the work and benefits are presented to emphasize the sustainable aspect of the study.

3.1 Objectives and hypothesis

The project's primary goal is to conduct a **feasibility study** about using wood-based material and 3D printing to re-create a specific part of the air filter system of the gas turbine package, the combustion air inlet part. The feasibility study must prove that a focused part can be redesigned and manufactured sustainably out of wood-based composite while keeping all its functionality. The three main points to be focused on are the following:

- Create a digital 3D design of the combustion air inlet piece of the gas turbine package and lead numerical simulations of the design to find what mechanical properties the 3D printable composite material should respect.
- Create a 3D printable wood-based composite with the highest wood percentage in weight that respect the mechanical properties found previously and realize tests on the composite to evaluate its mechanical properties.
- Evaluate the sustainability of the composite material and compare the environmental impact of the new piece design made out of the wood-based material with the previous design made out of metal.

The requirements of the project presented in this thesis can be grouped into two categories: the requirements concerning the wood-based composite and the sustainability requirements. Therefore, concerning the wood-based composite, a feasibility study can be conducted to provide evidence that the air filter system-focused component, the combustion Air Inlet, can be redesigned by using wood-based 3D printable composite instead of steel. The piece must achieve all the technical and mechanical requirements fulfilled by the previous package. Moreover, on the sustainability aspect, besides the material cost, ease of transport, and weight reduction, the pieces should be sustainable regarding the Traci 2.0 assessment tool compared to the previous part used in the metal-based package.

3.2 Methodology

Following a methodology is crucial for completing a project successfully and efficiently. A methodology provides a structured approach to managing the project's various aspects. The methodology for this project involves three main parts, the design study, the composite material study and the sustainability assessment part of the project.

3.2.1 Design study of the components

This part involves analyzing the system's functional requirements, conceptualizing the design, and running simulations to evaluate numerically the mechanical needs of the material used to create the piece.

The functional requirements of the GT have been studied in Chapter 1, which contains the loads that can be applied to the GT, especially on the GT combustion air inlet part. Then, the main steps are the following :

- Creation of a digital model of the GT combustion air inlet : SolidWorks will be used to create a basic 3D model of the GT combustion air inlet. The basic design is strongly inspired by the previous meta-based Siemens package presented in Figure 1.1.

- Running simulations on the digital model : Abaqus will be used to evaluate the load impacts on the structure in terms of stress applied. First, a mesh is generated on the model with at first, quadratic elements of $0.1m$ size. Afterward, the loads are implemented in Abaqus, and numerical simulations are conducted to evaluate the impacts in terms of the maximum stress of each load.
- Running a convergence study to validate the model : once the maximum pressure that can be applied to the structure is found, a convergence study is realized to verify the model and precise the value of the maximum stress applicable to the package. The convergence study is conducted by analysing the maximum stress result depending on the mesh size. The convergence study gives the real value of the maximum stress and the optimized size of the elements in the mesh.

This method will give a numerical tensile strength value that will serve in the next part, the composite material study.

3.2.2 Composite material study

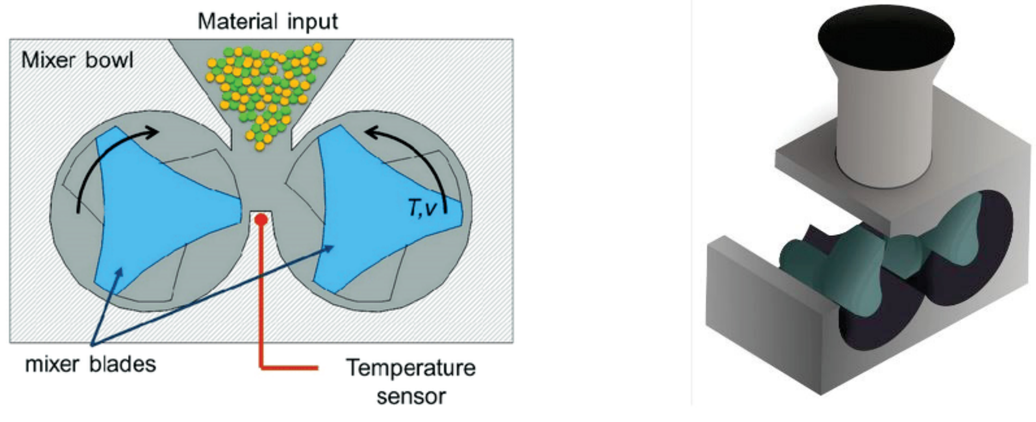
This part involves selecting and analyzing suitable materials for the 3D impression of the combustion air inlet. Once a material is chosen, an experimental part is led to create and 3D print this material. The 3D-printed material is then tested to evaluate its mechanical properties. The final mechanical results are compared with the mechanical requirements found in the design study.

Choosing a material is based on the literature review and the package requirements, where the most restrictive requirement is the twenty-year lifespan of the GT package. The composite material compound is then created by mixing dried wood, and PE treated with maleic anhydride. The objective of the experiment is to create eight different types of compounds and filaments. For the two types of wood dust sizes, a compound is created for 10, 20, 30, and 40% in weight. The different filaments then need to be characterized and compared before the 3D printing experiments.

Needed equipment and process

The equipment needed for the creation of the composite is the following :

- Vacuum Oven : The vacuum oven used is branded as Thermo Scientific™ vacuum oven. The oven can heat up to 220°C and has a vacuum range of 0 to 30 in.Hg.
- High speed mixer : A polymer mixer that can mix at high speed while heating. The mixer used is a HAAKE™ Rheomix mixer. The mixer working principle is presented in Figure 3.1.



a) b)

Figure 3.1 Functional schematic of the mixer used to mix the components

- Crusher : The crusher is a grinding machine that can crush a mixed solid composite into $1-2mm$ flakes following the process shown on Figure 3.2.

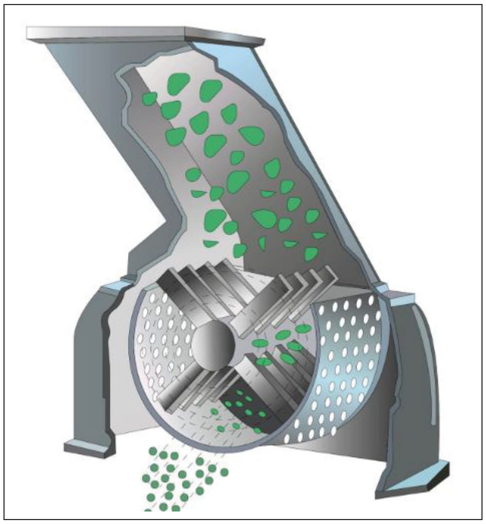
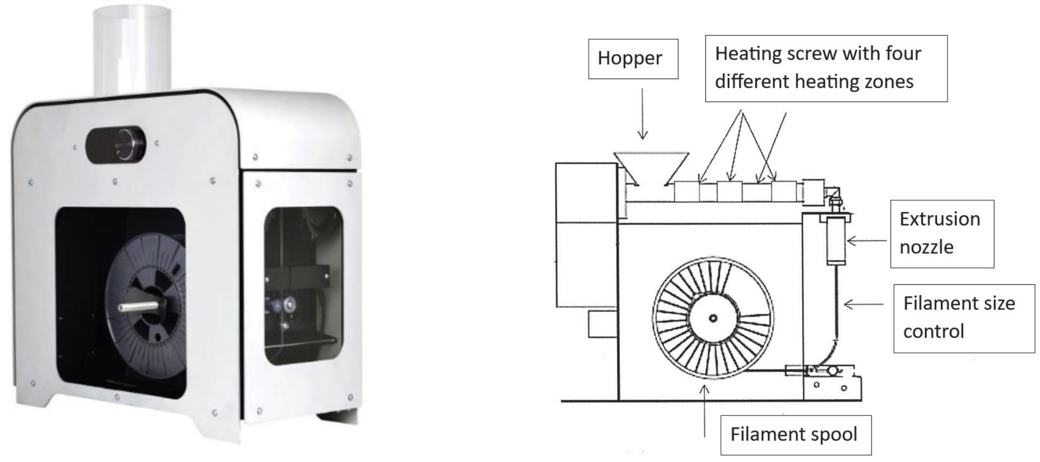


Figure 3.2 Crusher functional schematic

- Filament maker : The filament maker used is from the company 3Devo; a picture of the filament maker is presented in Figure 3.3. As shown in the Schematic Figure 3.3b, the 3Devo filament maker melts the composite through a four-heating zone screw, then extrude the composite into a filament and afterward control the size of the filament by measuring it. The size of the filament is adjusted by changing the extrusion speed.



a) 3Devo machine

b) 3Devo functional schematic

Figure 3.3 3Devo machine used to create composite filaments

Process for one batch of composite

The processing of the composite consisted of the following steps :

- Dry the wood in a vacuum drying oven at 120°C until moisture < 3% weight. To verify if the wood is well dried at <3% moisture, the wood is weighted after and before the drying session in the oven. The wood is put at 110°C in the oven and weighed every 30 minutes until the weight stabilizes.
- Mix all the components for 5 min in a high-speed mixer. The components are mixed at a very high speed at 180°C for 5 minutes. Wait for the mix to cool, and then crush the mixed compound in the crusher.
- Extrude the mix in an extruder and then create a filament with a filament maker.

Characterization of the composite filaments

The filaments created are characterized with the following characterization techniques :

- Differential Scanning Calorimetry analysis (DSC) : DSC is a thermal analysis that determines the temperature and heat flow associated with material transitions as a function of time and temperature. DSC analysis gives the exact melting point of the sample analyzed. A little sample ($< 0.5g$) is enough to conduct the analysis. The exact heat cycle used during the analysis is presented in Table 3.1.
- Thermogravimetric analysis (TGA) : TGA is technique for the measurement of thermal stability of materials. In this method, changes in the weight of a specimen are measured while its temperature is increased. This method will show the temperature at which the wood will decompose. A little sample ($< 0.5g$) is enough to conduct a TGA analysis. The heat cycle used during the analysis is presented in Table 3.1.
- Melt Flow Index measurements (MFI) : MFI is a simple measurement of the quantity of material pushed through a die of specified dimensions at a set temperature within 10 min. MFI measurement gives the fluidity of the material and will help to evaluate the printability of the different composites.
- Scanning Electron Microscope pictures (SEM) : SEM is a test process that scans a sample with an electron beam to produce a magnified image for analysis. SEM images will show

the microstructure of the filaments and give ideas of how the wood is integrated in the polymer matrix.

Table 3.1 Summary of the characterization techniques used on the filaments

Technique	Specification
Differential Scanning Calorimetry (DSC)	The heat cycle used in the experiment is the following : - Equilibrate to 40°C - Ramp at 10°C/min to 200°C - Isothermal segment of 1 min - Ramp at 10°C/min to 50°C
Thermogravimetric analysis (TGA)	The heat cycle used is heating from 40.00°C to 580.00°C at 10.00°C/min.
Melt Flow Index (MFI)	Test realized at 190°C with a weight of 2.16Kg
Scanning Electron Microscope (SEM)	As the polymer is not conductor, the samples are covered in gold before experiment.

3D printing of the composite and experiments on the composite samples

The last step is to 3D print samples with the filament to evaluate the mechanical properties of the composites. The 3D printer used to 3D print the samples is a Prusa i3 MK3S. Two types of samples are printed for two different printing temperatures, and each type of sample is printed three times for each filament. The samples are printed at a printing speed of 45mm/s except for the initial layer, which is printed at a lower speed of 25mm/s to ensure that the initial layer is sticking to the building plate. The samples are printed at 190°C and 200°C, the layer height is set at 0.3mm, and the temperature of the build plate is 40°C. The layer height, printing speed, and building plate temperature have been chosen by reading different articles about 3D printing and realizing experiments on pure PP printing.

- Tensile sample: The tensile sample geometry is presented in Figure 5.7. The objective is to realize a tensile test on the sample to obtain a Stress/Strain curve. The stress/strain curve gives the Young modulus and the maximum tensile strength of each sample. The Young modulus is obtained by measure the slope of the linear zone of the curve while the maximum strength is given by the maximum stress the sample can handle without breaking.
- Density sample: The density sample is a $1x1cm$ cube with 100% infill. The sample is weighted to obtain the density of the composite. Because the printed cube has a volume of $1cm^3$, the weight of the cube directly gives the density in g/cm^3.

3.2.3 Sustainability assessment of the composite material and designed structure

This part involves evaluating the environmental impact of the created composite material, considering factors such as the carbon footprint, recyclability, and other indices that assess the project's impact on air and water by using the TRACI v2.1 assessment method. The TRACI assessment method consists on assessing the impact of a material regarding the following categories :

- ATMOSPHERE RELATED INDICES
  - Global Warming Potential: Refers to the greenhouse gases in the atmosphere. It can cause changes in the global weather over the years. Quantified in terms of Kg of CO2 equivalent.
  - Ozone Depletion Potential: The attenuation of the ozone layer, which protects the earth and humans from air pollution. Quantified in terms of Kg of Kg Chlorofluorocarbon (CFC-11) equivalent.
  - Photochemical Ozone Creation Potential (Smog): Hydrocarbons, nitrogen, and oxides react with sunlight to create air pollution. Quantified in terms of Kg Trioxide (O3) equivalent.
- WATER RELATED INDICES

- Acidification Potential: It is the result of human wastes rejected in water, which increases the acidity of oceans, lakes, and streams. It also decreases the PH of water. Quantified in terms of Kg of Sulfur Dioxide (SO2) equivalent.
- Eutrophication Potential: "Excessive nutrients cause increased algae growth in lakes, blocking the underwater penetration of sunlight." It results in a loss of aquatic life. Quantified in terms of Kg of Nitrogen (N) equivalent.

The environmental impact of the 3D-printed combustion air inlet is then compared with the ecological impact of the metal-based one previously used by Siemens to conclude the presented work by using the same TRACI method.

