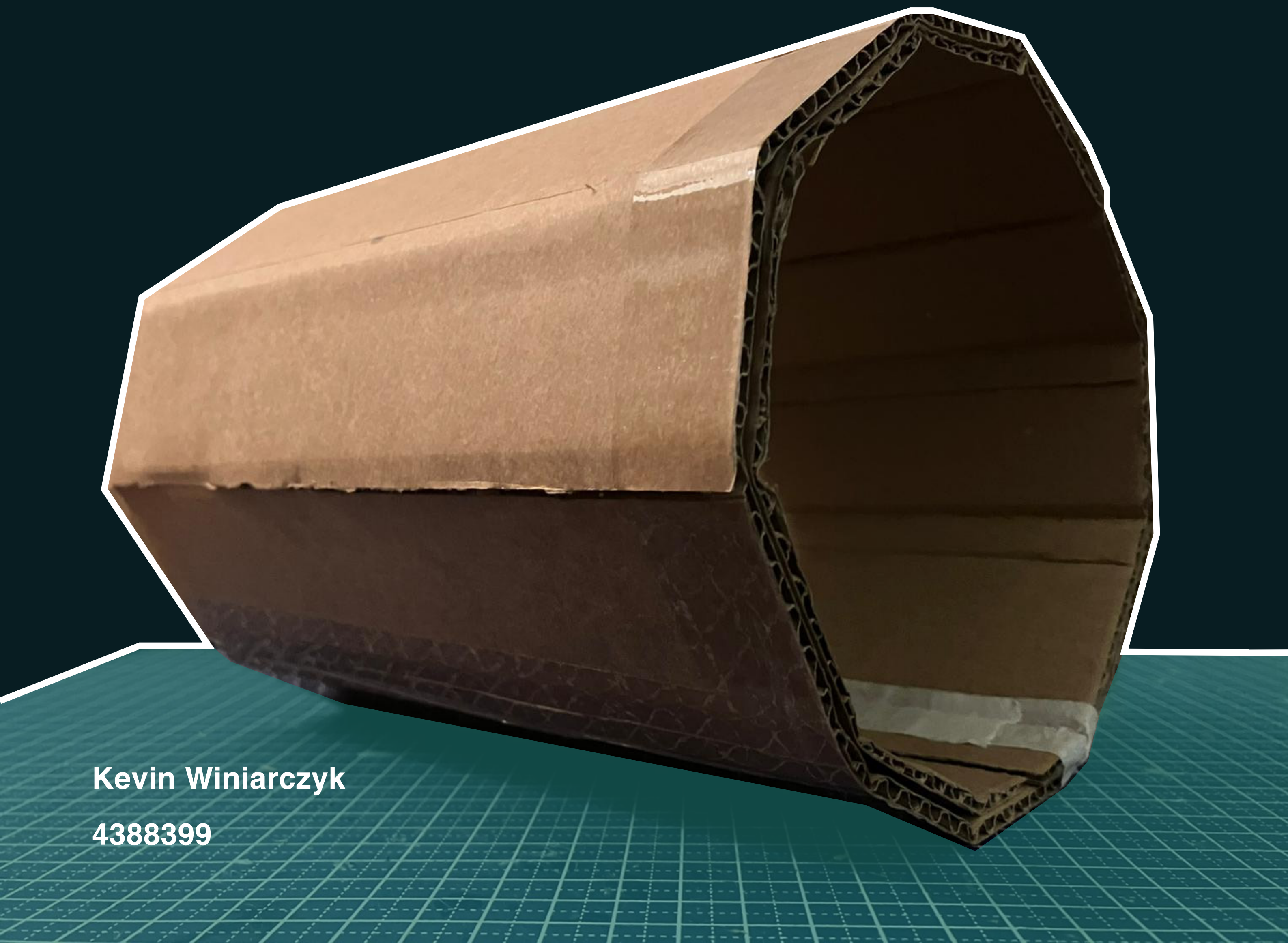
BIO-BASED AIR DUCTS

Research in the applicability of bio-based materials for the construction of air ducts.



Kevin Winiarczyk

4388399

Student

Kevin Winiarczyk
4388399
Delft University of Technology
Faculty of Architecture and the Built Environment
Master track Building Technology
Building Technology Graduation Studio

Mentors

Prof. Dr.-Ing. T. Klein
Architectural Engineering & Technology
Building Product Innovation

Prof. Dr. Ir. A.C Boerstra
Architectural Engineering & Technology
Building services

External supervisor

Drs.Ing. O. Oosting
Valstar Simonis

ABSTRACT

Nowadays, air ducts components for ventilation used in offices, hospitals and schools are made from non-renewable materials mainly sheet metal and plastics. Continuing to feed the high demand of metals is a challenge and could result of depletion of natural resources. This raises the importance to look into renewable resources with a lower environmental impact and contribute to the transition towards a circular economy. By rethinking the material usage for the duct components, solutions should be found in bio-based materials such as agricultural waste, cardboard, bio-composites or bio-plastics.

This research aims to explore the potential and limitations of bio-based materials for the applicability of air duct components. Therefore the following research question is formulated: What are the potential and limitations of bio-based materials to replace sheet metal for the construction of air ducts by maintaining the same quality?

Relevant literature reviews are conducted to give an understand of the construction and relevant requirements of sheet metal ducts. As well the circularity approaches and the categorization of bio-based materials and related manufacturing methods. A method is developed to classify the bio-based materials according their manufacturing efficiency per type of duct component: linear component, joint, bend and t-component. In addition, an assessment is described based on key criteria to select a suitable material per duct component in which the carbon footprint assessment and comparison is crucial.

In conclusion, the potential for linear bio-based components made from Tetra Pak is more advanced than complex components including joints, bends and t-components. This relates to the production efficiency and the LCA of the analyzed materials. Bio-plastics and composites as potential materials for complex components resulted in a relative high carbon footprint which made recycled plastic as non-renewable material a more realistic alternative.

The limitations lie by achieving a similar quality as sheet metal in terms of moisture resistance and chemical emission. Due to the porous character of most bio-based materials they are sensitive for humidity, increasing the risk of mold growth overtime making the use of bio-based materials and the design of the connections between components challenging. Furthermore, the lifespan of the bio-based materials is unknown which is crucial for an accurate LCA in terms of carbon footprint. Low lifespan indicates more replacements leading to potentially a higher carbon footprint overtime compared to sheet metal.

Keywords:
bio-based materials, circularity, air ducts, sheet metal, building services

CONTENT

1.

INTRODUCTION

This chapter describes the background for this research, the problem statement leading to the research objectives, the relevance of this research and research questions. Therefore, the methodology is explained with the used approaches to guide the research leading to the research results.

1.1. Background

From concrete, steel to brick it takes a large number of resources to construct our buildings. The building industry is accountable for more than 35% of global energy use, almost 45% of global resource consumption, and 30% of global waste production (Dahy, 2019). When buildings reach the end of their lifecycle only a part of the materials will be recycled or reused, while others turn into waste instantly. In terms of circularity, a significant challenge lies ahead for the building industry, but at the same time it opens possibilities to apply circular strategies: designing for modularity, demountability, and collective use. As well as the improvement in using renewable biobased building materials, applicable as construction, insulation or cladding materials.

In accordance with the Paris Climate Agreement, the Dutch government set the goal of being fully circular by 2050, with the least possible impact on the environment and limited CO_2 emissions. The first intermediate step aims for a 50% reduction of raw material use by 2030. The importance of the circular economy lies in the need to abandon the linear value chain, which is based on the logic of "take, make and dispose", and rather build a circular value chain, in which materials are used repeatedly in a closed chain (Stahel, 2016). Therefore the Dutch government formulated three principles to achieve a possible circular economy: by using available raw resources more efficiently, using (inexhaustible) renewable resources, as well new production methods and products should be designed circularly (Rijksoverheid, 2016).

The building services sector, accountable for approximately 20% of the total building material use (TVVL, 2020), is lacking behind concerning circularity. Nowadays, standard air duct solutions for schools, hospitals, offices, and other buildings are often made of non-renewable materials such as sheet metal, plastic or synthetic fabric. This results in a significant impact on all life cycle emissions in terms of raw material use, manufacturing process, construction use, and end-of-life usage. Ironically, while the ducts help to provide fresh air indoors and the fabrication of the ducts contributes to air pollution outdoors. In addition, buildings consist of a set of interlinked layers of components, which function at different timescales, perform differently, and should be upgraded or replaced independently as shown in Figure 1.1 (Durmisevic, 2010). In this concept building services, including air ducts, is an important layer, due to their relatively low lifespan of 7-15 years compared to other building layers (Croxford et al., 2018). Resulting in more often replacement and maintenance of duct components, leading to more material use over time. This asks for an urgent solution, which can be found in the use of renewable bio-based materials. Instead of using non-renewable materials which have harmful consequences on our environment and will be slowly depleting.

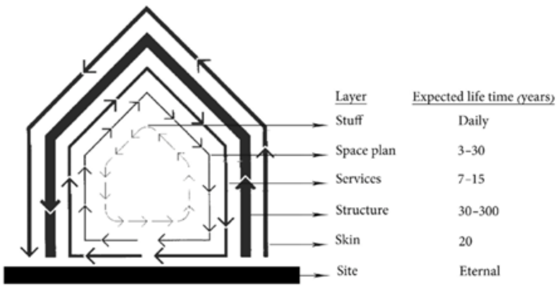


Figure 1.1 Building layers and lifespan (Durmisevic, 2010)

Alternatives can be found in bio-based materials, which are mainly delivered from trees, plants, or animals. Over the past decades, more interest is shown to protect the environment which made researchers show interest in bio-based materials like biofibres, biopolymers, and bio-composites, thus playing an important role in replacing raw materials. Many applications have already proven the potential of bio-based materials in other industries, such as building cladding, packaging, and furniture. Yet to be explored in the building services sector. The quality of bio-based materials can be found in their renewability by the planet as biological feedstock within a timeframe that corresponds to the service life of the materials without leaving behind any form of pollution (Klein, et al., n.d.). As well as reduce environmental impact due to the possibility of local production resulting in fewer transportation costs and emissions.

1.2. Problem statement

For the building industry, as one of the largest energy consumers, it is important to transition from a linear to a circular economy. New building products should be designed in such a way that the life cycle is extended, with the least possible energy use and waste production. Focussing on the material use of the product is crucial to be recycled and reused efficiently at end-of-life usage.

In the building services sector, products have a relatively low lifespan and therefore more replacements are needed, resulting in increased material use. Air ducts as a building installation are mostly made of non-renewable resources which are depleting overtime. All this together asks for an urgent circular approach. Therefore the following problem statement can be formulated:

Currently, standard air duct solutions in buildings are made of non-renewable resources such as sheet metal, resulting in high embodied carbon usage and harmful consequences for the environment.

1.3. Objectives

This project aims to fill the gap in the field of circular building services, in particular air ducts. This includes the construction of a circular air duct of a bio-based material and exploring if it can meet the same quality as current standard solutions by researching, prototyping, and evaluating according to the setup requirements.

This also includes several sub-objectives that should be achieved:

- Develop an understanding of standard air duct solutions and set up the design requirements related such as pressure drop, airtightness, noise production, cleaning, etc.
- General understanding of circularity and circular strategies.
- Determine strategies to apply circularity into the lifecycle of building services: air ducts.
- Determine suitable bio-based material(s) and how these materials can be manufactured into a functional air duct that meets design requirements.
- Analyse feasibility of selected bio-based material for local production, by performing a Life cycle assessment (LCA) in comparison to the benchmark sheet metal ducts.
- Design and evaluate different design options based on requirements.
- Prototype final design and test according to the requirements, evaluate and formulate a recommendation.

1.4. Relevance

The circular economy is important to tackle climate, environment, and pollution crises. Exploring the possibilities of renewable bio-based materials in the building services sector would keep resources in longer and closed loops, reducing the carbon footprint. Furthermore, raw materials can be saved for industries where they are more urgent and where bio-based materials have no potential to be applied, in this way these sectors can last for future generations. The research related to the relation between bio-based materials and air ducts is lacking. This project aims to fill the scientific gap in the circular applicability of bio-based materials in air ducts, by analysing and applying circular strategies in the building services sector. As well as the feasibility analysis of bio-based materials in terms of local production quantity and carbon footprint compared to the current produced quantity and carbon footprint of the current sheet metal duct. Lastly, the design by research approach should explain the research and design methods for the use of suitable bio-based materials and how to test these in a final prototype according to the setup requirements.