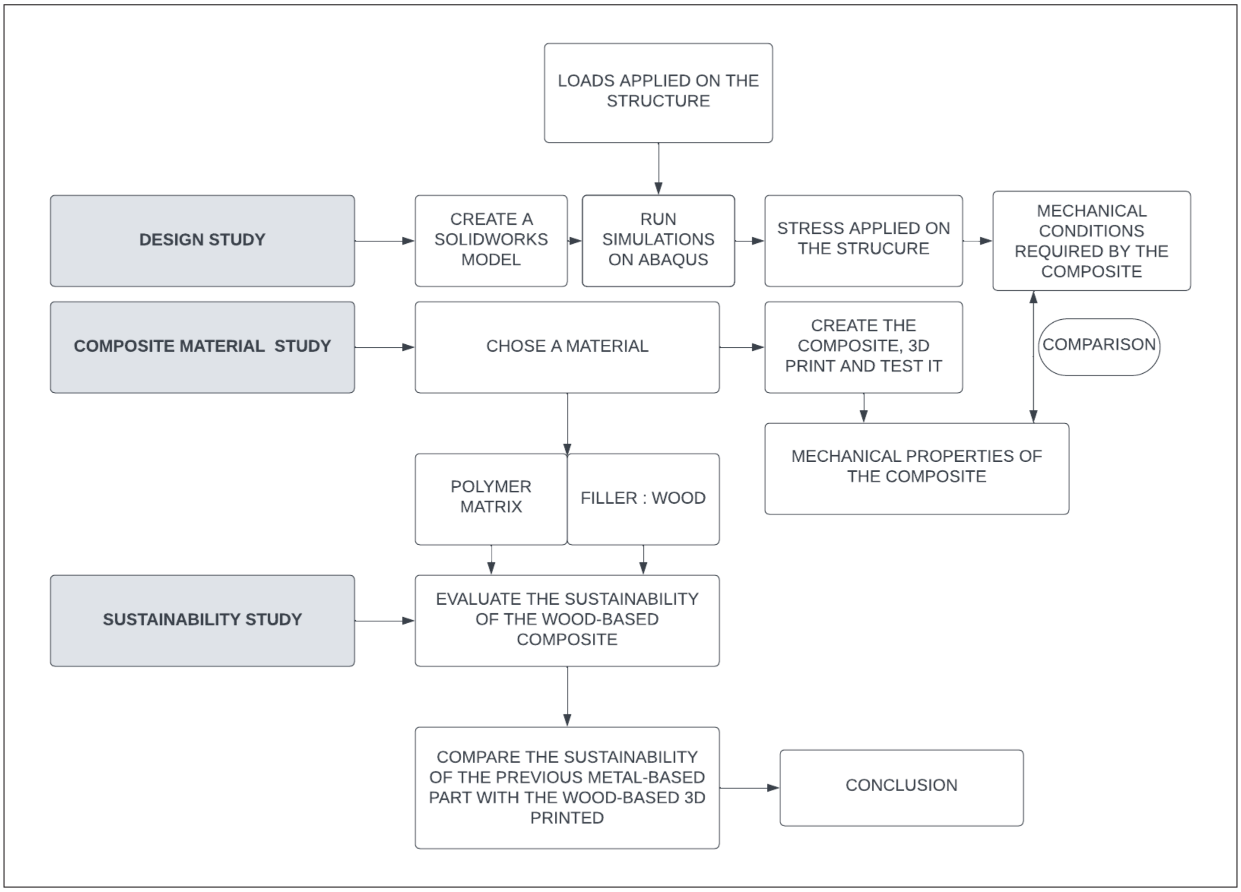


Figure 3.4 Summary flowchart representing the different aspects of the project

By combining these design part, the material study part, and the sustainability assessment part, the current project aims to create a sustainable and efficient redesigned combustion air inlet that meets the project's requirements.

3.3 Project requirements

This project is based on wood as a given by Siemens Energy. However, the composite material field is wide, even in the 3D printing application. Many different materials can be used for 3D printing, such as durable nylon, ABS (acrylonitrile butadiene styrene), ASA (Acrylic Styrene Acrylonitrile), Elastomers, etc. In addition, many other fillers than wood exist for a specific polymer matrix, such as glass powder, egg shells, and others. A polymer matrix made out of PP or PE has been chosen to create a wood-based composite.

On the other hand, in this study, only a few composite material properties have been evaluated. The main goal of the experiments is to see the 3D printability, the microstructure, and the mechanical properties of the composites. However, other parameters need to be evaluated for a more complete study, such as the composites' water absorption, UV degradation, fatigue resistance, and flammability. These properties need to be evaluated in a further study. The feasibility study conducted in this project aims to prove that Siemens Energy, in particular, can use the studied wood-base composite material for its package. The composite should be studied in more detail for more applications and other uses. Lastly, in terms of processes, the FDM 3D printing process has been chosen as the primary process for the study. Many other additive manufacturing processes exist, such as laminated object manufacturing or binder jetting, and could be suitable for creating wood-based composite material.

3.4 Importance of the work and benefits

Additive manufacturing, especially 3D printing, is a technology in development that is interesting to search for. 3D printing technology has a wide range of applications, including composite material. The efficiency and cost-effectiveness, particularly for complex parts, make it a sage choice of process for industries. Therefore, innovations in this field can lead to significant advances in the industries and the material area.

On the other hand, using sustainable materials has clear environmental benefits. That can include reducing greenhouse gas emissions and many other aspects discussed in the sustainability part. Using recycled wood can save much material from waste and create more sustainable composites. Lastly, using wood-based composite can mean cost savings, innovation leads, and a good reputation for a company.

Overall, using the 3D printing process combined with sustainable wood-based material has many benefits for the environment but also for industries and individuals who want to make progress and positively impact the world around them.

CHAPTER 4
DESIGN STUDY OF THE GT COMBUSTION AIR INLET

As presented before, the project's first step is the design study of the focused piece from the Air filter system and ducts part of the gas turbine package. The combustion air inlet has been chosen as the focused piece for its relatively complex geometry, making it a good candidate for 3D printing geometry improvement. Moreover, the combustion air inlet piece has dimensions of 3.5 x 2.0 x 1.5 meters, making it a large piece and thus a viable piece to improve as a geometry update would save a lot of weight and material. The Air filter system, as presented before, ensures clean air to the core and ventilation. On the other hand, the inlet ducting provides an inlet plenum to direct motive air into the turbine. In the previous package, made out of metal materials, the design of the combustion air is presented in Figure 4.1. This design is extracted from Figure 1.1 :

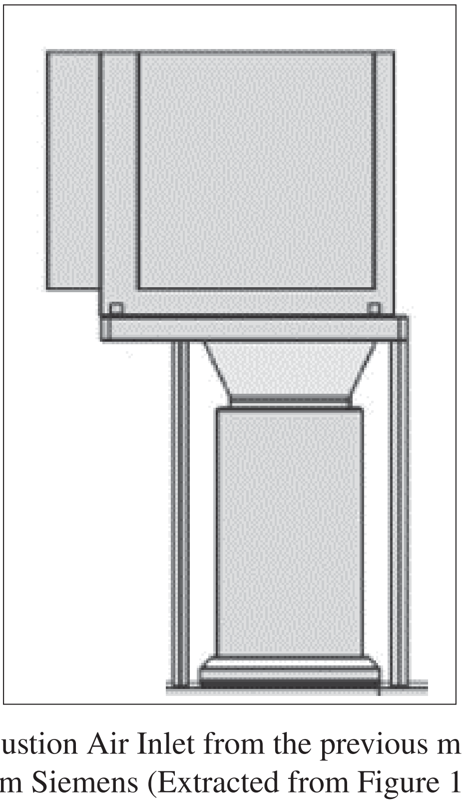
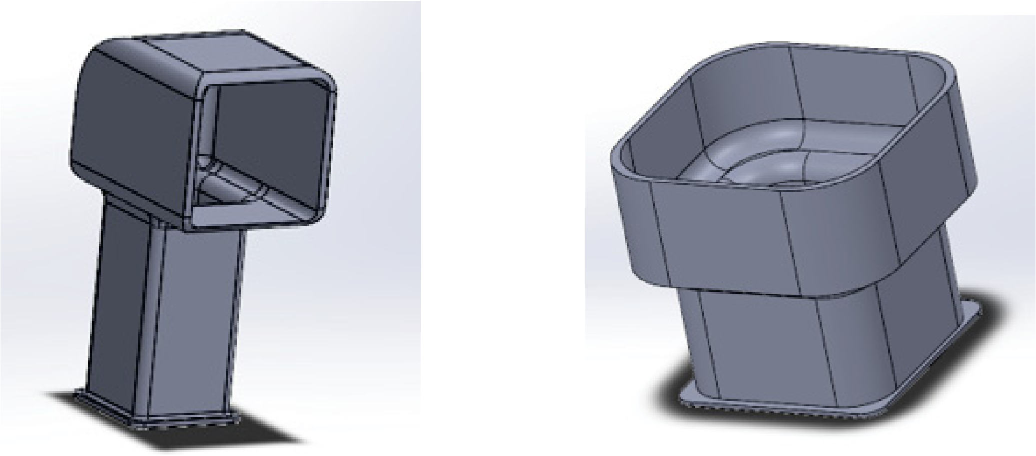


Figure 4.1 Combustion Air Inlet from the previous metal based package from Siemens (Extracted from Figure 1.1)

4.1 Basic 3D model of the combustion air inlet

The objective of the design study is to re-design the combustion air inlet of the Air filter system to make it suitable for 3D printing, use less material, be more resistant, and keep the airflow needed for the turbine. The Additive manufacturing process allows design freedom and, therefore, makes more complex shapes possible compared to traditional manufacturing/fabrication techniques. Thus, the objectives of printability and weight reduction are realistic.

Here are two basic 3D models for the two components presented before. These designs are close to the previous ones. The designs are to be improved later on in the project. However, for the first simulation, these two basic designs will give a good idea of what needs to be improved.



a) First 3D model for the Combustion Air Inlet

b) First 3D model for the Ventilation Air Inlet

Figure 4.2 First 3D models for two different pieces of the package air filter system

The primary 3D model of the combustion air inlet is based on the previous package air filter design presented in Figure 1.3. These models have been developed by following the same geometry and size as the previous metal-based pieces from the metal-based package from Siemens Energy. Therefore, this model has yet to be improved in terms of properties for 3D printing and weight optimization. Ideas of more elaborated designs will be presented later in this chapter; however, the design part is not the central point of the project, and the geometry presented in Figure 4.1 will be the primary geometry taken as reference for simulations. At first, this model will be used for numerical simulations to see the effects of the loads on the piece and have an idea of what part of the piece has to be reinforced.

4.2 Numerical simulation analysis

The numerical simulation analysis part of this chapter is based on the previously presented basic design of the combustion air inlet in Figure 4.2. As previously explained, this numerical simulation aims to understand better the geometry and the effects of the loads on the geometry. First of all, the mechanical properties used for the materials in the simulations will be taken from a company named GreenDotBioPlastics.The simulations will give the stress impact of the loads applied on the combustion air inlet. An absolute maximum stress that can be applied to the structure will be found and Chapter 5 will conclude on the composite suitability for the Siemens Energy gas turbine package project.

4.2.1 Mechanical properties of the material

To realize a simulation of the designs presented previously, mechanical properties of a material need to be used. The design chapter was realized before the experiment chapter. Thus, the material properties of the wood-based composite were unknown. It is known that the objective is to use a wood-polypropylene or wood-polyethylene composite. Terratek GreenDotBioPlastics, which sells Wood-polypropylene composites, has been chosen to get realistic value. The mechanical properties of one of their product containing 30% wood in weight named $Terratek\_NF3010$ will be mentioned later.

However, these mechanical properties given by Terratek and presented in Table 4.1 have been measured for components created with the injection molding process. As mentioned in the literature review, pieces manufactured out of injection molding have more excellent properties than 3D-printed pieces. Thus, the values used for the simulation are overestimated. However, the stress applied to the structure by the loads is independent of the material properties. Thus, the simulations and the analysis are conducted to show the effects of efforts on the part, and only the stress values will be kept as results. Once the composite material experimental part is done, the tensile strength of the composite will be compared with the maximum stress found in this section.

Table 4.1 Mechanical properties of the $Terratek\_NF3010$ composite by GreenDotBioPlastics

Properties	Value
Density	$1030Kg.m^{-3}$
Young Modulus	$2.482Gpa$
Poisson's ratio	0.2
Elasticity Modulus	$1.379Gpa$
shear Modulus	$1.034Gpa$

4.2.2 Boundary conditions, loads and mesh

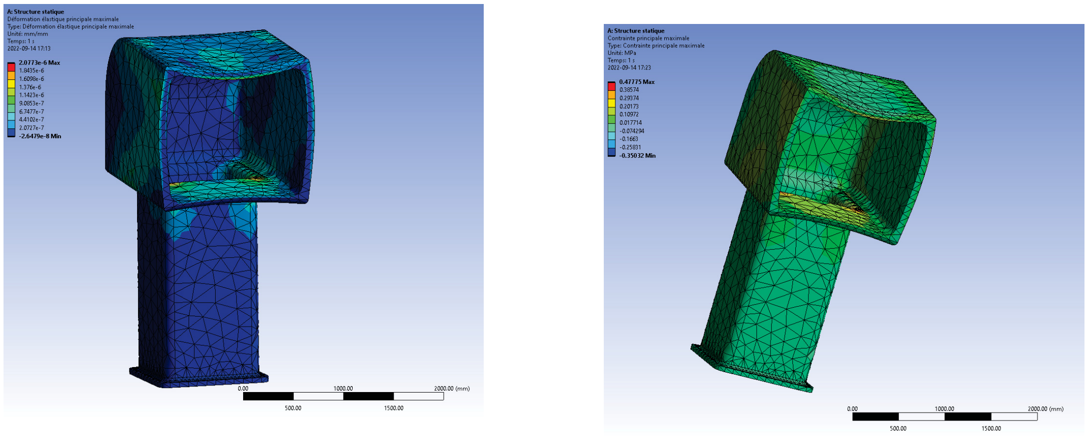
The objective of the section is to realize the first simulations to understand the weak points of the geometries. The possible loads that could be applied to the package are the following these loads are given by Siemens :

- A snow load value of $2.5kN/m^2$ on the roof of the package
- A Wind load applied on the exposed surfaces of $1.0kN/m^2$.
- An acceleration load of $0.5g$ lateral due to seismic activity and an acceleration load of $4.0g$ vertical due to transport of the package.

An automatically created mesh by Abaqus with quadratic elements has been used to realize the simulation. In order to choose the size of the elements, first, a $0.1m$ element size was used to witness which load would apply the most stress on the structure. Afterward, a convergence study is realized to define the elements needed for significant results.

4.2.3 Results

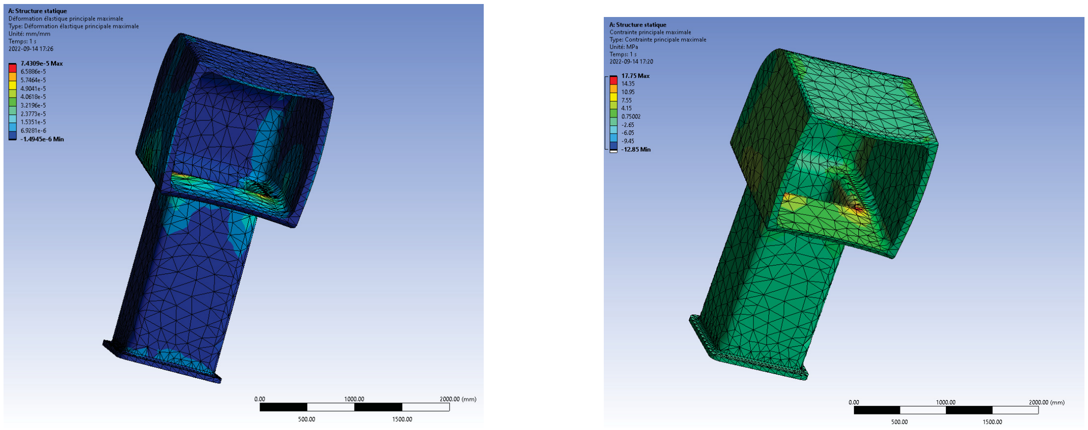
The results are presented for each load independently as Transport loads are not possible to stack with the wind and snow loads, and snow and wind loads are not applied on the same side of the piece. Figure 4.3 and Figure 4.4 presents the visual aspect of the simulations while Table 4.2 presents the important results, the stress values applied by each load on the structure.



a) Deformation due to Snow load of $2.5kN/m^2$ applied on the roof. Maximum deformation : $2.07 * 10^{-6}$mm

b) Mechanical Stress due to Snow load of $2.5kN/m^2$ applied on the roof. Maximum Stress : $0.47MPa$

Figure 4.3 Snow load effect on the 3D model of the combustion air inlet



a) Deformation due to vertical acceleration load of $4.0g$. Maximum deformation : $7.4 * 10^{-5}$mm

b) Mechanical stress due to vertical acceleration load of $4.0g$. Maximum Stress : $17.5MPa$

Figure 4.4 Transport acceleration load effect on the 3D model of the combustion air inlet

Table 4.2 Stress value applied on the strucutre by each load

Load	Stress applied on the structure
Snow load	$0.47MPa$
Wind load	$0.62MPa$
Transport acceleration load	$17.5MPa$

The maximum deformations of the model for each load are low as the mechanical properties of the material used are overestimated. Therefore, the deformation values will not be used. However, the results allow us to see the weak points of the structure and the maximum stress applied to the structure for each load. For the snow load, as can be seen in the Figure 4.3 the roof of the piece is bending, while the basis of the piece is the weak point for the wind load. Lastly, the abrupt angle in the interior is the main issue for the transport acceleration load stress impact present in Figure 4.4 and can be solved with a smoother geometry design. In the end, the stress applied by the acceleration load is by far the most predominant condition for the material to respect. The value of 17.5 MPa is first to be verified by model validation and then will be used as an objective for the tensile strength of the composite in Chapter 5.

4.2.4 Validation of the model

In order to verify the relevance of the model and the results, there needs to be a verification of the convergence of the results with the element size of the mesh. Thus, the model will be verified, and at the same time, the optimized element size for the mesh can be observed. As can be seen from the previous results, the transport load applies the most stress on the structure. What will be studied is the evolution of this maximum stress depending on the element size of the mesh.

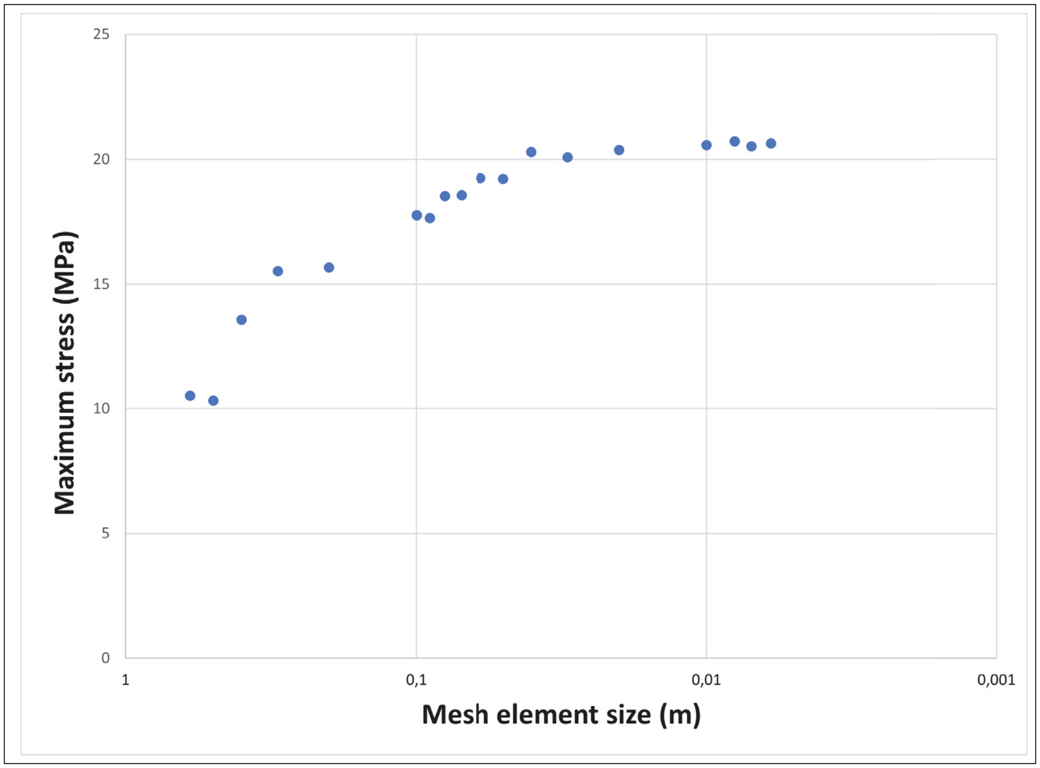


Figure 4.5 Evolution of the maximum stress applied by the transport load depending on the element size of the mesh

As the convergence study show in the Figure 4.5, the results for the maximum stress stabilize for elements sizes smaller than $0.05m$. The result of the maximum stress is then around $20Mpa$, which is higher than the $17Mpa$ obtained before with the $0.1m$ element size.

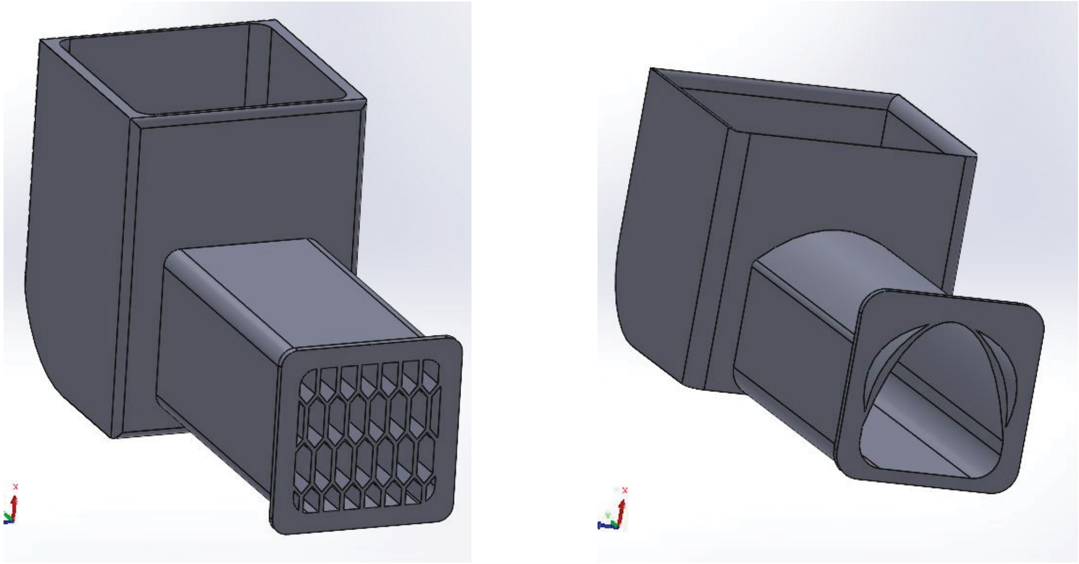
4.2.5 Discussion and Conclusion on what to improve on the models

As can be seen in Figure 4.5, the most restricting load is the transport load of $4.0g$ vertical, applying a mechanical stress maximum of $20Mpa$. The mechanical stress applied to the structure is independent of the characteristics of the material. Therefore, this $20Mpa$ stress is relevant for the rest of the project. The other loads, the snow and wind loads, apply slight pressure on the structure. Considering that the most critical points are the points colored in red in Figure 4.4b. The peak of stress is due to the rough angle in the structure. Considering the fact that additive manufacturing allows the creation of less angular shapes, the solution to that problem can be solved with a less abrupt design.

The clear objective of the composite material-making aspect of the current project is to create a wood-polypropylene composite with the highest wood percentage in weight while maintaining a tensile strength above $20Mpa$. The value of $20Mpa$ will evolve with the design improvement of the components.

4.3 Ideas of more elaborate models

The first 3D model presented just above will be used for the first simulations on Abaqus. However, the design of the components is meant to evolve and improve as long as the global Siemens gas turbine package project is progressing. Therefore, here are presented in Figure 4.6 some improved designs created for the Combustion Air Inlet component.



a) Honeycomb inspired design

b) Arch inspired design

Figure 4.6 Ideas of design aiming to improve the printability of the structure

The printability and mechanical properties of improved design are still to be studied but shall improve compared to basic designs. However, these designs have negative aspects. Adding structure in the air gateway adds weight and reduces the cross-section and, thus, the airflow.

One path of improvement that must be studied is weight reduction. As will be mentioned in the global conclusion and the material chapter conclusion, weight reduction is the central point of the design study to make the structure more sustainable regarding the environment. Less weight means less material, which reduces the CO2 emissions of the project. One way to reduce the weight of a 3D-printed structure is to optimize the structure in order to 3D-print the walls with a low percentage of infill. A structure can be printed with a 20% infill while keeping good mechanical properties. However, when 3D-printing large scale structures, other design requirements are demanded. Hence, it should be noted that this preliminary design study is designed for small scale processes only.

The honeycomb structure is promising. This type of structure improves the design in terms of 3D printability and mechanical properties. Honeycomb structures are already widely studied as a solution for 3D printing structures among scientific studies. (Sheedev Antony et al., 2020) (Chun Lu et al., 2018).

4.4 Future work on design and expected results

The improved designs are still to be analyzed with Ansys in the same way as the basic designs. Also, the weight added by these designs will be considered in the last chapter to evaluate the weight change and environmental impact of the parts. An optimized, improved design should include weight reduction, improvement of printability properties, and airflow optimization. On the other hand, an airflow analysis should be led to understand how the honeycomb structure changes the airflow in the duct. Then, this air flow should be compared with the previous metal design used by Siemens Energy.

For the results, improved designs are expected to show better mechanical properties and 3D printability while changing the airflow in the duct and adding weight to the structure. These changes need to be evaluated according to the Siemens requirements and evaluated to determine whether these designs are to be implemented.

CHAPTER 5
ADDITIVE MANUFACTURING OF WOOD FIBERS COMPOSITES

The experimental aspect of the current work is composed of three main phases: the first phase is about wood-based composite manufacturing, the second phase is the 3D printing experiments, and the last comes to the results, the analysis of the results, and some discussions. The current chapter is essential for the project developed in this work as the results of the 3D-printed test parts will give an idea of the composite's potential for Siemens Energy. The first section presents the components of the wood-based composite compound, the experimental plan for composite manufacturing, and the characterization of the filaments made out of the compounds. As the main objectives, the composite must be easily 3D printable, have as much wood in weight percent as possible, and show mechanical properties, especially tensile strength, that satisfy the conditions at the end of the design section.

5.1 Wood-based composite components and experimental process

The first section of this chapter discusses the creation of the wood-based composite compound and the characterization of the compound. First, the composition of the composite, the machinery needed to create the compound, and the process of creating the compound. A second time, the filaments made out of the compound will be characterized with Thermogravimetric analysis (TGA) analysis, Differential Scanning Calorimetry (DSC) analysis, Melt Flow Index (MFI) measurements, and images of the filament cross-section taken with a scanning electron microscope (SEM). TGA, DSC, and MFI results will help to understand the suitability of the filaments for 3D printing, while SEM images reveal the microstructure of the composite.

5.1.1 Wood-based composite compound and filament making

To achieve this WPC, wood dust and polymers will be used. This section will show the experimental plan and process to create the composite. The objective of the experiment is to create wood-based composites with wood dust and polymers for different percentages of wood dust and different sizes of wood dust and evaluate the properties of the composites.

Components of the composite

The composite comprises three main ingredients: a polymer, a wood flour, and a binding agent. The polymer chosen for the experiment is polyethylene. The reference polymer is Fusabond MA-M603, which already contains maleic anhydride as a binding agent. This polymer is commercialized by Dupond and created for Plastic composites. The second ingredient is wood flour. The wood used is recycled wood obtained in a laboratory at McGill and has two sizes. One wood flour is $< 100\mu m$ and will be referred to as the "fine" wood, and the other is $0.5 - 1mm$ and will be referred to as the coarse wood. The components of the composite are summarized in Table 5.2. Only the filaments made with fine wood will be 3D-printed at a small scale due to the filament size of 1.75mm.