1.5. Research Questions

Main research question:
What are the potential and limitations of bio-based materials to replace sheet metal for the construction of air ducts by maintaining the same quality?

1.6. Sub questions

The following sub-questions are formulated:
- How are standard air ducts constructed?
- What are important requirements when designing for air ducts?
- What is circularity in the built environment?
- How can circular strategies be applied to the lifecycle of air ducts?
- Which bio-based materials are suitable for the fabrication of air ducts?
- What are appropriate manufacturing methods for the selected suitable bio-based materials?
- How feasible is the use of bio-based materials for air ducts in terms of carbon footprint compared to sheet metal?
- How can performance criteria of bio-based air ducts be evaluated?

1.7. Approach and methodology

Literature research is conducted in three domains: benchmark sheet metal air ducts, circularity and bio-based materials including corresponding manufacturing methods. The literature is found in books, scientific articles, product brochures and a MOOC related to circularity.

The first part of this research focuses on standard air duct solutions. This research should give an understanding of how current sheet metal air ducts are constructed, this includes insights into the function, design, and manufacturing methods. Furthermore, gain knowledge of which requirements are needed to achieve the quality of an air duct, related to functionality, performance and maintenance.

The next research part contains the circularity aspects to gain knowledge about the principles of circularity and how strategies can be applied to a product or material. Therefore an additional online MOOC is followed: Circular Economy of a Sustainable Built Environment.

The last part of the research is related to the biobased materials and case studies, to achieve a circular air duct this part is crucial. It should give an understanding of which types of bio-based materials are available, which are suitable for this specific research, and how they can be manufactured into an actual product.

During the analysis phase the following aspects are determined based on literature research related to air ducts, circularity and bio-based materials:
- Benchmark sheet metal air duct design requirements: determines the quality of the duct in terms of performance.
- Circular strategy for future-proof and sustainable air duct design.
- Bio-based materials: feasibility in terms of a Life Cycle Assessment in comparison with sheet metal air ducts.

During the research by design phase, different material samples are created and evaluated, to explore the workability of the bio-based materials. Then the material samples with the highest potential will be further developed for the construction of different design alternatives, taking into account a suitable production method. Finally, the solution with the best option is chosen to construct the final prototypes. In case the final prototype can be developed from bio-based material, the design will be tested according to the set-up requirements to compare the quality of the duct, according to NEN-EN guidelines:
- Moisture resistance
- Chemical emission

To set up an accurate experiment every requirement requires a certain set of tools to measure and analyse the values. The results will be compared with the quality of sheet metal solutions. Conclusions and recommendations will be drawn based on the results. The research framework is visualised in Figure 1.2.

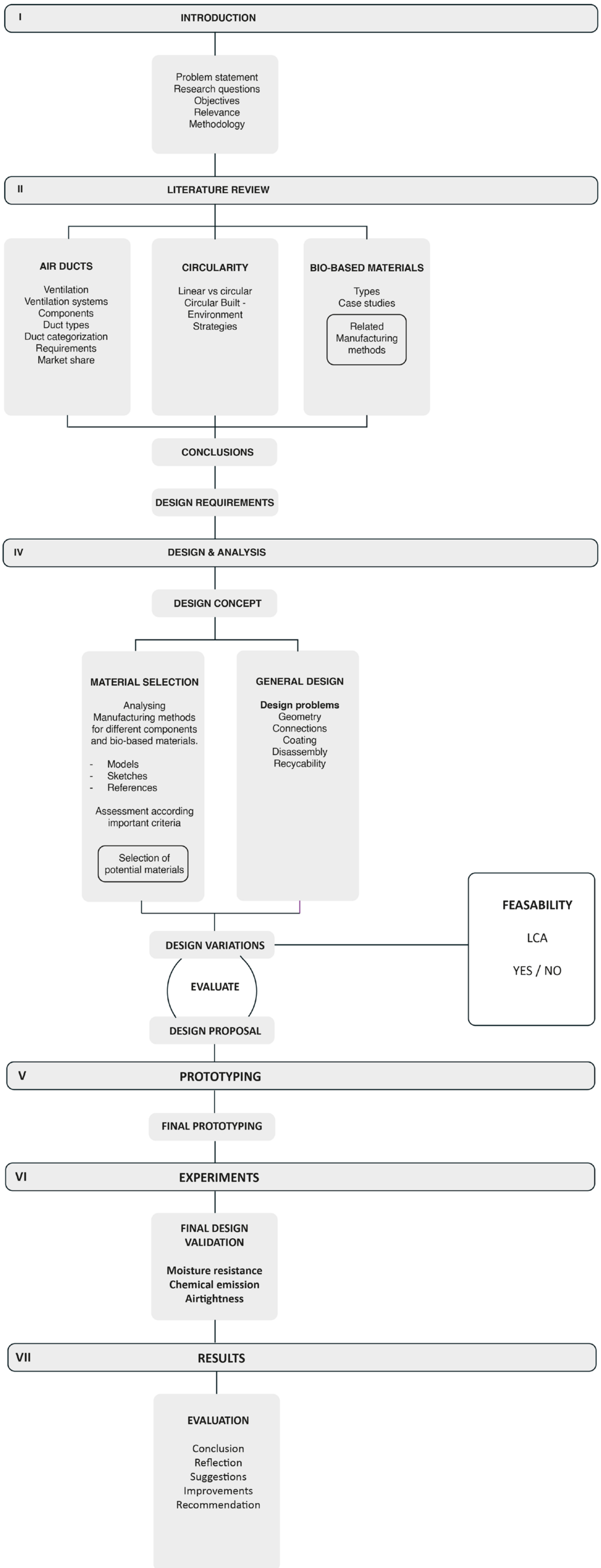


Figure 1.2 Research framework

1.8. Planning

The graduation project consists of five phases each ending with a presentation, as shown in the planning in Figure 1.3. In the first weeks at the p1, an understanding of the topic is conducted and presented. Until the p2 the focus lies on literature research and interviews to get an understanding of the mentioned topics. After the p2 the design phase starts until a few weeks after the p3, knowledge from literature research is used to create and evaluate different design alternatives. During the production phase, a final prototype is made, which will be tested according to setup requirements, presented at p4. Finally, conclusions and recommendations will be drawn based on the results of the experiment, regarding the possible construction of air ducts from bio-based materials

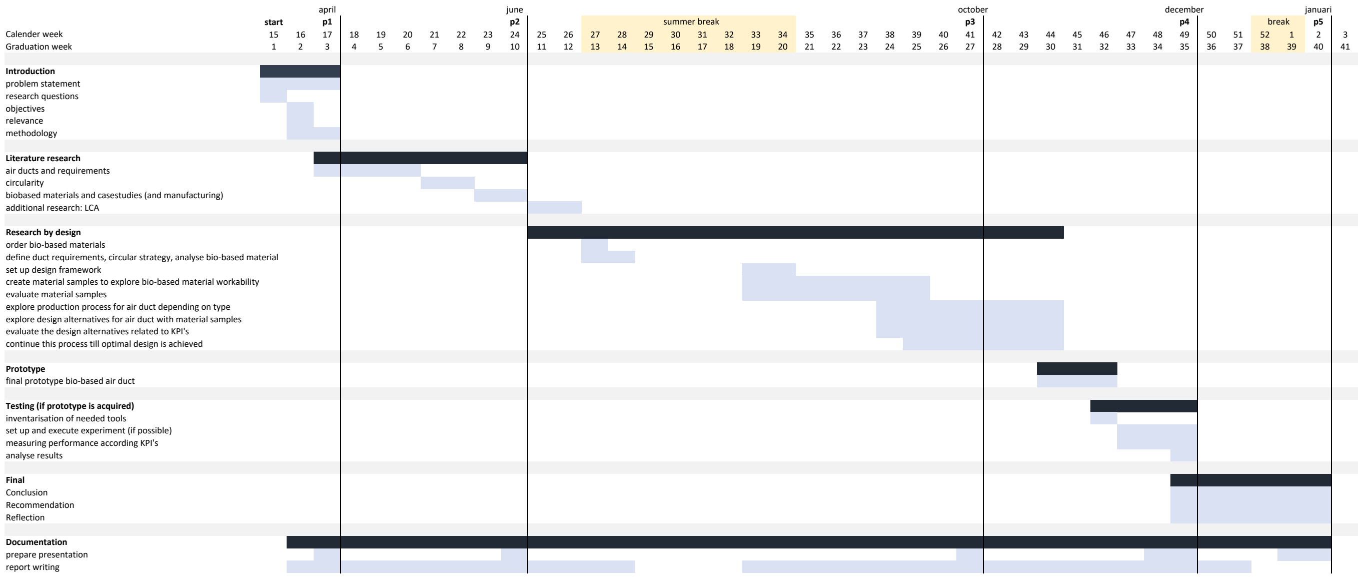


Figure 1.3 Graduation planning (own source)

2.

BENCHMARK SHEET-METAL AIRDUCTS

This chapter describes the literature related to sheetmetal air ducts on aspects including the types of air ducts, the manufacturing methods and important requirements for construction air ducts. The following sub-questions will be answered:

- How are standard air ducts constructed?
- What are important requirements when designing for air ducts? (partially)

2.1. Ventilation

Ventilation is the process of replacing polluted air with fresh air, by moving outdoor air into a building or room, distributing the air within the building or room, and exhausting air from the building or room. To maintain the indoor air quality (IAQ) and thermal comfort at a satisfactory level to meet the standards for the building occupants. Indoor air quality is a term that refers to the indoor quality within a building or room including the following aspects: the degree of aerosol and gases, temperature, humidity, and oxygen level. The general purpose of ventilation in buildings is to provide healthy air for breathing by diluting the pollutants originating in the building and removing the pollutants from it (Etheridge & Sandberg, 1996). Cao and Fang (2022) mention the importance of building ventilation for the health of occupants for several reasons:

- To bring fresh air into the building or room from the outside to improve the oxygen content of the air.
- To remove heat and moisture from the air to ensure the thermal comfort of the occupants.
- To remove pollutants from the air emitted by human beings as well as construction materials.

Before the development of mechanical ventilation methods, ventilation in buildings was mostly achieved passively with natural ventilation by window openings. However, due to the limitations of natural ventilation to reach a satisfactory healthy indoor environment, mechanical ventilation was introduced. This also had advantages for the designer, since the temperature, humidity, and ventilation rate could be controlled by a mechanical system, which resulted in fewer constraints for building design and window openings. The energy crisis made people realize to reevaluate existing ventilation methods, focusing on the reduction of global energy consumption by reducing the consumption of heating, cooling, and ventilation in buildings. However, this development of energy-saving buildings went together with the improvement of the airtightness of buildings and the amount of air entering the building was minimized. Consequently, pollutants could not be removed fast enough, which reached the attention of health problems of buildings in the past decades. This resulted in new ventilation standards since the sick building syndrome (SBS) was officially defined by the World Health Organization. Thus new ventilation systems nowadays are incorporated with smart control, which is necessary to achieve a high indoor air quality and energy efficiency in ventilation systems (Cao & Fang, 2022).

2.2. Ventilation systems

Depending on the type and size of the building, different types of ventilation can be applied to achieve a healthy breathing environment for the occupants. Two main ventilation types can be distinguished to ventilate a building: natural and mechanical ventilation. The principles of natural and mechanical ventilation are further explained in the next sections.

2.2.1. Natural ventilation

The essential of natural ventilation is supplying air and removing air from a building or room without the use of any mechanical systems, instead it relies on external airflow as a result of pressure differences caused by natural forces, which can be wind or temperature differences.

Natural forces drive outdoor air through building openings, such as windows, doors, or trickle ventilators. CIBSE (2016) describes two types of natural ventilation principles: respectively wind-driven ventilation and stack-driven ventilation illustrated in Figure 2.1 (CIBSE, 2016).