Table 5.1 Components of the composites summary

Material	Specification
Polyethylene treated with maleic anhydride	Polymer used as a matrix commercialized by Dupond, already mixed with maleic anhydride. Specific name : Fusabond MA-M603. - Density : $0.94g/cm^3$ - Melt Flow Rate : $25g/10min$ - Melting Point : $108°C$
Fine wood dust	Recycled wood dust from McGill laboratory. Size $< 100\mu m$
Coarse wood dust	Recycled wood dust from McGill laboratory. Size $0.5 - 1mm$

The Maleic Anhydride binding agent is used to ensure better compatibility between the wood flour and the polymer matrix. Studies already have been led to evaluate the impact of either polymer treated with maleic anhydride or wood flour treated with maleic anhydride on the properties of WPC.(S. Nenkova et al.,2014)

Process for one batch of composite

The processing of the composite consisted of the following steps, these steps are using the equipment presented in the methodology section :

- Dry the wood in a vacuum drying oven at 120°C until moisture < 3% weight. To verify if the wood is well dried at <3% moisture, the wood is weighted after and before the drying session in the oven. The wood is put at 110°C in the oven and weighed every 30 minutes until the weight stabilizes.
- Mix all the components for 5 min in a high-speed mixer. The components are mixed at a very high speed at 180°C for 5 minutes. Wait for the mix to cool, and then crush the mixed compound in the crusher.
- Extrude the mix in an extruder and then create a filament with a filament maker.

The objective of the experiment is to create eight different types of compounds and filaments. For the two types of wood dust sizes, a compound is created for 10, 20, 30, and 40% in weight. The different filaments then need to be characterized and compared before the 3D printing experiments.

Four different composites were obtained, two the fine wood and two with the coarse wood. Composites with 10% and 20% wood in weight were processed. Table 5.2 summurizes the four different composite obtained during the experiments.

Table 5.2 Components of the composites summary

Type of wood	Percentage of wood
Coarse wood dust	10% 20%
Fine wood dust	10% 20%

5.1.2 Filaments results and characterization of composite filaments

The filaments with 10% and 20% wood have been realized without difficulties, while the 30% wood filament has been made but cannot stay in a filament form due to too high rigidity, and the 40% could not even be mixed in the mixer due to the wood flour and the polymer not mixing together. A change in the binder quantities is to be investigated in a subsequent project for the 30% and 40% compounds. In fact, adding more binder could help creating composite with higher percentage of wood. For this project, the 10% and 20% filaments will be studied and tested.

After each filament is crafted, each filament needs to be evaluated to know its characteristics and have an idea of its printability. To realize that objective, each filament is studied with different characterization techniques presented in Table 3.1.

Thermogravimetric analysis (TGA) and Differential Scanning Calorimetry (DSC)

TGA is a method of analysis that measures a sample over time as the temperature changes. This measurement provides information about what phenomena occur during the heating of the material. DSC is a thermoanalytical technique in which the difference in the amount of heat required to increase the temperature of a sample and reference sample is measured.

In this precise case, the TGA and DSC tests will show the melting point of the composite and the temperature at which the wood in the composite will decompose. The heating cycles used for the experiments are precised in Table 3.1.

This test is critical as it will show the maximum temperature at which the different composites can be printed. Wood fibers decompose and have significant weight loss at an exact temperature. In order to 3D print wood, this precise temperature must be maintained, or the composite could lose all its mechanical properties.

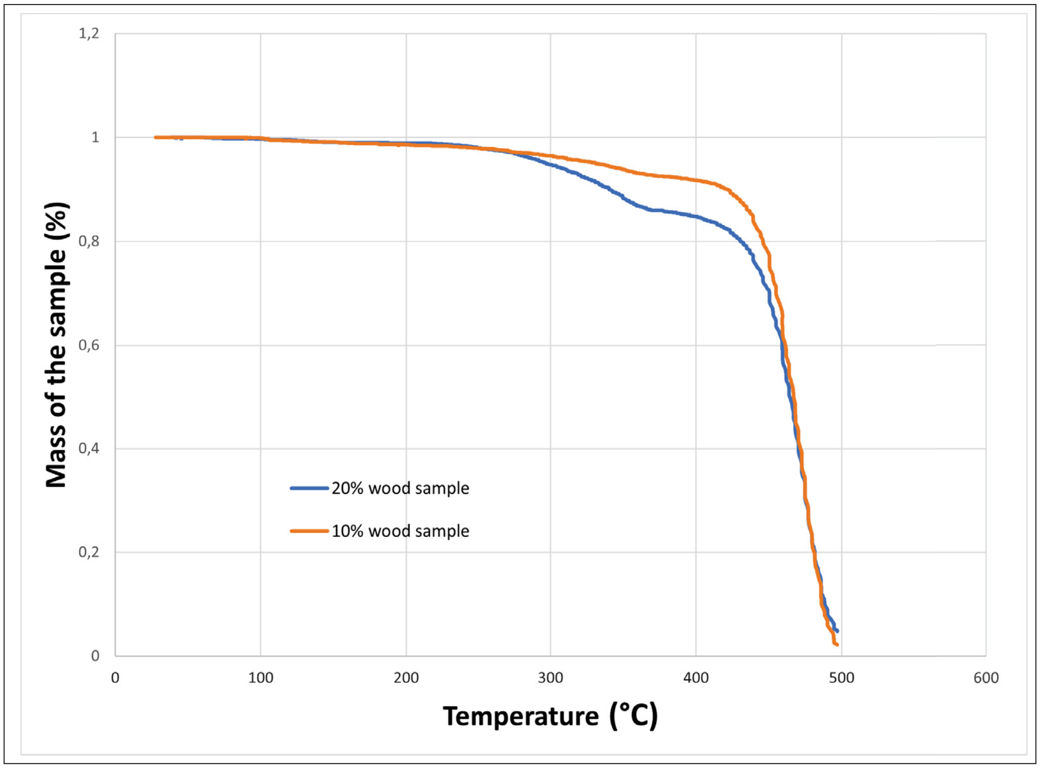


Figure 5.1 Typical TGA results for 10% and 20% wood samples

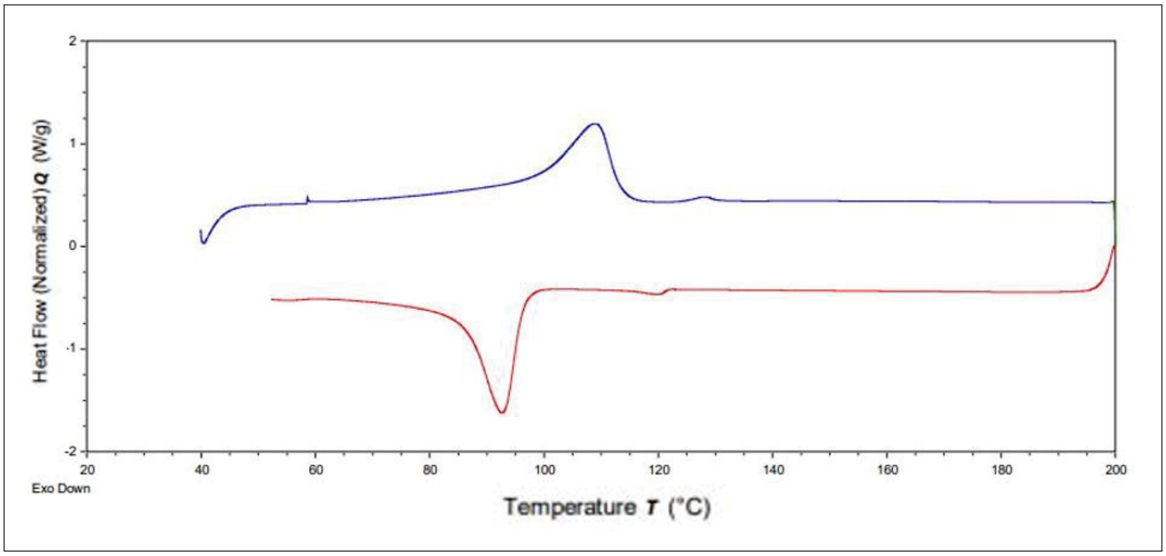


Figure 5.2 Typical DSC curve result obtained with a 20% fine wood sample

Table 5.3 Raw data obtained after TGA experiments on different filaments

Sample	Percentage of weight lost at 420 °C
10% fine wood	10.0%
20% fine wood	17.6%
10% coarse wood	6.0%
20% coarse wood	24.4%

Table 5.4 Raw data obtained after DSC experiments on different filaments

Sample	Maximum Heat flow (W/g) and corresponding temperature (°C)	Minimum Heat flow (W/g) and corresponding temperature (°C)
10% fine wood	1.396 W/g at 109 °C	-2.104 W/g at 92 °C
20% fine wood	1.196 W/g at 109 °C	-1.62 W/g at 92 °C
10% coarse wood	1.476 W/g at 110 °C	-1.947 W/g at 92 °C
20% coarse wood	0.969 W/g at 109(°C)	-1.562 W/g at 92 °C

The difference between 10% and 20% wood is noticeable in the TGA curves; the 10% wood sample has lost approximately 10% of its mass by 400°C area while the 20% wood sample lost around 20% of its mass in the same area, as it can be seen in the typical TGA curve presented in Figure 5.1. As it can be seen in Table 5.3, this observation is accurate for the fine wood filaments but not for the coarse wood filaments. As the wood is not well distributed in the coarse wood filaments, a 4g sample of filament has a low chance of containing exactly 10% or 20% of wood. Another observation within the TGA curves is the section where the wood is decomposed.

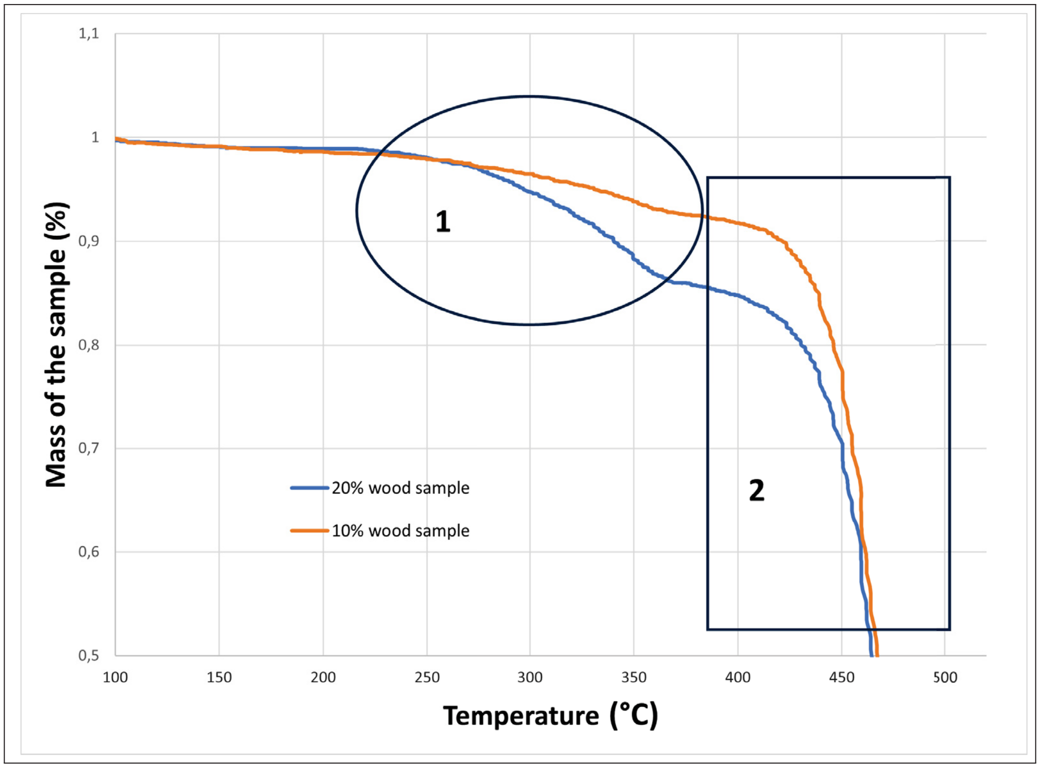


Figure 5.3 Recognition of the two phases, the decomposition of the wood and the decomposition of the PE

As can be seen in Figure 5.3, the phase where the wood is decomposed can be recognized by a linear slope in zone 1, while in zone 2, the curve follows a classic TGA PE decomposition curve. On the other hand, the difference between the 10% and 20% wood samples in the DSC curves is barely noticeable; Figure 5.2 and Table 5.4 present no noticeable difference between the 10% and the 20% composite samples. The tendency shown by the raw data is that adding more wood into the composite lowers the maximum and minimum heat flow reached by the DSC curves. Otherwise, no other significant observation can be made out of the DSC curves and raw data results.

Melt Flow Index (MFI)

MFI is a simple measurement of the quantity of material pushed through a die of specified dimensions at a set temperature within 10 min. MFI results will give information about the printability of a material. In order to 3D print material, this material must have a sufficient melt flow index to be 3D-printed. High MFI value is essential in high-speed 3D printing, which is not true in these experiments. However, a value of MFI that is too low could affect 3D printing. A typical acceptable range for MFI value for 3D printing by FDM is 5 to $30g/10min$ (Wang et al., 2018; Pascual-González et al., 2022). The MFI experiments have been repeated ten times for each composite, Figure 5.4 shows the principle of a MFI measurement while Table 5.5 presents the MFI results :

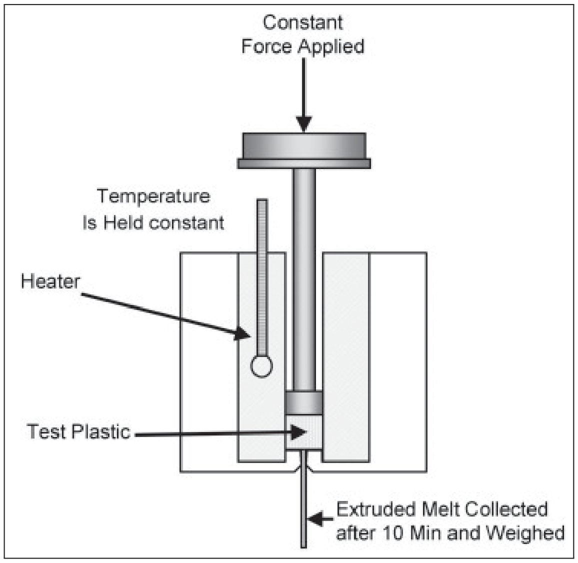


Figure 5.4 Schematic of the MFI measurment process

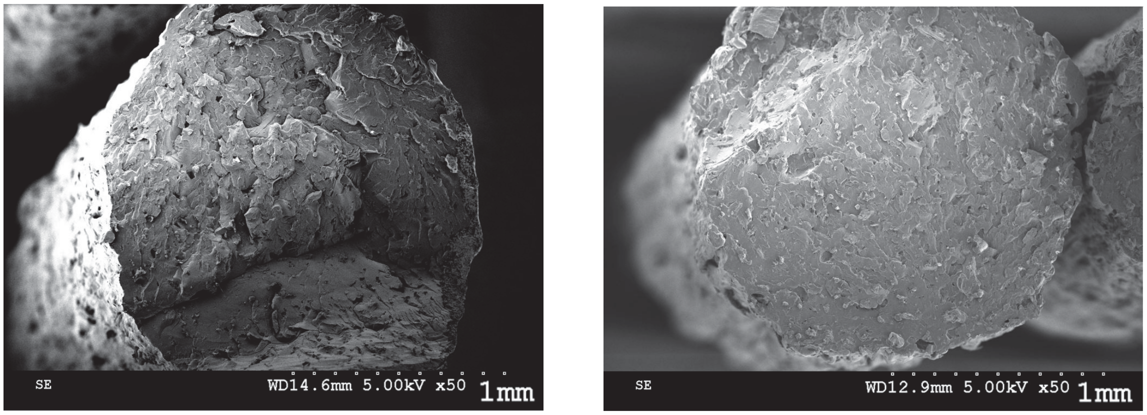
Table 5.5 Summary of obtained values from MFI testing of wood composites. Tested at 190°C/2.16kg

Composite	MFI value (g/10min)
10% fine wood	[13-15]
20% fine wood	[4-6]
10% coarse wood	[13-15]
20% coarse wood	[4-5]

As can be seen in Table 5.5, adding more wood to the composite drastically reduces the MFI of the final product. Low values of MFI will such as $5g/10min$ obtained in the experiments will be acceptable in this project as we use FDM 3D printing at low printing speeds, such as $45mm/s$ (Wang et al., 2018). However, the printability of the composites still needs to be verified in the experimental part of the project.

Scanning Electron Microscope pictures of the filaments

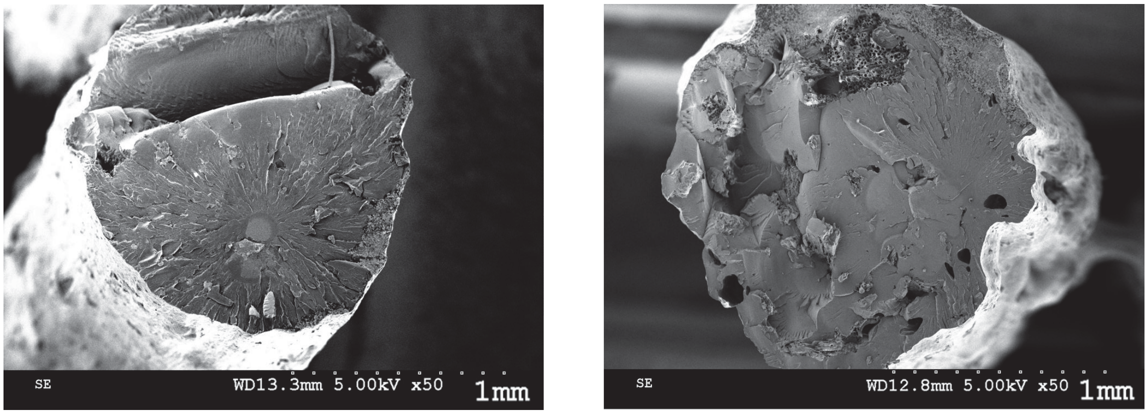
The two different filaments, the one with fine wood flour up to $100\mu m$ and the one with coarse wood flour of 0.5 to $1mm$, have been broken with liquid nitrogen to reveal clean cross sections. The cross sections were covered with gold and then observed with a scanning electron microscope. The results are presented in Figure 5.6 and Figure 5.7 :



a) 10% wood filament with fine wood flour, cross section view

b) 20% wood filament with fine wood flour , cross section view

Figure 5.5 SEM pictures of 10% and 20% wood-based filaments with fine wood



a) 10% wood filament with coarse wood flour, cross section view

b) 20% wood filament with coarse wood flour, cross section view

Figure 5.6 SEM pictures of 10% and 20% wood-based filaments with coarse wood

As expected, the two filaments made out of the fine wood ensure a better distribution of wood dust than the filaments made out of the coarse wood. At this scale, it is essential to 3D print with fine wood as it provides a better distribution of the wood. For the fine wood size and printer head, the maximum wood size is seventeen time smaller than the size of the filament at small-scale 3D printing. With this ratio, a good distribution of the wood can be expected. It can be seen in Figure 5.5 that fine wood effectively has a good distribution within the filament. However, the coarse wood at its maximum can be almost half the size of the filament, and then cannot be 3D-printed at a small scale, as can be seen in Figure 5.6a.

5.2 3D printing experiments

This section discusses the tests of the filaments created in the previous part on a small-scale 3D printer. The 3D printer used was a Prusa i3 MK3S+. The objective of this part is to see the printability of each filament, the density of the printed material, and the Young modulus of the 3D-printed composite material. The 3D print will be realized with two different temperatures, 190°C and 200°C. However, before the tests with the wood-based filaments, a first experiment on polypropylene filaments was conducted to evaluate the effect of temperature and layer size on the printed part properties.

5.2.1 First experiment on polypropylene

First of all, an experiment is realized on pure Polypropylene to better understand the impact of the 3D printing parameters. The study on Polypropylene evaluates the impact of:

- Printing temperature
- Thickness of the layers

Set of parameters :

- Temperature : $220°C$ and $240°C$
- Layer Height: $0.1mm$ and $0.3mm$

The objective is to print three tensile specimens and three density specimens for each set of parameters, leading to 12 specimens for each tensile and density test. For the density test, a $1x1$ cm cube is printed and weighted; for tensile test the Figure 5.7 presents the tensile specimen given by the standard ISO-527A-5A.

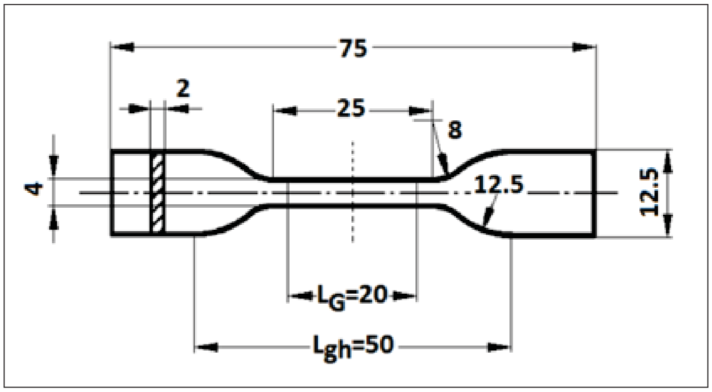
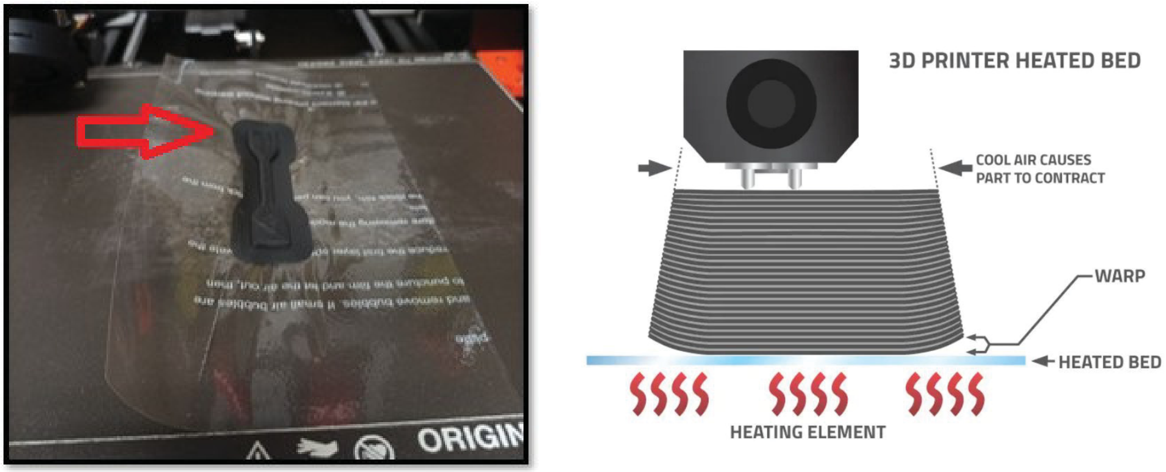


Figure 5.7 Tensile specimen used for the experiment (mm)

Expected results :

- One strain/stress curve for each specimen and evaluate the young modulus of each specimen. Evaluate the young modulus for each set of parameters
- Evaluate the density for each set of parameters

Printing objects using Polypropylene (PP) using 3D printing technology can be challenging. One of the primary challenges is the heavy warping that can occur while printing. To overcome this issue, a controlled printing environment is needed. Another issue is the difficulty in getting the PP to adhere to the bed and other adhesives while printing. Several practices can be followed to 3D print PP correctly to overcome these challenges. Firstly, it is essential to choose a suitable building surface. PP has excellent adhesion to itself, making PP tape a good choice for building surfaces. Secondly, using rafts can help protect the first layer of the 3D-printed structure. Finally, a heated enclosure can ensure a well-controlled 3D printing environment. A temperature of 45-60°C for a heated chamber usually works well to achieve optimal results when printing with PP.



a) Example of warping during the 3D printing of a PP tensile specimen

b) Schematic of the warping phenomenon

Figure 5.8 Warping during 3D printing, schematic and example

Figure 5.8a presents an example of warping during the printing of a PP tensile test, the warping is highlighted by the red arrow in the figure. The warping is greatly reduced by the PP sheet placed on the heating plate.

The main objective of this experiment is to determine the impact of the printing parameters, temperature, and height layer on the mechanical properties of the 3D-printed PP. The main mechanical properties that need to be studied are the tensile modulus and the flexural modulus. The tensile modulus of the printed material will be the priority of focus in this section.

The model of the tensile specimen I used for the experiment can be seen in figure 5.7. This is a normalized specimen given by the standard ISO-527A-5A.

Results of the experiment on PP tensile specimens

Each tensile specimen has been tested according to the ISO-527-1. These experiments lead to a stress-strain curve for each tensile specimen. In order to extract the young modulus of the material from the curve, the value of the slope of the linear portion of the stress-strain curve needs to be evaluated. The slope of this region represents the Young's modulus of the material. On the other hand, the end of the linear region gives the maximum stress the sample can endure before being deformed, and the absolute maximum of the curve indicates the absolute tensile strength of the sample. Figure 5.9 presents a typical stress strain curve of a material tested in this study. In this case, it shows the behavior of a PP sample which was 3D printed a 220°C with a layer of 0.15mm following the ISO 6892-1 standard.

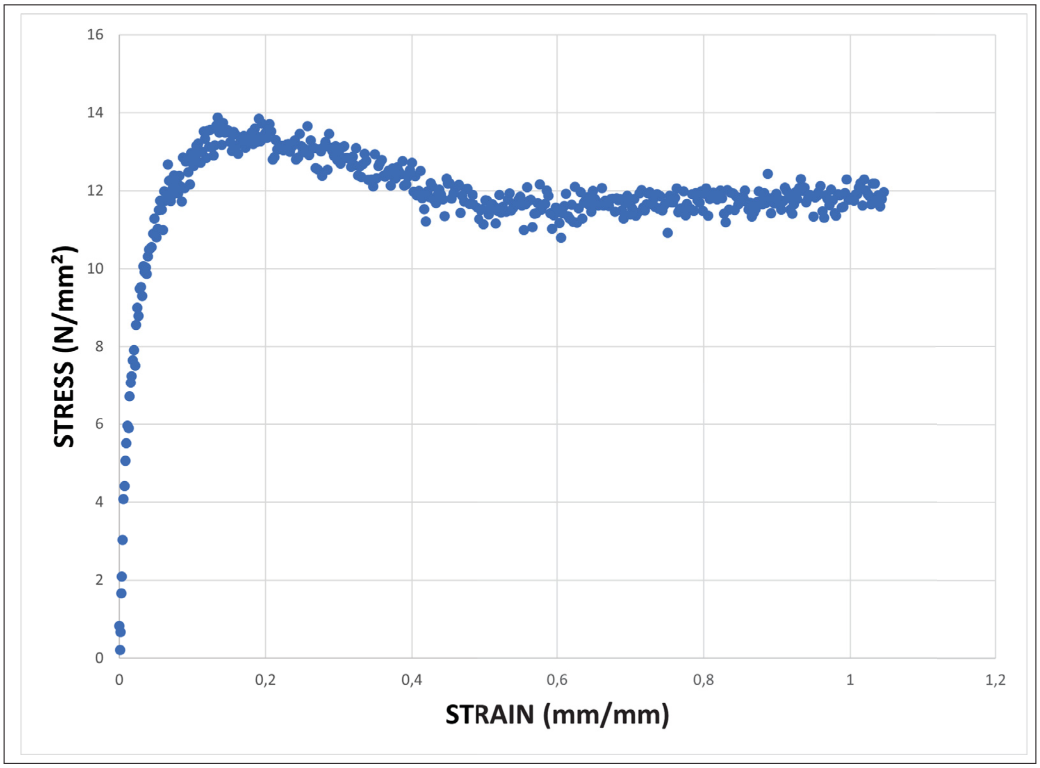


Figure 5.9 Stess/Strain typical curve obtained with PP tensile test - This example is 220°C/0.15mm tensile