Wind-driven ventilation relies on pressure differences around the external building envelope. The pressure difference results in the air moving from the windward side (positive pressure area) of the building, and the air exiting the building through the opening on the leeward side (negative pressure area). This pressure effect caused by wind is determined by the shape of the building, the wind direction, the wind speed, and the surrounding environment: terrain, trees or other buildings.

Stack-driven ventilation is based on pressure differences on the inside and outside of a building by differences in temperature. Warm air rises and is replaced by cold air, when the inside of the building or room is warmer than the outside, the pressure difference moves inwards at the lower part of the building and moves outwards on the higher part. Stack ventilation is a good passive design strategy which can be applied for lower or high-rise buildings by placing openings at different levels.

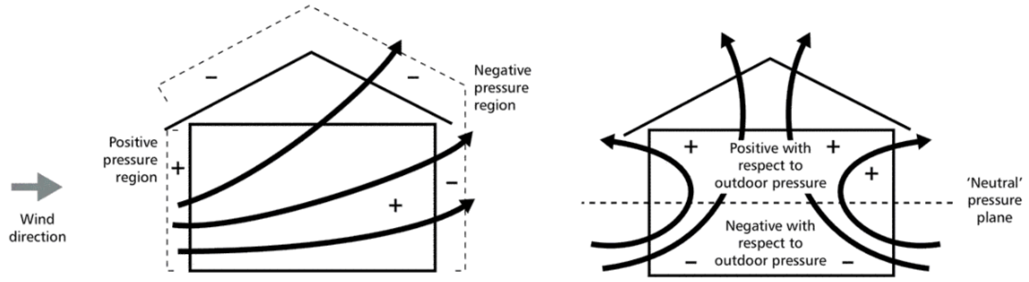


Figure 2.1 Respectively wind-driven and stack-driven Ventilation (CIBSE, 2016).

2.2.2. Mechanical ventilation

Mechanical systems are used to provide the ventilation, provided by fans. Therefore mechanical ventilation is provided without the necesarry use of natural forces. However natural and mechanical ventilation can be combined as ventilation method. There are three mechanical ventilation methods:

- Natural supply, mechanical exhaust: Fans extract air from 'wet' and polluted areas such as kitchens, toilets and bathrooms. The air is provided by natural supply openings to the occupied areas.
- Mechanical supply, natural exhaust: Fans are used to mechanicaly supply fresh air to the occupied areas, and polluted air is exhausted through passive vents or openings.
- Balanced, mechanical supply and exhaust: This approach includes a separate network of ducts and fans to supply fresh air and extract polluted air from the occupied areas, usually combined with air heat recovery. In smaller buildings, mainly residential buildings, normal fans are applied. Larger utility buildings make use of an air handling unit (AHU) or a modern heating, ventilation and air conditioning (HVAC) system. Supplied air from outside is taken from outside via an air intake, which has the possibility to be pre-heated or cooled by exhausted air in the heat recovery unit before it enters the mixing box with recirculated air (via a bypass). Then the air gets filtered, cooled or heated, and supplied to the ventilated area. Polluted air is exhausted, partly to the mixing box, potentially heat recovery unit and outdoors, illustrated in Figure 2.2 (CIBSE, 2016).

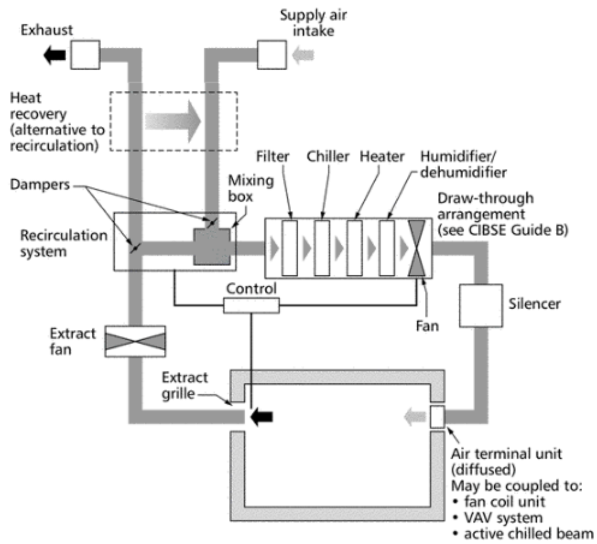
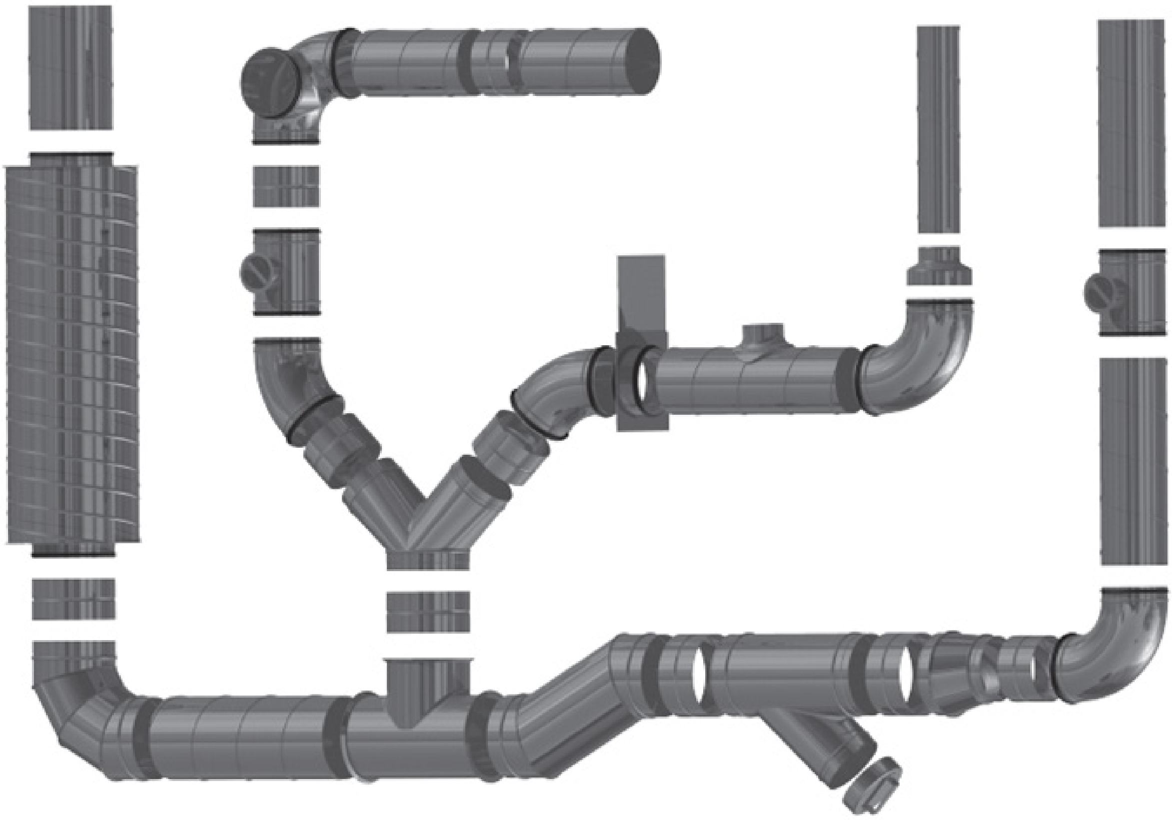


Figure 2.2 Mechanical balanced ventilation for larger utility buildings with an HVAC system (CIBSE, 2016).

2.3. Components ventilation system

Ventilation systems consist of many different components which together make it possible that fresh air and polluted air to be moved throughout the building. There are many configurations of a ventilation system possible, depending on the type of building, room or function. However, each component in this system contributes to the mentioned purpose above. Ventilation systems differ in terms of manufacturing, which usually fabricate the components related to their system. These systems vary in their shape, size, section, materiality, performance and cost. For a general understanding of which components a ventilation system is made of a ventilation system consisting of circular spiral ducts is further elaborated, Figure 2.3 (Alnor, n.d.).



1. Air distribution: fan-unit, AHU or HVAC
2. Ducts and fittings: ducts, bends, t-pieces, y-pieces, x-pieces, reducers, couplers
3. Airflow regulation: air dampers
4. Sound protection: sound attenuations, duct insulation
5. Fire protection: fire dampers, smoke dampers
6. Support systems: support brackets, clamps
7. Finishing trimp: plenum boxes, valves, diffusers and grills

Figure 2.3 Different components of circular ventilation system (Alnor, n.d.).

Fan-unit, AHU, HVAC
In general a fan is introduced to supply or exhaust air from an area. Depending on the type of building this will be just a fan, airhandling unit (AHU) or heating, ventilation and air conditioning system (HVAC). For larger buildings, mechanical ventilation is often regulated by air handling units (AHU) and connected to ductwork to supply or exhaust air from the indoor spaces. In general an air handling unit contains filters, a integrated fan, and in some cases heating elements, cooling elements, sound attenuators and dampers. In indoor spaces with higher humidity, the air handling unit can include dehumidification. In other cases where mechanical ventilation includes heating and cooling, Heating Ventilation and Air Conditioning system (HVAC) is applied. However, usually the air handling unit (AHU) is integrated, so there is hardly any difference between these systems.

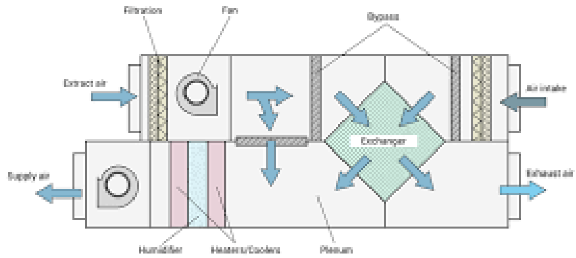


Figure 2.4 Schematic AHU (HVAC Global, 2022).


Figure 2.5 AHU (Airways Partners, 2002).

Ducts
The main component of a ventilation system is the ductwork, often rigid ducts and sometimes flexible ducts, which are important to supply and exhaust the air through a building. The ducts usually have a circular, rectangular or oval cross-section, and are available in a varity of materials. This will be further explained in section 2.4; classification of air ducts.


Figure 2.6 Spiral rigid duct (Saiductfab, 2020).

Bends
In order to allow air to move in an other direction bends with an angle of 45 or 90 degrees are applied to reach the room to provide ventilation. Usually the amount of bends is limited since it will cause higher friction resulting in pressure loss, means more energy is required to compensate.


Figure 2.7 Circular bends 45° and 90° (Alnor, n.d.).

Branches
These parts are applied when the main duct branches into ducts with a smaller section to each room or area to supply or exhaust air. Therefore often t-pieces, or y-pieces and x-pieces are
used.


Figure 2.8 Y and T-piece circular (Alnor, n.d.).

Reducers
If the air duct transitions from one size to another, reducers are applied, in this way the airflow in the ductwork is maintained.


Figure 2.9 Reducers with and without gaskets (Alnor, n.d.).

Couplers

Airtightness for a ductwork system is one of the most important aspects to prevent pressure loses. Therefore an airtight connection between different duct components is key. The couplings in this case allow spiral ducts to join by pressing both ends into the ducts to be joined, untill the thicker middle part. Accordingly the coupling is fastened to both ducts with self-drilling screws or rivets. The couplet with the gasket reach a higher airtightness class compared to the coupling without the gasket, respectively class D and B (Alnor, n.d.).

Figure 2.10 Couplers with and without gaskets (Alnor, n.d.).

Air dampers

This component are applied to regulate the air flow in the ventilation system. This duct piece contains a blade, which can be manually or dynamically set. The angle of the blade can be adjusted which makes it possible to change the air flow mechanically.

Figure 2.11 Air damper (Alnor, n.d.).

Sound attenuation

A duct attenuator is a component to reduce the noise transmittion inside the ventilion ducts. These components are installed near the source which produces noise, such as fans and air handling units (AHU).

Figure 2.12 Sound attenuator (Alnor, n.d.).