After obtaining the Young modulus of each curve, the average Young modulus is calculated for each couple of parameters, and here are the results. Each set of parameters has three separated values, and the results presented on Figure 5.10 are obtained with the average of these three results :

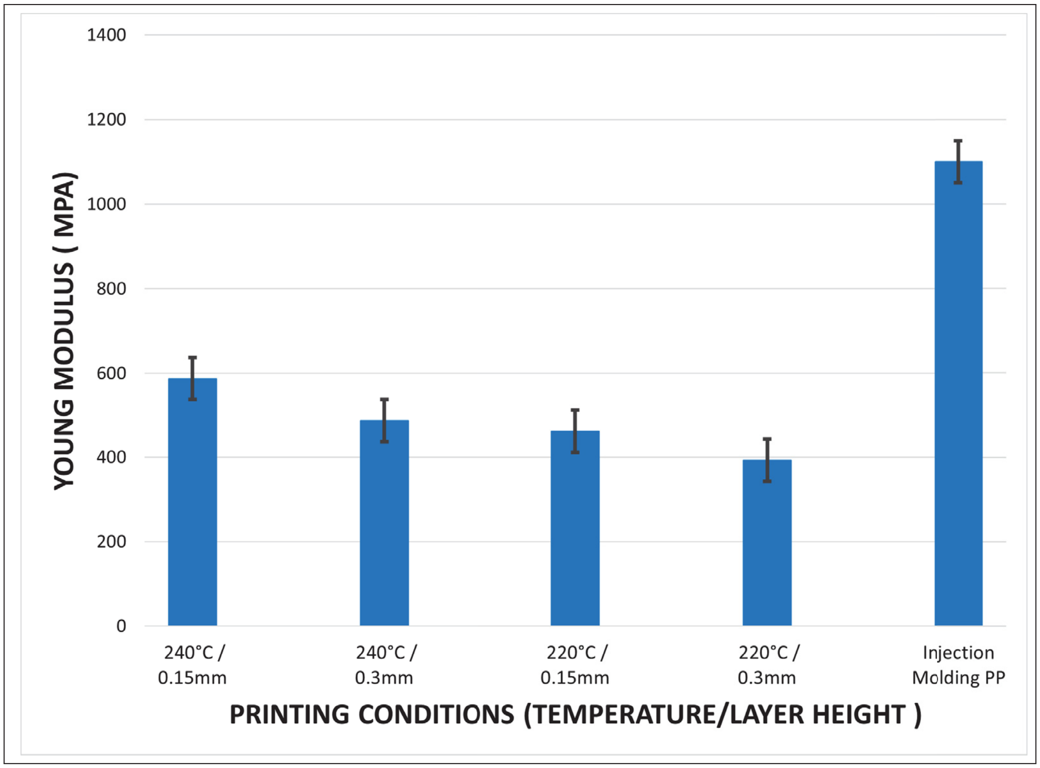


Figure 5.10 Young modulus of 3D-printed PP depending on the 3D printing parameters

As can be seen in the results, the printing temperature is the most important parameter concerning the young modulus of the resulting material. With a higher printing temperature, the PP becomes more fluent and leaves fewer empty spaces in the structure. On the other hand, the layer height also has an impact on the young modulus of the material. The thinner the layer, the higher the young modulus.

On the other hand, the parameters used have very little impact on the result of the 3D-printed PP density. All the specimens of density tests shared the same density. These results give some information for the next part of the project, especially about the printing parameters that must be chosen to print material with the material jetting process.

5.2.2 Wood-based composite printing results

The printing tests are realized on the 10% and 20% wood weight filament made with fine wood. The results are classed into two categories: the printability of the filaments, the difficulties related to the filaments themselves and the warping of the composite, and the mechanical properties of the different composites. The printed parts have been printed at 190°C and 200°C for a layer height of $0.3mm$.

Printability of the composites

Many printing difficulties come from the filament itself. The regularity of the filament width is essential to ensure good printability and a good regularity during the printing. An insufficient regularity in the filament width has caused many issues during the printing. One possible solution for the width regularity issue is to make a 3D print with a $2.85mm$ filament. As the filament is wider, the irregularities impact the printing less than a 1.75mm filament. On the other hand, the composites, either the 10% and the 20% filaments, show way less warping than with pure polymer. The addition of wood added printability properties such as less warping, in the same way as presented in Figure 2.5, and better adhesion to the building plate. Compared with pure PP, the wood-based composite could be 3D printed directly on the building plate without using a sheet, as presented in Figure 5.9.

To conclude, the 10% and the 20% composites show good printability properties at both 190°C and 200°C and are easier to print than pure polymer.

Printed samples and results

The final part of the experiment chapter is printing the 3D tensile tests to evaluate the mechanical properties needed for the composite material. The tensile samples printed follow the geometry given in Figure 5.7. For each filament, the 10% and the 20% wood filaments, two to three tensile, have been printed for each temperature. The tensile samples are used to evaluate the Young modulus and the tensile strength of the composite. It is important to remember that the mechanical properties of the tensile samples are highly dependent on the quality of the printing, and the results may vary from one tensile to another. Printing more than one tensile for each set of parameters reduces the variability of the results. However, the results will be displayed as a range of values. On the other hand, in the same way as the Polypropylene experiment, $1x1cm$ cubes are printed to evaluate the density of the printed composite. All the samples are printed with 100% infill with a printing speed of $45mm/s$.

Table 5.6 summarizes the type of samples printed to evaluate the mechanical properties of the composite while Figure 5.12 shows two tensile samples after tensile test.

Table 5.6 Samples printed to evaluate the mechanical properties of the wood-based composite

Type of sample	Tests realized on the sample	Mechanical properties obtained
Tensile specimen presented Figure 5.8	Tensile test	Young modulus Tensile strength Elongation at break
Density sample $1x1cm$ **cube**	density test	Density value of the composite

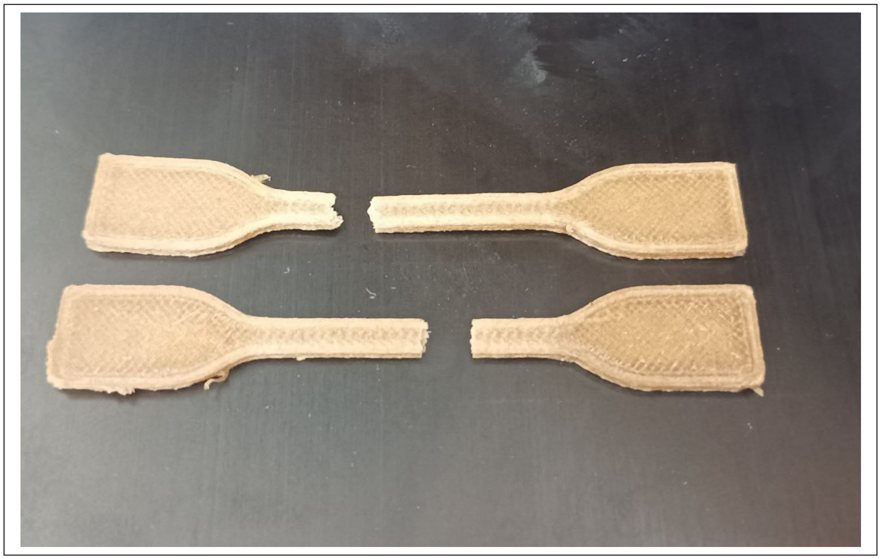


Figure 5.11 Wood-based composite tensile test after tensile test

For each tensile test printed, the sample is tested on a traction machine until it breaks using the ISO 6892-1 standard as shown in the Figure 5.12. A Strain/Stress curve is obtained for each sample, which can be used to determine the Young modulus, the elongation at break, and the tensile strength. The young modulus is found by measuring the slope on the linear zone of the curve, the elongation at break is the maximum strain reached by the sample before it breaks, and the tensile strength is the maximum stress in Pa a tensile sample can handle before it breaks. Figure 5.9 presents two typical strain stress curves obtained with Wood-PE composites tensile printed at 200°C .

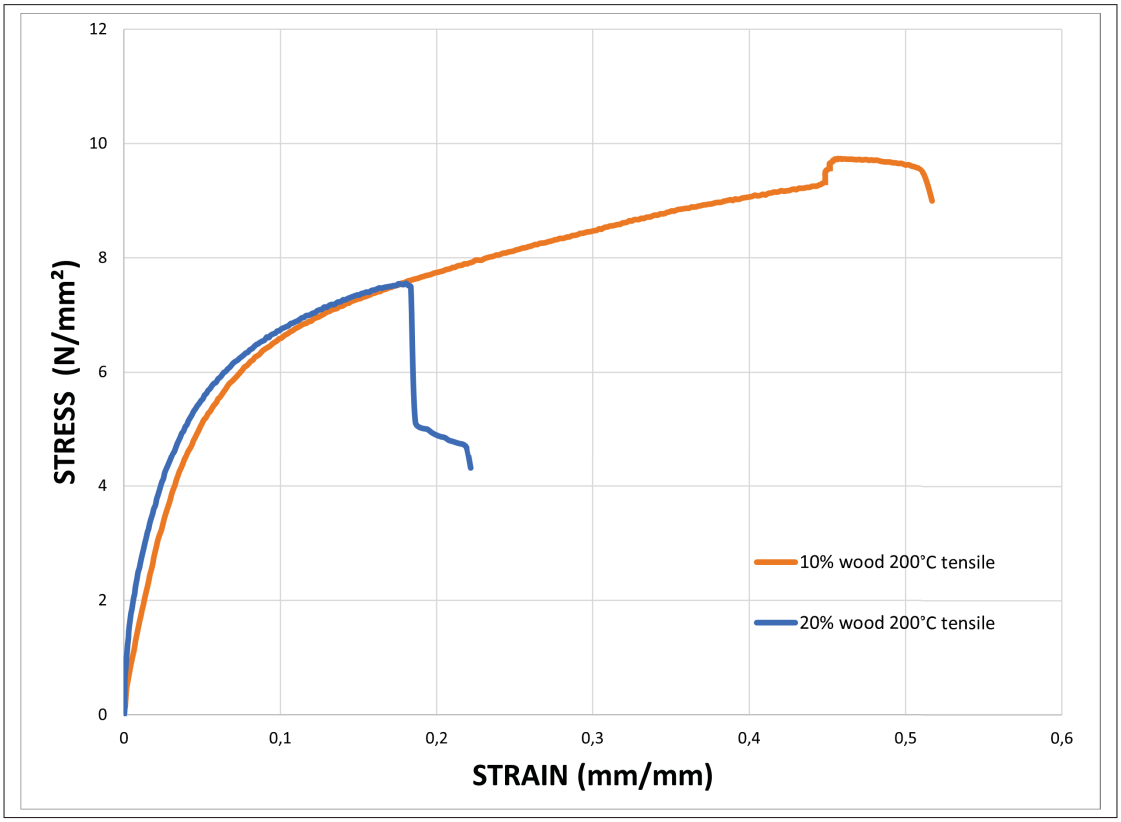


Figure 5.12 Typical Strain/Stress curves for two different tensile tests printed with the wood-PE composite

All the mechanical properties measured on the tensile curves are summarized in the following table. For each set of parameters, two to three samples have been printed and tested, and the final result is the range of the results obtained for each sample. The results for the σ max (MPa) and ϵ (%) are consistent, but the results for the Young modulus have very high variations between samples :

Table 5.7 Summary of obtained values from tensile testing and density testing of 3D-printed specimens with wood composite. Three tests have been conducted for each type of sample

Sample	E (Mpa)	σ max (Mpa)	ϵ (%)	Density (g/cm^3)
10% wood printed at 190°	225 ± 25	11 ± 0.5	6 ± 0.5	0.95 ± 0.15
10% wood printed at 200°	225 ± 25	10 ± 0.5	5 ± 0.5	0.95 ± 0.15
20% wood printed at 190°	255 ± 25	7 ± 0.5	1-2	0.93 ± 0.15
20% wood printed at 200°	255 ± 25	7 ± 0.5	1-2	0.93 ± 0.15

Analysis of the raw data

As can be seen in Table 5.7, changing the printing temperature does not change much the properties of the printed parts, even if a minor change in the tensile strength can be observed as the printing temperature change for the 10% wood composite; this change is not observable in the 20% wood composite. The change in the 10% wood printed at 190°C and the 10% wood printed at 200°C could be explained by the variability in the structure of the 3D-printed tensile. As well as the mechanical properties, a change in the printing temperature did not change the printability of the composite. On the other hand, the difference in terms of mechanical properties between the 10% wood composite printed parts and the 20% wood composite printed part is very remarkable. The composite containing 10% wood is more flexible and handles more pressure before breaking, while the composite containing 20% is more rigid, has a higher young modulus and a lower tensile strength. Both composites have advantages and cons; while the 10% wood composite has better mechanical properties, the 20% wood composite ensures a better environmental statement on the global turbine package piece 3D printing. Therefore, analyzing the potential loads to which the 3D-printed piece can be exposed is essential to choosing which composite should be used for the printed part.