Fire protection products

Fire dampers are meant to seal off fire and smoke between adjacent fire partitions. In addition to increase the fire resistance of the ductwork, the blade of the fire damper is made from a silicate cement board (Alnor, n.d.).

Figure 2.13 Fire damper (Alnor, n.d.).

Smoke dampers are mostly applied to exhaust the smoke in duct systems to remove heat and smoke from effected components. When fire occurs the ventilation system opens the damper in the affected partition and removes the heat and combustion of that specific part. An actuating system makes in possible to rotate the blade inside the smoke damper.

Figure 2.14 Smoke damper (Alnor, n.d.).

Finishing trimp products

To finalise the ventilation system, several finish trim products can be distinguished such as valves, diffusers and grilles. In this way, the air is distributed equally into or from the desired space.

Figure 2.15 Valves, grilles and diffuser (Alnor, n.d.).

Plenum boxes are often combined with diffusers for balancing the airflow and universe the airflow to the diffusers, applied in low and medium ventilation - systems.

Figure 2.16 Plenum box(Alnor, n.d.).

Fixing products

Support systems are needed to mount the ductwork on the ceiling by bolting the fixing rail to the ceiling. Then connect the threaded rods to the suspension rings (in case it is a circular duct) which are connected to the ductwork. Finally, the threaded rod is fixed to the rail with connection parts.

Figure 2.17 Suspension rings, threaded rod (Alnor, n.d.).

2.4. Air ducts classification

Air ducts are manufactured in all sorts of materials, shapes and dimensions. A classification of the most applied materials is shown in Figure 2.18. All the materials are based on non-renewable resources. For understanding the different duct types, a selection is further explored on shape, dimensions, material use, connections and manufacturing process. This selection is established on the most commonly used duct types, which include sheet metal ducts including spiral ducts, rigid rectangular ducts and flat oval ducts.

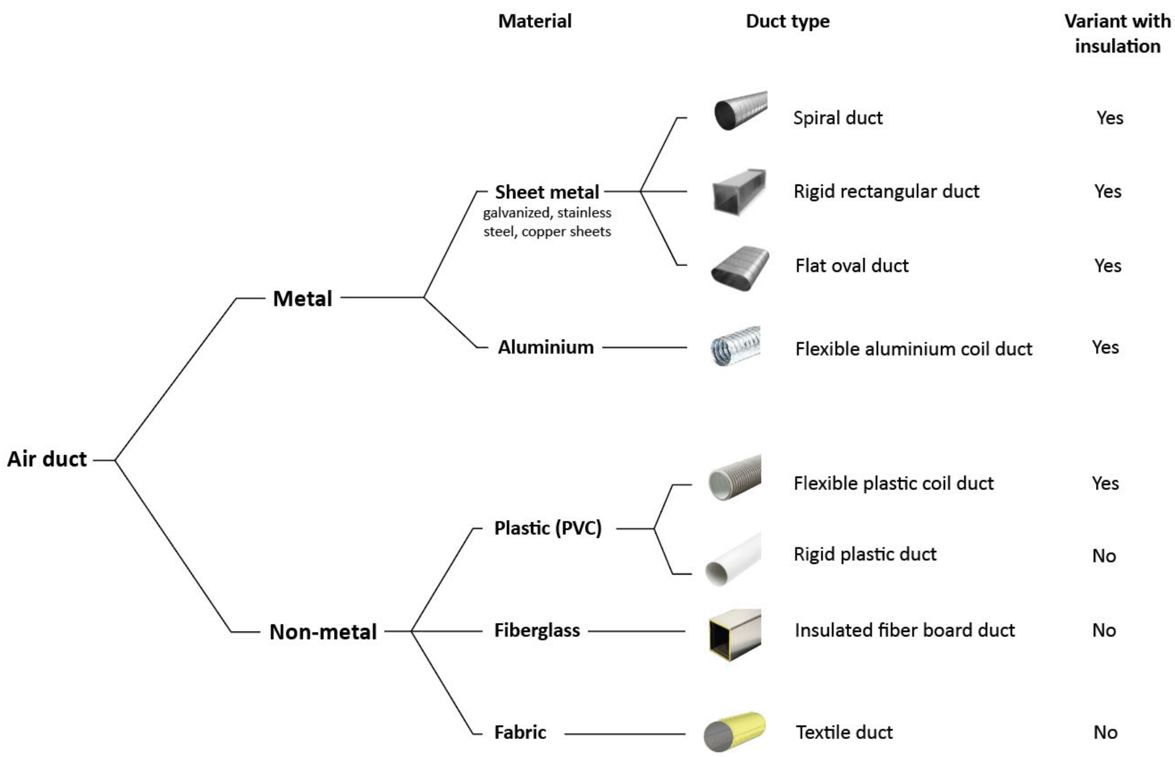


Figure 2.18 Classification of air ducts (own source).

2.5. Manufacturing

2.5.1. Spiral duct

In general, a round duct shape is the most efficient for air distribution, due to the large cross-sectional area and a minimum contact area (less resistance). It uses 30% less material than a rectangular duct for the same volume of air handled through the duct, therefore it would reduce the cost significantly compared to rectangular ductwork. In addition, the supports and maintenance are higher for rectangular ducts with similar capacity compared to the round duct (Bhatia, 2014).

The manufacturing process of spiral ducts occurs in several steps with a spiral duct forming machine, schematically illustrated in Figure 2.19 (Aslani et al., 2015). Firstly large metal sheet coils, often galvanised steel are cut into narrower coils depending on the duct size. The narrow coils are placed on an uncoiler and a leveller to flatten the metal sheets, then the edges are trimmed and formed. Next, the coil is forced to move in a circular motion to create a spiral, where the coils are pinched and in some cases welded together to achieve a lightweight, airtight and rigid spiral duct. Lastly, the spiral duct is cut to the required length with a maximum of 6.0 m for ease of transportation. Using a larger duct length is beneficial because it will limit the number of joints and speed up the installation process. However, the standard length is usually 3.0 m larger duct components Spiral ducts are manufactured in different sizes, which differ from a diameter of 63 to 1250 mm according to NEN-EN 1506 (2007).

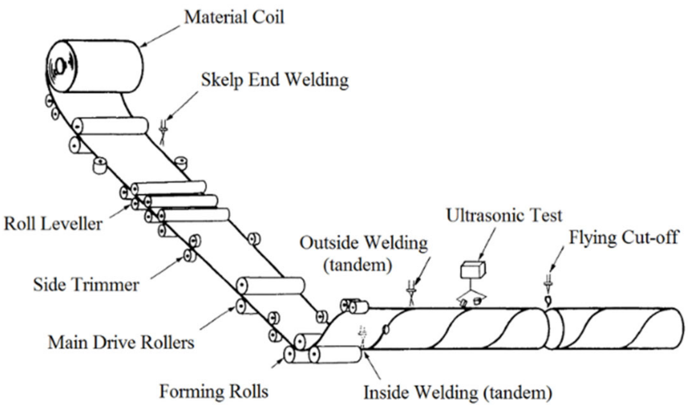


Figure 2.19 Manufacturing process spiral ducts (Aslani et al., 2015)

Airtightness is an important factor for duct design to prevent duct leakage. In spiral ducts, this is achieved with lock seams during the manufacturing process where the sheet metal coils are locked and pinched together. In addition, ribs can be implemented to add extra rigidity, which makes it possible to manufacture longer ducts as illustrated in Figure 2.20 (Accu duct, 2006).

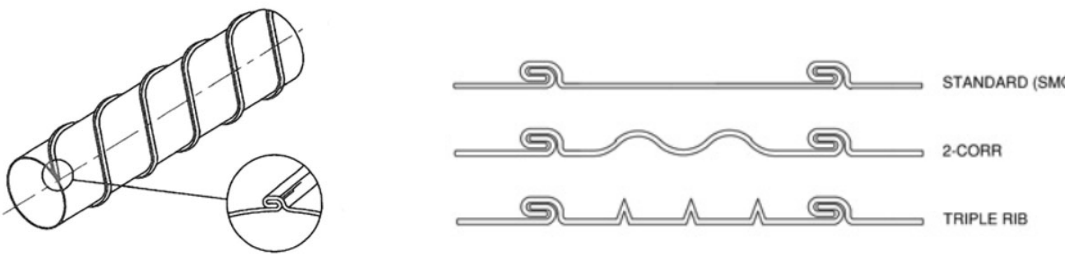


Figure 2.20 Seams for spiral ducts (Accu duct, 2006)

Slip joints are created by using a coupler that fits inside the duct sections which can be fastened with screws or rivets to keep the ducts in position. The amount of screws or rivets depends on the size of the duct. In addition, duct sealant or sealant tape can be applied to reach better airtightness. There are multiple types of slip joints possible (right part in the figure), duct-to-duct (no coupler required), with a coupler or an inside/outside coupler. When designing for high-pressure ventilation systems another connection method can be applied to secure the overall system to meet the ventilation requirements. Therefore several flange joints have been developed to connect both sides of the ducts: accuflange and angle ring flange as illustrated in Figure 2.21 (Accu duct, 2006). The accuflange is an efficient way to fasten the duct and both flanges together with screws and welding, as well as adding a gasket in between. Therefore there are no concerns about aligning bolt holes, for the rest the process is similar.

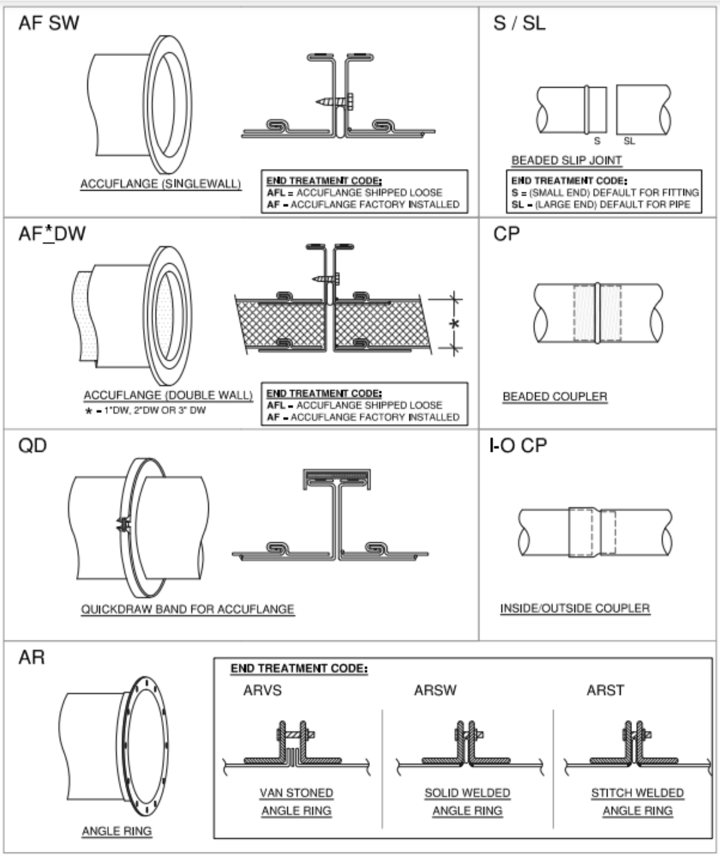


Figure 2.21 Joints for spiral ducts (Accu duct, 2006)

2.5.2. Rectangular duct

Rectangular ducts are manufactured from sheet metal, often galvanised steel or stainless steel illustrated in Figure 2.22 (Preda, n.d.) Large coils of sheet metal are required, which are placed on an uncoiler and leveller to flatten the sheet metal. The levelling and grooving process occurs at the same time, where the dimensions of the duct are set. The grooving process is especially required for ducts with larger widths and heights to make the ducts stiffer for internal air pressure. In the next steps, the sheet metal is cut and folded to create seams and flanges (optional) for the connection between two duct components. Lastly, often two L-shaped components are manufactured which is connected in the final step. The maximum length of a rectangular duct is depended on the coil line, which is around 2.4 meters. Consequently, since the maximum length is relative short more joints between the ducts are required, which makes the duct less effective as well increasing the material use and costs. Rectangular ducts can be manufactured in a large number of sizes, the dimensions differ from 200x150 mm to 2000x1500 mm according to NEN-EN 1505 (1998).

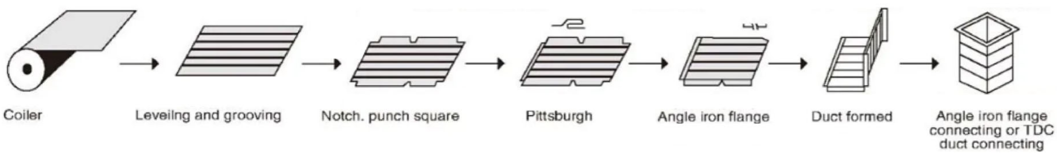


Figure 2.22 Manufacturing process rectangular ducts (Preda, n.d.).

The mentioned two L-shaped components are joined together with two longitudinal seams all across the length of the duct. The seam can be designed in two ways: Pittsburgh seam or snap-lock seam. Both seams are made during the manufacturing process by rolling and folding the metal sheet into a profile to create a flange and pocket which fit together to achieve an airtight longitudinal seam. Rectangular ducts are connected with a transverse joint. For smaller low-pressure ductwork a slip (S) and drive (D) cleat system are applied, a simple and low labour clamping system. The clamps covering the connection of two metal sheets, in de width slip cleats are applied and in the height drive cleats which cover the slip cleats on the corners, as illustrated in Figure 2.23 (Accu duct, 2006).

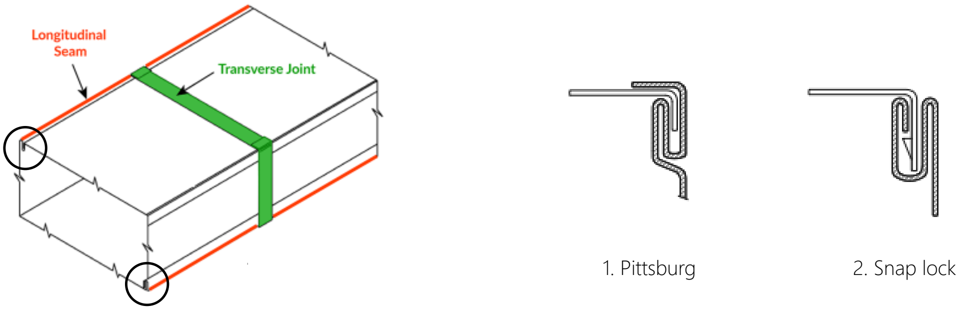


Figure 2.23 Joints for rectangular ducts (Accu duct, 2006)

Another approach, mainly applied for high-pressure ductwork, is connecting the flanges on both sides with a rubber sealing gasket in between. In the corners, connector components are applied, and these components are bolted together. One bolt per corner ensures the connection between two rectangular ducts. In addition, on every side, two cleats are applied which cover both flanges of the two ducts. Reinforcement is applied with beads in the transverse direction. This approach requires more components, nevertheless it ensures a more reliable airtight joint as illustrated in Figure 2.24 (Accu Duct, 2006).

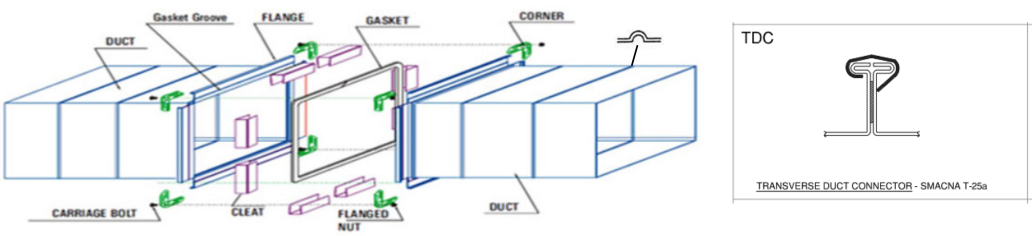


Figure 2.24 Seams for rectangular ducts (Accu duct, 2006)

2.5.3. Flat oval duct

The manufacturing process of the oval ducts occurs in the same steps as the spiral duct, when the spiral duct is finished it is placed in an ovalizer duct machine which presses and stretches the duct into an oval flat duct as illustrated in Figure 2.25 (Spot, n.d.). Resulting in a duct with similar requirements as a spiral duct, but flatter which makes it easier applicable in construction where space is limited. The maximum manufacturing length can reach 3000 mm. Flat oval ducts are manufactured in a large number of sizes, which differs from a diameter of 450 to 1500 mm with corresponding heights of 100 to 500 mm
(Aiva, n.d.).

Figure 2.25 Stretching of spiral ducts to flat oval ducts (Spot, n.d.).

Since the oval duct is manufactured from a spiral duct, the seam designs are similar to achieve airtightness in the ductwork as shown in Figure 2.23 (Accu duct, 2006). In terms of joints between two flat oval ducts, similar flange joints as spiral ducts are applied: accuflange and ring flange. In addition, one type of slip joint is applicable for the flat oval duct. The coupler fits in both duct sections and is fastened with screws or rivets to keep the flat oval duct in position as illustrated in Figure 2.26 (Accu duct, 2006). Extra duct sealant or tape can be applied to increase the airtightness of the duct.

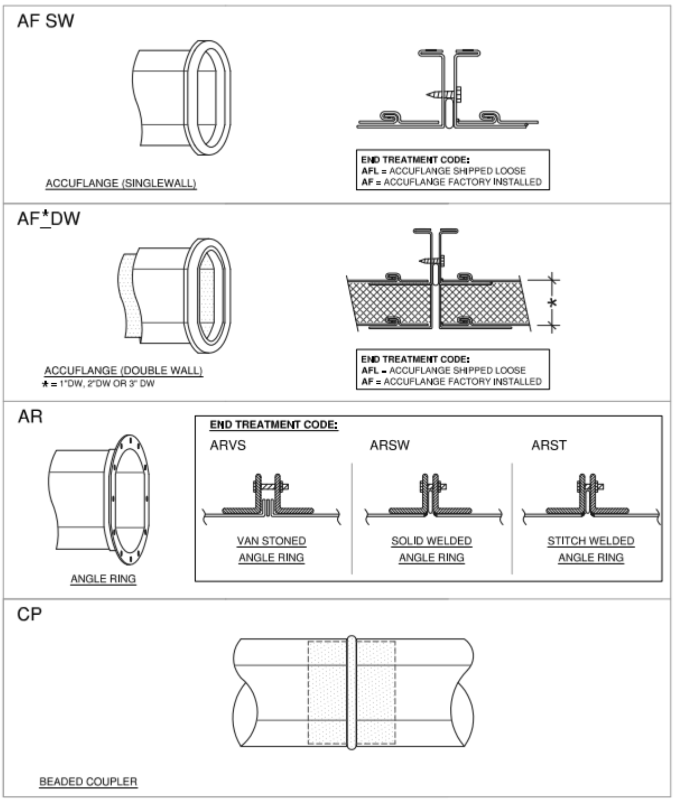


Figure 2.26 Joints for flat oval ducts (Accu duct, 2006).

2.6. Installation

In general ductwork are large components compared to other building services, which makes it difficult to displace. This especially counts for rectangular ducts, which are normally heavier due to the larger size and require at least two workers for the installation. The installation begins with the duct hangers one on each side which are fixed to the ceiling. Next different duct components are connected, however there should be enough free space available to connect the flanges and cover the sides with cleats.

The installation of circular and flat oval ducts requires less intense labour since the material used is less and often one worker is sufficient to install the ductwork with a diameter up to 200 mm. Duct hangers for circular and flat oval ducts require often less space between the hangers, resulting in less material usage as well one hanger or strap is enough to connect the ducts to the ceiling as illustrated in Figure 2.27 (Airways Parters, 2002). In addition, both can be produced in larger lengths and therefore require fewer joints for the same length of ductwork which reduces the material usage as well makes the installation easier and less costly (Airways Partners, 2002).

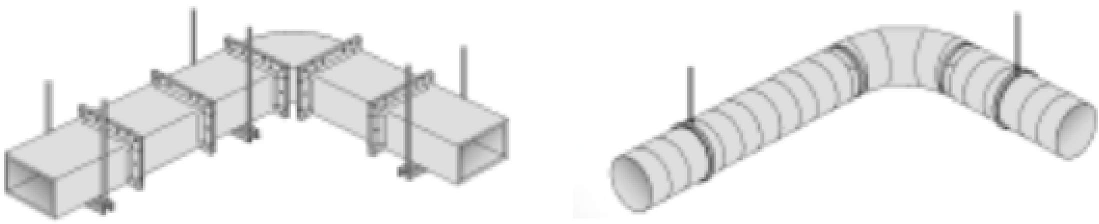


Figure 2.27 Installation hangers rectangular and circular ducts (Airways Partners, 2002).

2.7. Costs

Over the years spiral ducts have been used more often since this type is the most cost-effective choice. Even though there is possibility to make rectangular ducts of the same quality as circular ducts in terms of airtightness etc., the solutions will often increase the costs. Airways Partners (2002) states that the costs for ductwork can be divided into several main components:

- Initial costs: include costs for space, defining requirements for the ductwork system, materials,installation and testing.
- Operating costs: refers to the costs required to train employee to operate the total system, in terms of service and maintenance.
- Replacement costs: the costs for repairing or replacing broken components.

Circular ducts and oval ducts are easier to construct, make airtight and to install compared to rectangular ducts, which reduces the costs. Furthermore, the thickness of the circular duct can be limited due to the spiral production method which enables the possibility for efficient rigid ducts. As mentioned in section 2.5.1 the total weight of rectangular ducts is about 30% higher than circular ducts. Lastly, circular ducts are often stock items which can be delivered relatively quick. The amount of possibilites in terms of dimensions for rectangular ducts is enormous, which often results in smaller production amounts and longer delivery time.

2.8. Comparison ducts

A comparison of the different aspects related to properties, performance, maintenance, installation and costs have been made for spiral, rectangular and flat oval ducts. Therefore the strength and limitations for each type of duct have been researched and concluded in table 1. The table can help to make decisions during the design process, as well indicates which aspects or requirements are important for duct design.

Strength and limitations of spiral ducts

+ Spiral ducts have a relatively small surface area, around 30% less material use compared to rectangular ducts, and therefore relative lightweight.
+ Possible to manufacture in longer lengths compared to rectangular ducts, which limits the number of joints needed. In addition, the manufacturing process is faster.
+ Spiral ducts have a better acoustic performance, due to the curved shape.
+ Better airflow is achieved due to the lack of sharp angles.

- More space is needed for installing round ducts, more clear height is required.
- It can be difficult to connect the fan to the spiral duct

Strength and limitations rectangular ducts

+ Easier to fit in construction, less height is required to fit the duct.
+ The transportation is efficient since units of ducts are easily stackable.

- Higher pressure drop since the connections between the ducts are more difficult to seal.
- More material is needed to achieve the same airflow as in spiral or flat oval ducts.
- Production length is significant lower compared to circular ducts and flat oval ducts, which results in more joint connections between the ducts.
- Sharp edges make it more difficult to clean the duct, higher chances of dirt accumulating in the duct.
- Costly alternative, due to the relative high material use, extra joints needed and more detailed connections.

Strength and limitations flat oval ducts

+ Almost as efficient as round ducts
+ Uses less height like rectangular ducts, which make them easier applicable in construction.

- Slip joints between flat oval ducts are difficult to connect, resulting in less possibilities to connect oval ducts.
- Under pressure the oval shape can become more round.

Table 1 Comparison sheetmetal ducts, + positive, 0 neutral, - negative.