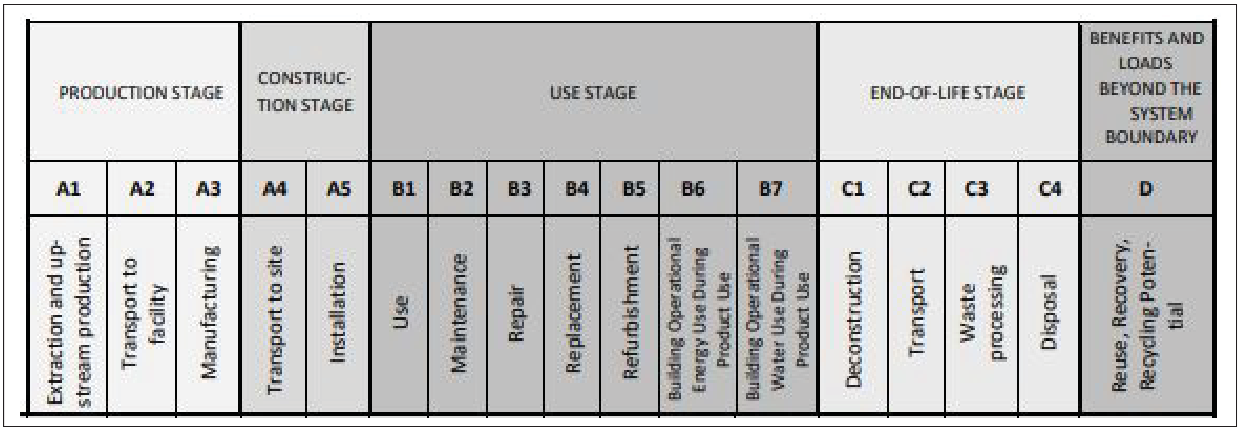
Validation of the composite for the current project

In this project, all the loads and their impact on the geometry have been studied in Chapter 4. At the end of the design and loads study, the final tensile strength condition for the composite was found to be $20MPa$, which is double the composite obtained values during the experiments. This is why the basic geometry presented in Figure 4.2a could not be used in the gas turbine package project. Two leading solutions can be implemented to make the wood-based composite work for the project. The first solution is to improve the structure by adding more curves and making it less square-shaped; this would reduce the local stress of $20MPa$ found during the simulations and presented in Figure 4.5. This solution alone would allow Siemens to use the wood-based composite for the Turbine package project. The other solution is to reduce the load applied on the structure; as explained previously, the critical load applied on the structure is the vertical acceleration load that may occur during the transport of the part. In Chapter 4, it was taken as a given that this vertical acceleration load would be applied from the bottom to the top of the piece. However, the piece could be transported detached from the whole package and thus be transported on the side. Transporting the part on the side would change the repartition of the stress and then could reduce the impact of this load on the structure.

In conclusion to this chapter, the wood-based composite obtained for this project is suitable for 3D printing pieces used in low-load applications, which means the structure is not exposed to any loads applying more than $5MPa$, as the tensile strength of both composites is limited. The case of the Combustion Air Inlet part of the gas turbine package is an excellent example of a low-stress application due to the nature of the loads, which are wind, snow, and transport. Even if a redesign of the combustion air inlet part is clearly needed for the composite to be used, the wood-based composite created in this project is a competitive solution for the combustion air inlet to be 3D-printed and for Siemens to realize environmental progress.

CHAPTER 6
ENVIRONMENTAL STATEMENT

The sustainability of the package can be measured in a few different ways. At first, the carbon print is the first objective that comes to mind, but other indices can be considered to evaluate the sustainability of the potential new package created with wood-based materials. The primary way to evaluate the sustainability of a structure is a life cycle assessment; during a life cycle assessment, every stage of the structure's life cycle is evaluated in terms of carbon emissions. Figure 6.1 presents an example of the life cycle found on the Environmental Product Declaration of North American softwood lumber published in 2018 by the American Wood. Here are the life cycle stages defined in the following figure 6.1:



PRODUCTION STAGE			CONSTRUCTION STAGE		USE STAGE							END-OF-LIFE STAGE				BENEFITS AND LOADS BEYOND THE SYSTEM BOUNDARY
A1	**A2**	**A3**	**A4**	**A5**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**C1**	**C2**	**C3**	**C4**	**D**
Extraction and upstream production	Transport to facility	Manufacturing	Transport to site	Installation	Use	Maintenance	Repair	Replacement	Refurbishment	Building Operational Energy Use During Product Use	Building Operational Water Use During Product Use	Deconstruction	Transport	Waste processing	Disposal	Reuse, Recovery, Recycling Potential

Figure 6.1 Life cycle stages of wood products, American wood Council of 2021

In order to compare the old version of the focused piece, the air combustion inlet, it is essential to define what life cycle stages are changed by the redesign of the piece. First, by redesigning, a weight reduction is achieved. Therefore, all the stages, including transport, will have less carbon emissions. However, the primary carbon emission reduction will be on the material itself. This section aims to evaluate the piece's weight change and compare the two materials, the previous steel used and the wood-based composite studied in this project. .

6.1 Traci v2.1 evaluation tool and example

Numerous other indices can be considered to evaluate the sustainability of materials. In order to evaluate the sustainability of a material with an evaluation index other than carbon emission, The TRACI (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) method is used. The TRACI method provides a standardized approach for calculating the environmental impacts of a product or process, which makes it easier to compare different products or processes. The most critical indices can also be found on the official material reports of **American Wood Council of 2021**. The TRACI method uses the following indices to evaluate the sustainability of a material :

- ATMOSPHERE
  - Global Warming Potential: Refers to the greenhouse gases in the atmosphere. It can cause changes in the global weather over the years.
  - Ozone Depletion Potential: The attenuation of the ozone layer, which protects the earth and humans from air pollution.
  - Photochemical Ozone Creation Potential: Hydrocarbons, nitrogen, and oxides react with sunlight to create air pollution.
- WATER
  - Acidification Potential: It is the result of human wastes rejected in water which increases the acidity of oceans, lakes, and streams. It also decreases the PH of water.
  - Eutrophication Potential: "Excessive nutrients cause increased algae growth in lakes, blocking the underwater penetration of sunlight." It results in a loss of aquatic life.

Table 6.1 presents an example of the use of the TRACI method. The objective is to give an idea of how this method is used. The sustainability assessment of different materials will be compared using this method. The objective is to compare a wood-plastic composite made out of Wood flour and polypropylene with steel that is commonly used in this type of package structure.

Table 6.1 Comparison according to TRACI tool for steel and wood-based composite components

1000Kg of material	Global Warming	Ozone Depletion	Smog	Acidification	Eutrophication
Units	Kg CO2 eq.	Kg CFC-11 eq.	Kg O3 eq.	Kg SO2 eq.	Kg N eq.
Steel (used in steel pipe)	2 000	1.0E-04	250	12	1.1
Wood flour	147	1.98E-06	56.7	1.47	7.63E-02
Polypropylene	2 000	0.0	102	12.8	1.2

As Table 6.1 above shows, steel and polypropylene have almost the same environmental impact. However, a composite made out of 30% wood in weight with a PP matrix will, therefore, emit 28% less carbon emission. On the other hand, one objective of the wood-based package is achieving at least a 30% weight reduction, which means more carbon emission reduction. The previous data lead to a global 50% carbon emission reduction on the air filter system of the package.

The objective of the current work is to evaluate the sustainability of the final chosen material according to the TRACI tool. This will give an idea of the impact of the product on the environment and will enable the comparison of the new redesign piece with the previous model used in the metal turbine package by Siemens.

6.2 Sustainability assessment for the redesign of the combustion air inlet

The main challenge of this part is to evaluate the quantity of material used for both the redesigned and the old geometry of the combustion air inlet. The evaluation of the redesigned geometry will be based on the piece presented in Figure 4.2. The old design of the combustion air inlet is made of 1/2" wide 6061-T6 ALUMINUM sheets. The quantity of material necessary for the redesigned geometry can be directly found on SolidWorks. As Figure 4.2 design is directly inspired by the previous metal-based combustion Air inlet, the number of metal sheets required for the old metal-based design will also be found on Solidworks in the Figure 4.2 part. The evaluation of the weight of the aluminum piece is simplified; the objective is to have an idea of the difference between an aluminum-based piece and a piece 3D-printed with the wood-based composite studied in this project.

First, the quantity of material needed for the 3D-printed part inspired by Figure 4.2 is found by using the volume of the piece on SolidWork and the density of the composite. On the other hand, the quantity of aluminum sheets needed for the old design is found using the exterior surface of the same geometry.

- Density of the wood-based composites
  - 10% wood : $D_{10} = 0.95 g/cm^3$
  - 20% wood : $D_{20} = 0.93 g/cm^3$
- Aluminum sheets
  - Density : $D_{alu} = 2.7 g/cm^3$
  - $w = 1/2" = 1.27 cm$ wide sheets
- Volume of the Solidwork piece : $V = 1.32 m^3$
- Surface needed to build the geometry out of aluminum sheets : $S = 20.91 m^2$

Calculation of the aluminum based combustion air inlet weight W_{alu}:

$$W_{alu} = S * w * D_{alu} \tag{6.1}$$

$$W_{alu} = 20.91 * 0,0127 * 2700 = 717 Kg \tag{6.2}$$

Calculation of the wood-based 3D-printed combustion air inlet weight $W_{wood10\%}$ and $W_{wood20\%}$:

$$W_{wood10\%} = V * D_{10} = 1250 Kg \tag{6.3}$$

$$W_{wood20\%} = V * D_{20} = 1227 Kg \tag{6.4}$$

First, there is a 42.6% and 41.5% mass difference between the aluminum-based structure and, respectively, the 10% and 20% wood-based 3D-printed parts. The design of the 3D-printed piece should be improved, for example, by reducing the wall thickness.

Once the weight of the printed structures is evaluated, the objective is now to evaluate the impact of the composite per Kg to have the total impact of the structure on the environment. The calculations will be presented here for the Global Warming Potential (CO2 emissions). The data for wood are presented in Table 6.1 while the data for the PE comes from the article by Hottle, Troy. (2015).

Global Warming potential value G in Kg of Co2 eq. per Kg of material :

- $G_{PE} = 2.0Kg$
- $G_{Wood} = 0.147Kg$

Calculation of the composites global warming potential impact, $G_{wood10\%}$ and $G_{wood20\%}$:

$$G_{wood10\%} = G_{PE} * 0.9 + G_{Wood} * 0.1 \tag{6.5}$$

$$G_{wood20\%} = G_{PE} * 0.8 + G_{Wood} * 0.2 \tag{6.6}$$

The final results for $G_{wood10\%}$ and $G_{wood20\%}$ are the following :

- $G_{wood10\%} = 2 * 0.9 + 0.147 * 0.1 = 1.81$ Kg of CO2 eq. per Kg.
- $G_{wood20\%} = 2 * 0.8 + 0.147 * 0.2 = 1.62$ Kg of CO2 eq. per Kg.

According to the TRACI assessment tool, the two designs will be compared regarding their impact on Global warning potential, Ozone depletion potential, Acidification potential, Eutrophication potential, and smog creation potential. All the data used for the aluminum has been found on the EPD Background Report of North American Semi-Fabricated Aluminum Products for Building & Construction. In this report, the aluminum evaluated is declared as Industry-average sheet aluminum. Especially, the value of $G_{Aluminum}$ has been found in this report : $G_{Aluminum} = 2.92Kg$. Table 6.2 summarizes the final results of the sustainability evaluation the combustion air inlet depending on the material used to create the piece.

Table 6.2 Environmental impact results for the metal based part and the 3D-printed part with 10% and 20% wood wt. composites

Combustion Air Inlet	Global Warming	Ozone Depletion	Smog	Acidification	Eutrophication
Units	Kg CO2 eq.	Kg CFC-11 eq.	Kg O3 eq.	Kg SO2 eq.	Kg N eq.
Aluminum based structure	2100	3.20E-08	71.7	6.31	0.21
3D-printed with 10% wood-based composite	2268	1.98E-07	101.43	1.66E-03	0.12
3D-printed with 20% wood-based composite	1999	3.96E-07	90.36	3.31E-03	0.12

The 3D-printed parts with 10% and 20% wood weight composites have around the same environmental impact as the metal-based part. However, the design used for the calculations is basic and is meant to be improved. An improved design should aim to have an identical weight or less than the metal-based part. What is to be mentioned is the Global warming impact per Kg of each material; aluminum has a global warming impact of 2.92 Kg of CO2 eq per Kg while 10% and 20% wood-based composites have an impact of 1.81 and 1.62 Kg of Co2 eq per Kg respectively. With an optimized design for the combustion air inlet aiming to reduce the weight of the 3D-printed part by 30%, the global warming impact of this redesigned part would be 1 417Kg of Co2 eq, which is 32% less than the impact of the metal-based combustion air inlet.

As can be witnessed in the previous Figure 6.3, the 3D-printed part made out of 20% wood composite has better results regarding Smog and acidification. On the other hand, both metal and composite-based parts have an insignificant impact on eutrophication compared to other types of materials such as PLA, which would have an impact of ~ 30 Kg N Eq for a 1 227

Kg piece. Aluminum-based part have a slightly lesser impact regarding ozone depletion; however, it does not justify keeping metal as a base material for this turbine package piece.

Conclusion of the environmental statement

Regarding the sustainability aspect, wood-based composites have a better impact per Kg than aluminum. Using the basic geometry of Figure 4.2 results in a 3D-printed piece being 41.5% heavier while having a 4.7% CO2 emission reduction. A redesign of the geometry is essential to reduce its weight and, therefore, vastly reduce the CO2 emission of the 3D-printed part compared to the metal-based combustion air inlet. Regarding the other sustainability indices, the 3D-printed part has a better impact regarding acidification and around the same impact on the other indices. Thus, the material studied is good to be used in industrial projects regarding sustainability aspects.

CONCLUSION AND RECOMMENDATIONS

During the last decades, industries have tried to be more careful about the environment by using greener materials. According to this objective, wood has been actively studied for construction, leading to engineered wood such as cross-laminated timbers or plywood. Wood has proven to have remarkable mechanical properties, high durability, and low environmental cost. However, engineered wood is limited in shape and cannot be used in complex geometry, such as the air filter system studied in this project. On the other hand, additive manufacturing, especially FDM 3D printing, has rapidly developed in recent years, allowing new materials to be used in complex-shaped pieces and structures. In this context, Siemens Energy started a project about using wood as a base material to re-design their gas turbine packages. Some parts of the package, such as the enclosure or the baseplate, can be crafted out of engineered wood, while other parts with more complex geometry are more suited for 3D printing. This project consisted of the study of the air filter system of the package, with a focus on the combustion air inlet piece and creating a wood-based composite 3D printable suitable to create the air combustion air inlet.