Properties	Spiral	Rectangular	Flat oval
Thickness [mm]	0,4 - 1,1	0,6 - 1,2	0,6 - 1,8
Dimensions [mm]	⌀ 63 - 1250	200 x 150 - 2000 x 1500	⌀ 450 - 1500 - 100 - 500
Length [mm]	≤ 6000	≤ 2400	≤ 3000
Density galvanised steel[kg/m3]	7850	7850	7850
Weight [kg/m]	10,4 - 33,4	12,8 - 39,6	12,4 - 34,1
Production			
Production length	++	-	+
Lightweight	++	-	+
Material usage	+	-	+
Manufacturing time	++	+	+
Price	++	+	+
Performance			
Airflow	++	+	+
Airtigthness	++	o	+
Pressure resistance; strength	+	+	o
Pressure loss	++	o	+
Acoustic performance	++	+	+
Firesafety	++	++	++
Installation			
Required building space	o	++	+
Installation time	++	o	+
Installation feasability	++	o	++
Minimum amount of joints	+	-	+
Cleaning; limited dust pollution	+	o	+
Costs			
Low material costs	++	o	+
Low installation costs	++	-	+

2.9. Requirements air ducts

Multiple requirements are important when designing for air ducts, which are generally similar for the different types of sheet metal ducts. In this research the requirements for spiral ducts are set up, which are categorized in three main categories: physical properties which relates to meassurable properties, performance indicates the quality and durability to the lifespan of the duct. These categories are subdivided in requirements as stated in Figure 2.28.

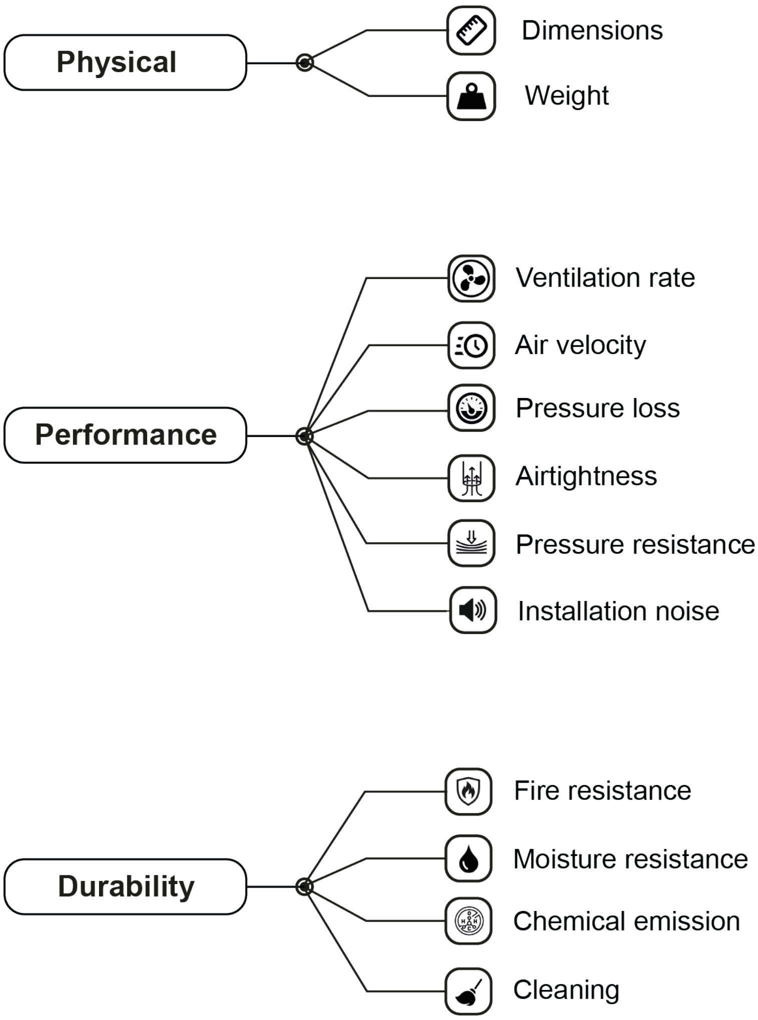


Figure 2.28 Installation hangers rectangular and circular ducts (own source).

2.9.1. Dimensions and weight

Spiral ducts are manufactured in standard dimensions according NEN-EN 1506 (2007) aswell the related thickness and weight as tabled in Table 3 (R-vent, 2022).

Table 3 Dimensions and weight (kg/m) for spiral ducts (R-vent, 2022).

Diameter (mm)	Tickness (mm)							
	0,4	**0,5**	**0,6**	**0,8**	**1,0**	**1,25**	**1,4**	**1,6**
63	0,68	0,85	1,06					
80	0,86	1,08	1,35	1,80				
100	1,08	1,35	1,68	2,25	2,81			
125	1,35	1,69	2,11	2,81	3,51			
140	1,51	1,89	2,36	3,15	3,94			
150	1,62	2,03	2,53	3,37	4,22			
160		2,17	2,70	3,60	4,60	5,75		
180		2,44	3,04	4,05	5,06	6,47		
200		2,71	3,37	4,50	5,63	7,19	8,63	
224		3,03	3,78	5,04	6,30	8,05	9,66	
250		3,39	4,22	5,63	7,03	8,99	10,78	
280			4,73	6,30	7,88	10,07	12,08	13,81
300			5,06	6,75	8,44	10,78	12,94	14,79
315			5,32	7,09	8,86	11,32	13,59	15,53
355			5,99	7,99	9,99	12,76	15,32	17,50
400			6,75	9,00	11,26	14,38	17,26	19,72
450			7,60	10,13	12,66	16,18	19,42	22,19
500			8,44	11,26	14,07	17,98	21,57	24,66
560				12,61	15,76	20,14	24,16	27,62
600				13,51	16,89	21,57	25,89	29,59
630				14,19	17,73	22,65	27,18	31,07
710				15,99	19,99	25,53	30,64	35,01
800				18,01	22,52	28,77	34,52	39,45
900					25,33	32,36	38,84	44,39
1000					28,15	35,96	43,15	49,32
1120					31,53	40,28	48,33	55,24
1250					35,19	44,95	53,54	61,65
1400					39,41	50,35	60,42	69,05
1500					42,23	53,94	64,73	73,89
1600						57,54	69,05	78,91
1800						64,73	77,68	88,78
2000						71,92	86,31	98,64

2.9.2. Ventilation rate

Sufficient air supply and exhaust is mandatory for an healthy indoor environment in buildings, therefore a consistent ventilation rate is required. The ventilation rate is the amount of air which is moved within a unit of time, which is usually expressed in m3/h or dm3/s. The ventilation rate can also be calculated with the following formula, which expresses the relation between ventilation rate, air velocity and cross section area of the duct (Climate Construct, n.d.):

$$q = (3600 \cdot v) \times A$$

where

q	Ventilation rate	m3/h
A	Cross sectional area	m2
v	Air velocity	m/s

In table 4 the requirements are stated according NEN 1087 (2019), which are dependant on the function of the building and the amount of people in the room. The values are minimum requirements, the ventilation rate should not be under these values. However, in order to improve the air quality the decision can be made to increase the ventilation rate.

Table 4 Ventilation rate requirements according NEN 1087 (2019).

Residential function	**Minimal required ventilation rate**
Living area	> 0,9 dm^3/s per m^2 floor space with a minimum of 7 dm^3/s
Living space	> 0,7 dm^3/s per m^2 with a minimum of 7 dm^3/s
Toilet	> 7 dm^3/s
Bathroom	> 14 dm^3/s
Kitchen*	> 21 dm^3/s

* Living area with place for cooking appliance

Utility function	**Minimal required ventilation rate p.p in dm^3/s**
Meeting	
a. childcare	6,5
b. other meeting area	4
Cell function	
a. cell	12
b. other area	6,5
Healthcare	
a. bed area	12
b. other area	6,5
Industrial	6,5
Office	6,5
Hotel, dormitory	12
Education	8,5
Sport	6,5
Other function	-

2.9.3. Air velocity

The air velocity in a duct is depended on the function of the building and type of duct component. According to Airways Partners (2002) the maximum air velocity in main ducts and branch ducts should not exceed the following values for dwellings and utility buildings as described in Table 5:

Table 5 Air velocity requirements (Airways Partners, 2002).

Duct type	Dwellings	Offices, schools
Main ducts	4 m/s	6 m/s
Branch ducts	3 m/s	4,5 m/s

2.9.4. Pressure loss

Air movement through ductwork results in three types of pressure: static pressure, dynamic/velocity pressure and total pressure. These values are meassured with a probe inserted in the duct as discribed and illustrated in Figure 2.29 (Bhatia, 2014):

1. Static pressure (SP): is the outward pressure that occurs against the duct surface in all directions.
2. Velocity pressure (VP): is the pressure that makes the air accelerates to the desired velocity in the duct system. The velocity pressure will only occur in the direction of the air movement and is always positive.
3. Total pressure (TP): is the sum of velocity and static pressure. TP = VP + SP

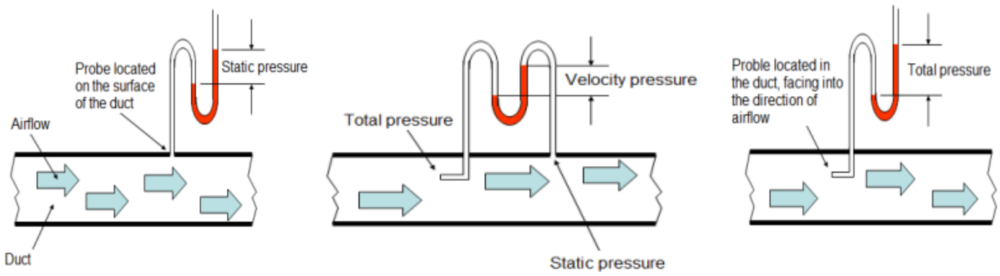


Figure 2.29 Pressure types (Bhatia, 2014)

Pressure loss is the difference of total pressure between two points of a system, in this case a duct. The airflow in a duct results in pressure loss in the flow direction. Pressure losses in a straight duct with a constant diameter are mainly caused by friction, known as friction loss. This friction is caused due to the resistance of air velocity, duct size, material roughness and the duct length. The duct friction loss (Pa/m) can be determined with a friction loss chart in Figure 2.30 (R-vent, 2022) when the airflow, air velocity and duct size are known.

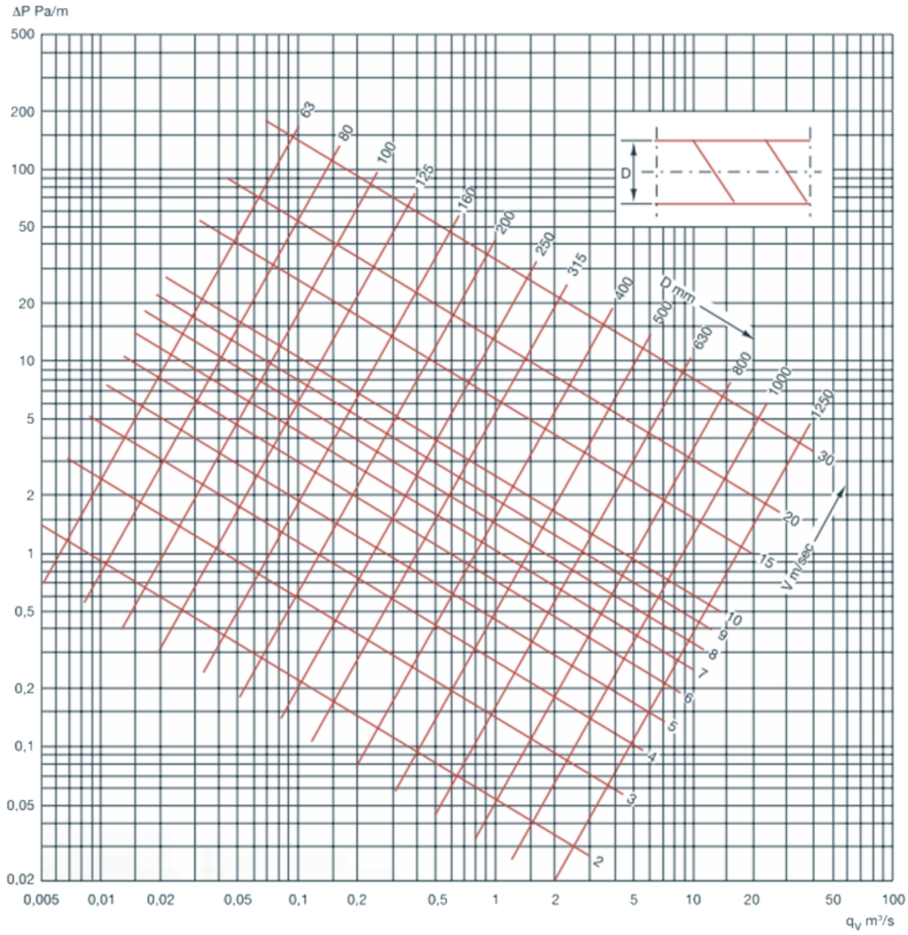


Figure 2.30 Friction loss chart spiral duct (R-vent, 2022).

2.9.5. Airtightness

The quality of the air duct is largely dependent on to what extent the leakage losses are prevented in the seams and connections between the ducts or the duct material itself. Duct leakage is related to a large number of other aspects, which could potentially result in many problems if the airtightness of the duct is not achieved. One of the aspects is energy usage, if the airtightness in the ductwork is low the fans have to compensate with an increased fan flow. This results in pressure loss and over dimensioning of ventilation system parts, such as fans, filters, heat and cool batteries. Leading to higher energy consumption and costs. In addition, duct leakage allows pollutants to enter the ductwork, resulting in extra health and hygiene measures.

The airtightness classes are defined as conforming NEN-EN 12237 (2003) for circular ducts as stated in table 6. The airtightness classes vary from A to D, class D is classified as the most airtight class and A as the most leakiest. In the current duct design two factors are important, the leakage factor and the static pressure limit. The first mentioned refers to the airtightness of the duct. The static pressure limit refers to the strength, which indicates the maximum operating pressure for the duct according to the airtightness class without deforming. According to NEN-EN 15727 (2010), the leakage factor (fc) should be lower than the air leakage limit (fmax), related to the required airtightness class, for the different test pressures (Ptest) between the static pressure limit (ps). This will determine in which class the duct can be subdivided, a more elaborated way to determine the airtightness class is explained in the leakage test method described in Appendix A.

Table 6 Classification of air tightness circular ducts according to NEN-EN 12237 (2003).

Air tightness class	Static pressure limit (p_s) Pa		Air leakage limit (f_{max}) $m^3 \cdot s^{-1} \cdot m^{-2}$
	Positive	Negative	
A	500	500	$0{,}027 \times p_{test}^{0{,}65} \times 10^{-3}$
B	1 000	750	$0{,}009 \times p_{test}^{0{,}65} \times 10^{-3}$
C	2 000	750	$0{,}003 \times p_{test}^{0{,}65} \times 10^{-3}$
D	2 000	750	$0{,}001 \times p_{test}^{0{,}65} \times 10^{-3}$

2.9.6. Installation noise

Noise production is an important factor for duct designing and should be limited as much as possible, to prevent noise disturbance in rooms. Figure 2.31 illustrated by Bhatia (2014) describes the major noise sources from the mechanical ventilation system, where five sources are distinguished:

1. Ductborne noise: caused by the airflow and is depending on the ventilation speed. Poor airtightness could result in whistling noises, due to small leakages.
2. Radiated equipment noise: caused by equipment which will start vibrating as well interior sound pressure of the equipment.
3. Break-in noise: noise from equipment will enter the duct and transmits down the duct system.
4. Break-out noise: noise that transmits through the wall of the duct itself.
5. Terminal end noise: caused by airflows at finishing trims such as diffusers and grills.

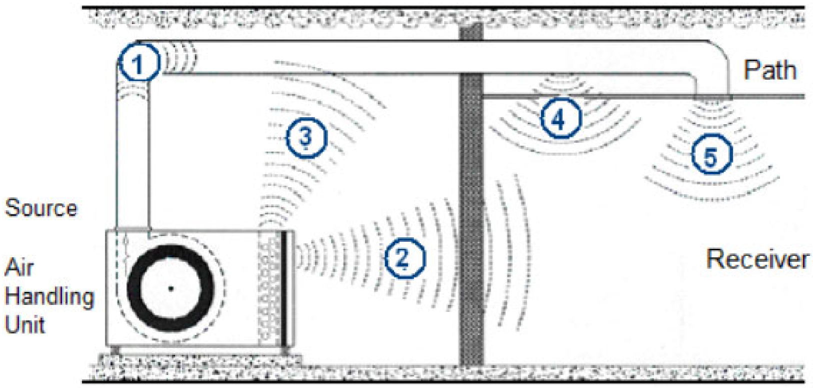


Figure 2.31 Installation noise in mechanical ventilation system (Bhatia, 2014).

Insulation material inside ductwork is an efficient solution for sound attenuating and lowering the break-out noise if it is applied to the rigid component. Another efficient location is duct bends, where the noise directly hit the bend, resulting that the insulation material will absorb sound energy. Placing insulation material at the part of the duct which is connected to the fan outlet is also an efficient way to lower noise levels. However, there should be attention paid to the material itself when designing for high-velocity duct systems, the high airspeed could cause the material to lose particles leading to polluted ducts. Consequently, the choice of air velocity in ducts is often dependent on the noise generation leading to less economically optimal solutions (Airways Partners, 2002).

Noise disturbance could result in health issues, caused by the noise itself or the occupant will shut down the ventilation system, which influences the indoor comfort. According to NEN-EN 5077 (2019) maximum installation noise level (LI,A;k) requirements are set up and calculated to protect user and living comfort. For residential buildings, the value should not exceed 30 dB (A), for utility buildings such as offices, schools, and healthcare the requirements are set between 30 and 40 dB (A).

2.9.7. Fire resistance

Fire resistance in buildings is important for the safety of occupants. The building component should be able to withstand a developed fire and fulfill in the fire resistance requirements of load bearing capacity, integrity and insulation. The fire resistance is expressed in minutes and can be tested according the requirements stated by NEN-EN 13501-2 (2021):

- Loadbearing capacity (R): The fire resistance of a construction component for a period of time in minuts without losing the structural function during the test. This criteria applies for construction components only.
- Integrity (E): The time which the test product continues to maintain its seperating function without the passage of flames or gasses.
- Insulation (I): The time which the test product continues to maintain its seperating function without transferring heat, resulting in temperature increase.

In order to prevent fire spreading through ventilation ducts without fire dampers, a fire test should be carried out accordance the test method described in NEN 6076, where the time of each criteria is meassured. Therefore the following classification is introduced: 20, 30, 45, 60, 90, 120, 180, 240 or 360 minuts. The duct should comply in the criteria of integrity (E) and insulation (I), based on the test results a fire rating can be assigned to the duct. For example EI30 indicates the duct is classified for 30 minutes of integrity and thermal insulation, if E fails I automatically fails. The aim is to achieve a fire resistance of 60 to 30 minuts for ducts.

In addition, 7 Euro fire classes are introduced according NEN-EN 13501-1 (2019). The principal of the fire class system is that the best material must not contribute in any way to fire. A non-combustable material belong in the highest class A1, and is therefore classified as the safest material. The most flammable material or a material without any data is assigned to the lowest class F. The Euro fire classification are combined with classification related to smoke production (s) and burning droplets (d). Burning droplets occur when the materials starts burning and smaller particles of the material drop, which can result in firespread. The table related to Euro fire classes and the corresponding smoke and burning droplets classes is stated in table 7.

Table 7 Fire Euro class according NEN-EN 13501-1 (2019).

Euro class	Smoke class	Burning droplets class
A1	-	-
A2	s1, s2 or s3	d0, d1 or d2
B	s1, s2 or s3	d0, d1 or d2
C	s1, s2 or s3	d0, d1 or d2
D	s1, s2 or s3	d0, d1 or d2
E	s1, s2 or s3	- or d2
F	-	-

s1 = none
s2 = little
s3 = average
s4 = large

d0 = none
d1 = droplets burn < 10 seconds
d2 = droplets burn > 10 seconds

2.9.8. Moisture resistance

Condensation in a ventilation duct primarly occurs by the temperature difference between the vent, outside air and the humidity in the outside air. For standard metal sheet ventilation ducts condensation is not a direct issue, nevertheless it is recommended to check the quality of the ducts after a certain lifespan. However, when taking into account bio-based materials a potential problem occurs since bio-based materials are more porous leading to water absorption and potential molding of the material. A way to prevent this would be by applying a coating at the inner surface of the duct.

2.9.9. Chemical emission

Volotile organic compounds, including common folmaldehyde, under the name TVOC, are a critical aspect under normal conditions by a variety of commonly used products. Including the evaporation of materials such as building materials, glue, paint, MDF, leather, carpet, cosmetics and ventilationsystems. Consequently, the exposure to high concentration of these gasses results in higher chanches of health problems, including sickness and headache. In order to secure a healthy and comfortable living environment NEN set up strict requirements as stated in Table 8 (TVVL, 2018). The values are meassured with respectively a TVOC or formaldehyde meter.

Table 8 Chemical emission classification and limits (TVVL, 2018).

Class A (Very good)	Class B (Good)	Class C (Sufficient)
The formaldehyde (HCOH) concentration is max. **30 micogram/m3**. The total volotile organic compounds, TVOC concentration is max. **200 microgram/m3**.	The formaldehyde (HCOH) concentration is max. **30 micogram/m3**. The total volotile organic compounds, TVOC concentration is max. **500 microgram/m3**. **Explanation:** The formaldehyde measurements are conform NEN-ISO 16000-3. The TVOC measurements are conform NEN-ISO 16000-4	The formaldehyde (HCOH) concentration is max. **120 micogram/m3**. The total volotile organic compounds, TVOC concentration is max. **1000 microgram/m3**.

2.9.10. Duct cleaning

Duct cleaning is important to prevent several problems, which could occur when cleaning of the ducts is ignored. There are three main reasons to clean ducts (Airways Partners, 2002):

- The pollutants block the ducts which has a negative consequence on the functionality, meaning a higher pressure drop and air ventilation rate to compensate, or
- combustable pollutants can pile up inside the duct that can cause fire, or
- the ducts contain contaminants which result in poor air quality and can cause danger for the occupants health.

According to Bhatia (2014) there are multiple ways to clean the ducts as, three common methods will be explained: vacuum method, air sweep method and the power brushing method. Illustrated in Figures 2.32, 2.33 and 2.34.

Vacuum method

The interior of the duct is cleaned through openings and outlets. A vacuum unit HEPA (High Efficiency Particle Air) is used to collect the dust or other contiminants. The end of the vacuum cleaner is placed in the duct using the opening at the start of the duct system. The dust and other contaminants are collected when the vacuum starts proceding through the duct resulting the particles to move to the head of the vacuum cleaner.

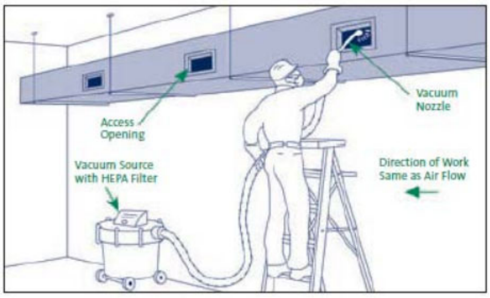


Figure 2.32 Vacuum cleaning in duct (Bhatia, 2014).

Air sweep method

The air sweep method makes use compressed air which is lead through the duct with a skipper nozzle and collected by a hose connected to a vacuum collection unit at the end of the duct. The nozzle is propelled by the compressed air through the inside of the duct. The air pressure should be reaching a value between 160 and 200 psi to be effective enough to remove the dirt and dust particles from the duct.

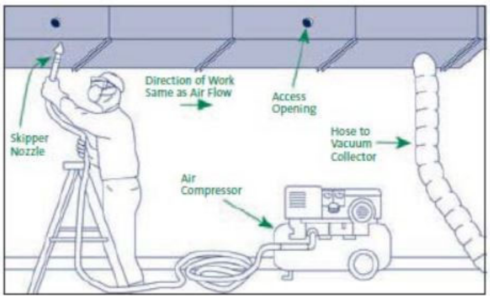


Figure 2.33 Sweep cleaning in duct (Bhatia, 2014).

Power brushing method

This method makes use of a vacuum collection unit connected to the duct in the same way as the air sweep method. In the power brushing method, electric rotary brushes are used to remove dirt and dust particles, which are collected in the vacuum unit. In general brushing require larger openings, due to the large brush size, but fewer openings are required since brushes can reach 6 meter of distance in both direction.