The design part of the thesis had two main objectives, the first one being the creation of a 3D Solidwork model of the combustion air inlet. A very basic design has been borrowed from the previous metal-based package from Siemens Energy to create the model. Since all the loads had been identified in Chapter 4, the second main objective of this section is to evaluate the impact of the loads on the piece using mechanical simulations. The simulation gave a maximum stress of $20MPa$ that could be applied to the structure by the acceleration load that could occur during the transport of the piece. The maximum stress found in this section will serve as a guideline for the wood-based composite created in Chapter 5, even if this value can be reduced with a 3D model redesign. Some improved designs have been presented at the end of the design section to give ideas of how to improve the model; however, the main work on the design part is still to be done since the 3D model has to be improved regarding the total weight of the piece, the 3D printability and other aspects mentioned in section 4.4. The previous chapter highlighted a maximum stress value applicable to the piece. Wood-based composite creation has a clear goal of tensile strength for the material. Chapter 5 followed the different steps of the wood-based composite creation, from the components and the process to the final testing of the 3D-printed parts with the composite. First, filaments were created and characterized with TGA, DSC, MFI measurements, and SEM pictures of the microstructure. Afterward, the first 3D printing experiment was conducted on pure polypropylene to gain a better understanding of the impact of the 3D printing condition on the mechanical properties of the 3D-printed parts. In the end, the wood-based filaments were used to 3D print tensile tests, and the final material was tested in order to obtain its mechanical properties. The wood-based composite with 10% wood in weight achieved a tensile strength of 11 ± 0.5 Mpa while the 20% wood composite achieved a tensile strength of 7 ± 0.5 MPa. Therefore, the composites tested are not suitable for the basic model studied in the last chapter and the hypotheses on the material mechanical properties are not verified. However, with a redesign of the 3D model to minimize the load impacts, the wood-based composites created in this section could be suitable for the project.

The last part of the thesis is the final sustainability evaluation. This section aims to evaluate the impact the 3D-printed large-scale combustion air inlet would have on the environment and compare this impact with the impact of the previous metal-based combustion air inlet used by Siemens Energy in their metal Gas turbine package. In order to evaluate the sustainability aspect of the 3D-printed piece, the TRACI v2.0 assessment method has been used to evaluate the impact of the wood-based composite per Kg and the impact of the previously sued metal per Kg. According to the TRACI method, the 20% wood composite has a 44% lesser global warming impact than the aluminum studied. The results are mitigated concerning the entire combustion air inlet structure, as the 3D model still needs to be improved in terms of total weight. However, even with the basic model, a combustion air inlet 3D-printed with the 20% wood composite would have a better environmental impact than the aluminum-based combustion air inlet. Therefore, the hypotheses concerning the sustainability of the material are validated, and the final result regarding the package depends on the 3D model redesign of the piece.

To conclude, this project has proven that wood-based composite is suitable for 3D printing and can even be used in industrial projects as a primary material for low-stress applications. The final result of the Siemens global project highly depends on a 3D model design that has yet to be conducted in this project; however, the feasibility of the study has shown promising results, and the hypotheses regarding the sustainability aspect of the material have been validated which makes the wood-based composite studied in this project a promising material for Siemens and many other industrial projects.

RECOMMENDATIONS

Next steps of the project

To further support and confirm the results of this work, the wood-based GT package must continue with an extensive and in-depth design study of the combustion air inlet geometry. Improving the geometry in terms of weight reduction, printability, noise reduction, and airflow optimization would highlight the results of this thesis. It would further validate the use of wood-based composite in the industry. The direct next steps of this work is the large-scale 3D printing of the GT combustion air inlet and the mechanical testing of this 3D printing piece. Another important next step of the project is the creation of 30% and 40% wood composites. In this work, these composites have not been created. However, it may be possible with a change in the recipe of the composite. Adding more binder could be the solution to add more wood to the composite.

On the other hand, the use of 3D printable wood-based composite could be studied for many different industrial low-load applications.

3D printing issues and recommendations

Making 3D printing filaments can come with many issues. The main issue encountered in this work is the regularity of the filaments. 1.75mm filaments created out of composites were not regular enough to ensure stable printing. If the filament is too wide or too narrow at some point, the printing may just stop, and the 3D printed part is not entirely printed. A solution that could solve this problem is to craft 2.85mm filaments. By doing so, the irregularities will have less impact compared to the size of the filament. On the other hand, even if wood-based composite has shown good printing properties, printing in a controlled environment may avoid some warping issues and could help save some time.

APPENDIX I
TABLES

Table-A I-1 Risks and Descriptions

Risk	Description
Increased Fuel Load	Gas turbine already has a lot of Fuel sources. Usage of wood-based materials to create the package would increased the list of the potential Fuel sources. Which is a problem to respect official norms.
Surface Flame Spread	With package component made out of wood-based materials, the wood surface would be very important. Moreover, wood allow flames to spread across its surface.
Proximity to other structures	An ignition of wooden component would result in the spread of fire to other structures by radiative heat. A minimum separation distance between the gas turbine and other structure must be evaluated during the site planning stage.
Fire Suppression Systems	Gas turbine are often equipped with Carbon Dioxide fire suppression systems. Certain of this fire suppression systems may not be listed for use with wood components. Fire suppression systems could be suitable for use with wood-based materials structures.
Exposure to High Temperatures	The exhaust of high temperature Air can deteriorate and even ignite combustibles such as wood.

BIBLIOGRAPHY

AmericanWoodCouncil. [Accessed: 2023-09-15]. Environmental Product declaration of North american softwood lumber. Retrieved from: https://awc.org/wp-content/uploads/2021/11/AWC_EPD_NorthAmericanSoftwoodLumber_20200605.pdf.

Antony,S., C. A. . M. G. (2018). Mechanical performance of 3D-printing plastic honeycomb sandwich structure. *International Journal of Precision Engineering and Manufacturing-Green Technology*, 5(1). doi: https://doi.org/10.1007/s40684-018-0005-x.

CanadaGovernment. [Sustainable Development Goals Unit, Employment and Social Development Canada, “Canada’s 2030 Agenda National Strategy - Moving Forward Together”, 2021]. Government of Canada.

Chen,F., N. X. L. Y. X. X. . G.-X. (2022). Preparation and properties of heat-treated esterified wood flour/polylactic acid composites for FDM 3D printing. *Journal of Materials Science*, 57(31). doi: https://doi.org/10.1007/s10853-022-07419-x.

CSPI. [Accessed: 2022-02-21]. STEEL. Retrieved from: https://cspi.ca/wp-content/uploads/2021/04/AGECO_CSPI_CSP_RCP_LCAreport_20201116_vFINAL.pdf.

Das, A. K., Agar, D. A., Rudolfsson, M. & Larsson, S. H. (2021). A review on wood powders in 3D printing: processes, properties and potential applications. *Journal of Materials Research and Technology*, 15, 241–255. doi: 10.1016/j.jmrt.2021.07.110.

Elsheikh,A. H., P. H. S. S. M. T. E.-K. A. M. . R. B. (2022). Recent progresses in wood-plastic composites: preprocessing treatments, manufacturing techniques, recyclability, and eco-friendly assessment. *Cleaner Engineering and Technology*, 8. doi: https://doi.org/10.1016/j.clet.2022.100450.

EPA, U. S. E. P. A. [Accessed: 2022-03-10]. TRACI USER GUIDE. Retrieved from: https://nepis.epa.gov/Adobe/PDF/P100HN53.pdf.

Goodship,V., M. B. . C. R. (2016). Design and Manufacture of plastic components for multifunctionality: structural composites, injection molding, and 3D printing. doi: https://doi.org/10.1016/C2014-0-00223-7.

GreenDotBioplastic. [Accessed: 2022-02-13]. terratek Products. Retrieved from: https://www.greendotbioplastics.com/wp-content/uploads/2021/03/GreenDotBioplastics-Terratek-Product-Guide.pdf.

Hottle, T. (2015). Assessment and Solutions for Waste Handling of Compostable Biopolymers. doi: 10.13140/RG.2.1.1850.2489.

InternationalEnergyAgency. World Energy Balances Databas.

Kam,D., L. I. K. Y. L. O. S. E.-S. O. . M. S. (2022). Wood Warping Composite by 3D Printing. *Polymers*, 14(4). doi: https://doi.org/10.3390/polym14040733.

Kananathan,J., S. M. K. K. R. D. . R.-M. M. (2022). Comprehensive investigation and prediction model for mechanical properties of coconut wood–polylactic acid composites filaments for FDM 3D printing. *uropean Journal of Wood and Wood Products*, 80(1). doi: https://doi.org/10.1007/s00107-021-01768-1.

Khan, M. H., Deviatkin, I., Havukainen, J. & Horttanainen, M. (2021). Environmental impacts of wooden, plastic, and wood-polymer composite pallet: a life cycle assessment approach. *The International Journal of Life Cycle Assessment*, 26(8), 1607–1622. doi: 10.1007/s11367-021-01953-7.

Koffi,A., T. L. J. M. K. D. D. F.-S. H.-W. . N. C. (2022). Extrusion-based 3D printing with high-density polyethylene Birch-fiber compos- ites. *ournal of Applied Polymer Science*, 139(15). doi: https://doi.org/10.1002/app.51937.

Montay, S. A. C. (2020). Fabrication and Characterization of Hemp Fibre Based 3D Printed Honeycomb Sandwich Structure by FDM Process. *Applied Composite Materials : An International Journal for the Science and Application of Composite Materials*, 27(6). doi: https://doi.org/10.1007/s10443-020-09837-z.

Patti,A., C. G. . A. S. (2021). Rotational Rheology of Wood Flour Composites Based on Recycled Polyethylene. *Polymers*, 13(14). doi: https://doi.org/10.3390/polym13142226.

Philipp F. Sommerhuber,Jan L. Wenker, S. R. A. K. (2017). Life cycle assessment of wood-plastic composites: analysing alternative materials and identifying an environmental sound end-of-life option. *Conservation and Recycling*, 117. doi: https://doi.org/10.1016/j.resconrec.2016.10.012.

Plarre, R., Zocca, A., Spitzer, A., Benemann, S., Gorbushina, A. A., Li, Y., Wilbig, J. & Günste, J. (2020). Searching for biological feedstock material: 3D printing of wood particles from house borer and drywood termite frass. doi: 10.1101/2020.05.27.118562.

Pokhrel G,Gu H, G. D. O. S. Life Cycle Assessment (LCA) of Wood Flour and Pellets for Manufacturing Wood-Plastic Composites (WPCs). doi: 10.21926/rpm.2201003.

Prusa, C. [Accessed: 2022-02-15]. Web page of Prusa Research Company. Retrieved from: https://www.prusa3d.com/fr/categorie/original-prusa-i3-mk3s/.

Rong Xiao,Qinghan Yu, H. Y. Y. S. Y. S.-M. Z.-P. N. S. G. (2011). Visual design of high-density polyethylene into wood plastic composite with multiple desirable features: A promising strategy for plastic waste valorization. *Journal of Building Engineering*, 63. doi: https://doi.org/10.1016/j.jobe.2022.105445.

S. Nenkova,Cv. Dobrilova, M. N. S. V. & Velev, P. (2006). Modification of Wood Flour with Maleic Anhydride for Manufacture of Wood-Polymer Composites.

Sahoo, K., Bergman, R., Alanya-Rosenbaum, S., Gu, H. & Liang, S. (2019). Life Cycle Assessment of Forest-Based Products: A Review. *Sustainability*, 11(17), 4722. doi: 10.3390/su11174722.

Sivrikaya, H., Hafizoglu, H., Cragg, S., Carrillo, A., Militz, H., Mai, C. & Borges, L. (2012). Evaluation of wooden materials deteriorated by marine-wood boring organisms in the Black Sea. *Maderas. Ciencia y tecnología*, 14(1), 79–90. doi: 10.4067/s0718-221x2012000100007.

Sujal Bhattacharjee, D. S. B. (2018). Degradation in the mechanical and thermo-mechanical properties of natural fiber filled polymer composites due to recycling. *Construction and Building Materials*, 172. doi: https://doi.org/10.1016/j.conbuildmat.2018.03.010.

Tabarsa,T., K. H. P. H. (2011). Manufacturing of wood-plastic composite from completely recycled materials. *Key Engineering Materials*. doi: https://doi.org/10.4028/www.scientific.net/KEM.471-472.62.

Treu,A., Z. K. B. C. L. E. G. L. R. A.-F. C. S. M. F. P.-O. H. M. W. M. B. L. & Williams, J. (2019). Durability and protection of timber structures in marine environments in Europe: An overview. *BioResources*, 14(4), 10161–10184. doi: 10.15376/biores.14.4.10161-10184.

Troy A. Hottle,Melissa M. Bilec, A. E. L. POLYMER. Retrieved from: https://doi.org/10.1016/j.polymdegradstab.2013.06.016.

UnitedNationsGeneralAssembly. [Resolution adopted by the General Assembly on 25 September 2015, Seventieth session, A/RES/70/1]. Transforming our world: the 2030 Agenda for Sustainable Development.

WorldEconomicForum. [The Davos Agenda, Switzerland, January 17-21, 2021]. Government of Canada.

Xu,J., H. X. Z. H. S. L. L. T. W. Q.-. O. R. (2021). High-and low-temperature performance of ultra-highly filled polypropylene-based wood plastic composite. *Fuhe Cailiao Xuebao/Acta Materiae Compositae Sinica*, 38(12). doi: https://doi.org/10.13801/j.cnki.fhclxb.20210317.002.

Yang, A., Zhang, R., Xu, Z., Liu, T., Fang, Y., Wang, W., Xu, M., Song, Y. & Wang, Q. (2023). Preparation of Situ Microfiber-Reinforced Co-Extruded High-Filled Wood-Plastic Composite with Excellent Mechanical, Creep Resistance, and Water Resistance Properties. doi: http://dx.doi.org/10.2139/ssrn.4570571.