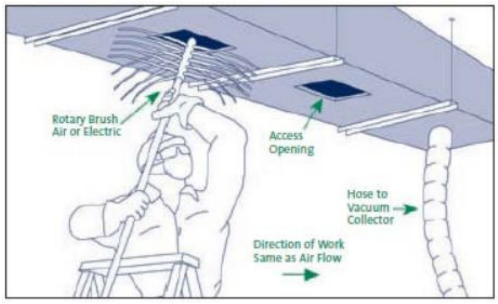
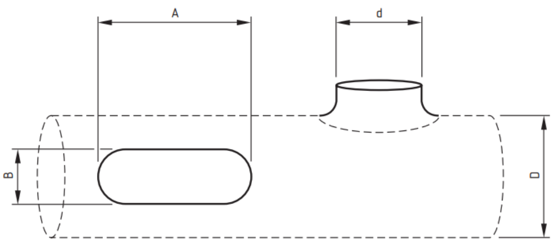


Figure 2.34 Brush cleaning in duct (Bhatia, 2014).

In order to access the ducts for cleaning, NEN-EN 12097 (2006) set up maximum required opening sizes for circular ducts. The sizes according to the diameter of the duct are stated in Figure 2.35.



Rectangular or oval opening		Branch/T-piece + end cap with minimum diameter	
Duct diameter nominal (mm) D	Minimum dimensions of openings in duct walls (mm) A x B	Duct diameter, nominal (mm) D [a)]	Nominal EN 1506 male dimension or minimum opening (mm) d
100 ≤ D < 200	180 x 80	100	100
200 ≤ D ≤ 315	200 x 100	125	100
315 < D ≤ 500	300 x 200	160	125
500 < D	400 x 300	200	160
		250	200
		315	250
		400	315
		500	400
		≥ 630	500

[a)] For additional sizes the requirements of the nearest larger nominal size apply.

Figure 2.35 Access openings rigid circular ducts according NEN-EN 12097 (2006).

2.10. Conclusion

Ventilation is important to replace polluted air with fresh air by using natural or mechanical ventilation. Natural ventilation makes use of pressure difference resulting the air the move. In case of mechanical ventilation, ventilation systems are mandatory which consists of many components to transfer the air from one point to another.

Air ducts are manufactured in different materials, sizes and shapes depending on their applicability. However, the most common ducts are made from sheet metal, often galvanised steel, in three shapes including round, rectangular and oval. The difference in shape results in a variaty in performance, manufacturing method, installation efficiency and cost. By comparing the three different shapes the round or spiral winding sheet metal duct is the most efficient in the previous mentioned aspects. The main advantage lies in the limited material usage due to its low surface area, resulting in 30% less material than a rectangular duct resulting a significant weight reduction. In addition, the round sheet metal duct is manufactured as a spiral which makes it possible to make the air ducts more rigid resulting in longer ducts. This is achieved with lock seams by pinching and locking the metal coils together, which also function as seams to make airtight ducts.

Lastly, the design and construction of air duct components comes together with important requirements in order to maintain the quality conform the regulations. These requirements are related to general properties, including dimensions and weight, performance aspects such as airtightness, moisture resistance and chemical emission, and maintenance related to the openings for cleaning.

3.
CIRCULARITY

This chapter describes the definition of circularity, aswell the general principles of circularity and approaches for the built environment and building services. The following sub-questions will be answered:

- What is circularity in the built environment?
- How can circular strategies be applied to the lifecycle of air ducts?

3.1. The circular economy

Today's linear economy of take-make-dispose relies on products produced from raw materials, used and discarded as waste. There already have been progression made by improving the efficiency of resources, however the linear approach which focuses on consumption rather than restoring the used resources facing losses along the lifecycle of the product. Therefore the transition from a linear to circular economy is crucial to reduce material consumption, emission and waste generation.

The circular economy relies on restorative and renewable design by keeping products, components and materials in their highest value as long as possible. The development of circular approaches throughout the years led to many interpretations for the term circular economy. Interpretations rely on different principles, many are based on the 3R framework of reducing, reusing and recycling, others rely on more variated approaches such as the 10R framework. The interpretations focus on the perspective of the systems as well sustainable development. The Ellen MacArthur Foundation (2012) defines the circular economy as follows:

> 'A circular economy is an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models.' (Ellen MacArthur Foundation, 2012, p. 7)

The transition to a circular economy will change how products are designed, fabricated and how materials are applied. Many innovative approaches have already been explored, however current challenges are lacking circularity guidelines and assessment tools for materials as well building components.

3.2. Circularity principals

The circular economy is based on three main principles, Ellen MacArthur Foundation (n.d.) distinguishes the following principles: eliminate waste, circulate products and materials, and regenerate nature.

- Eliminate waste: The first principle is to eliminate waste and pollution. Currently raw materials are harvested, made into products and eventually thrown away in a linear way of take-make-dispose. Much of this ends up in landfills and the quality of the product is lost. To eliminate waste the design flow should be shifted from linear to circular, making it possible that materials can re-enter the economy at the end of life stage.
- Circulate products and materials: The second principle is to circulate products and materials at their highest quality. Therefore it is important to keep the materials in use, either as a component or raw materials. In this way no waste is created and the quality of the products and materials is maintained.
- Regenerate nature: The last principle is to regenerate nature. Instead of extracting materials the focus shifts to the regeneration of materials. The focus lies on recreating nature rather than degrading the nature, which allows to rebuild soils and increase the biodiversity, as well return renewable biological materials on the planet.

3.3. Circularity approaches

There are many principles developed throughout the years to achieve and indicate a circular approach. Due to the amount of different approaches it is impossible to apply them all at once. Therefore, an overview of common and relevant approaches are elaborated for this research, which are relevant to set up a suitable strategy for the design of a circular bio based air duct.

3.3.1. Resource loops

In order to distinguish the circular economy and linear economy, Braungart et al. compared both models for the development of products. The main distinguish can be made between “cradle-to grave” flows of materials and cyclical “cradle-to-cradle” flows, which marks a difference in resource flows. In addition, Stahel refers to “closed loop systems” distinguishing two different types of loops within a closed loop system: reuse of goods and the cycling of materials. Building on of work by Stahel and Braungart et al., Bocken et al. (2016) describes two main strategies and regarding the cycling of resources, which indicate the resource flow in a system as illustrated in Figure 3.1. As well a third strategy which comply the two main strategies to reduce the resource flow.

- **Slowing resource flows:** By designing durable products and product-life extension, the lifespan of the products is extended and/or intensified, resulting in a slowdown of the resource flow.
- **Closing resource flows:** By recycling, the loop between post-use and the production phase is closed, leading to a circular flow of used resources.
- **Narrowing flows:** By using resources more efficiently and less resources per product. This flow is more related to sustainable use of resources rather than circularity.

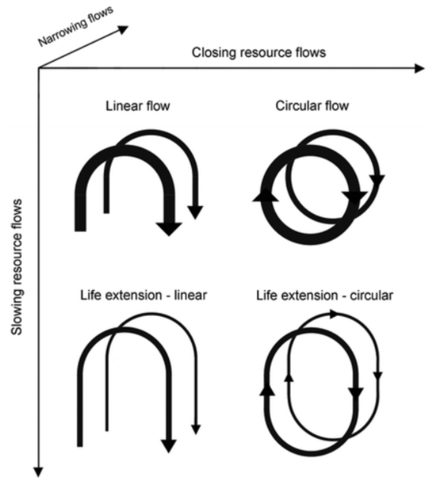


Figure 3.1 Resource loops. Bocken et al. (2016)

3.3.2. The Butterfly diagram

In the circular economy there are two type of material cycles are distinguished: the biological and the technical cycle illustrated in Figure 3.2 (Ellen McArthur Foundation, 2015). The difference between the cycles give an understanding of how materials can be used in a such a way that the lifespan is increased and high quality is achieved. In general the material has a higher quality if it has to go through less steps of reuse.

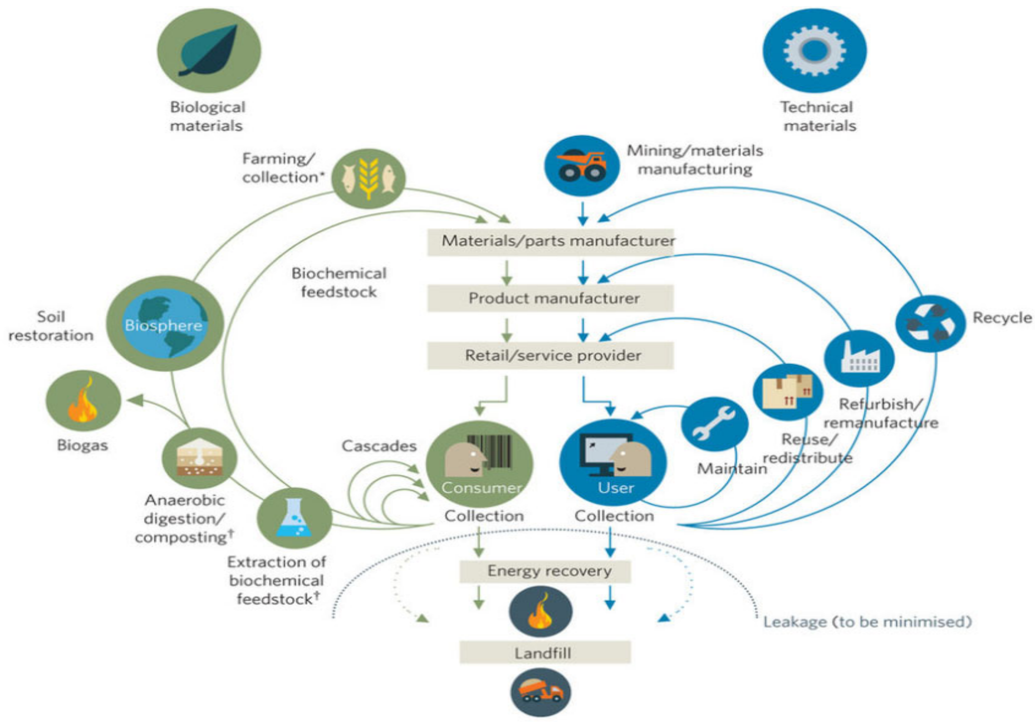


Figure 3.2 Butterfly diagram (Ellen MacArthur Foundation, 2015).

Biological materials such as wood, straw, and flax are incorporated into the ecosystem and re-generated through biological processes. In the biological cycle it is important that the ecosystem do its work properly. Biological materials are organic and renewable. However, technical materials such as metals, plastic and fossil fuels are not infinite and cannot be renewed. Therefore, it is important that materials in the technical cycle are managed efficiently and that the lifespan of the materials is extended as long as possible (Kenniskaarten, 2016).

For the biological cycle the reuse takes place in cascades or they go back in the biosphere. For cascading the parts of a product are used for another application. This is the case when the product cannot fulfil the origin function and it is assigned to be reused. During the cascading cycle the quality of the product is reduced and energy is consumed.

In the technical cycle there are multiple levels of reuse, indicated as inner circles. The smaller the inner circles, the less processing, labour, new material and energy is required to be on the origin quality of the material. The following levels of reuse are distinguished within the technical cycle (Ellen MacArthur Foundation, 2015):

- Maintenance/prolong: Maintain to extend the lifespan of the materials and products.
- Reuse/redistribution: Reuse materials and products and distributing them to new company or user.
- Refurbish/remanufacture: The refurbishment and repair of the product by the manufacturer.
- Recycle: Reusing parts of the materials or products.

3.3.3. R-ladder

The 10R framework (Cramer, 2017): Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle and Recover, represents an waste hierarchy framework in Figure 3.3. In addition, it is an approach to use materials and close material loops. The classification is divided in three main strategies: smart product use and manufacturing, extension of product lifespan and useful application of materials. The higher priority is on the top of the framework (R0-R2), by avoiding resource and energy consumption in the life cycle of the product, which results in tighter loops and more circular strategy. The longer the loops (R8-R9), the less priority it has in achieving a circular strategy. However, recycle and recover can be chosen to be the best option if there are no other options.

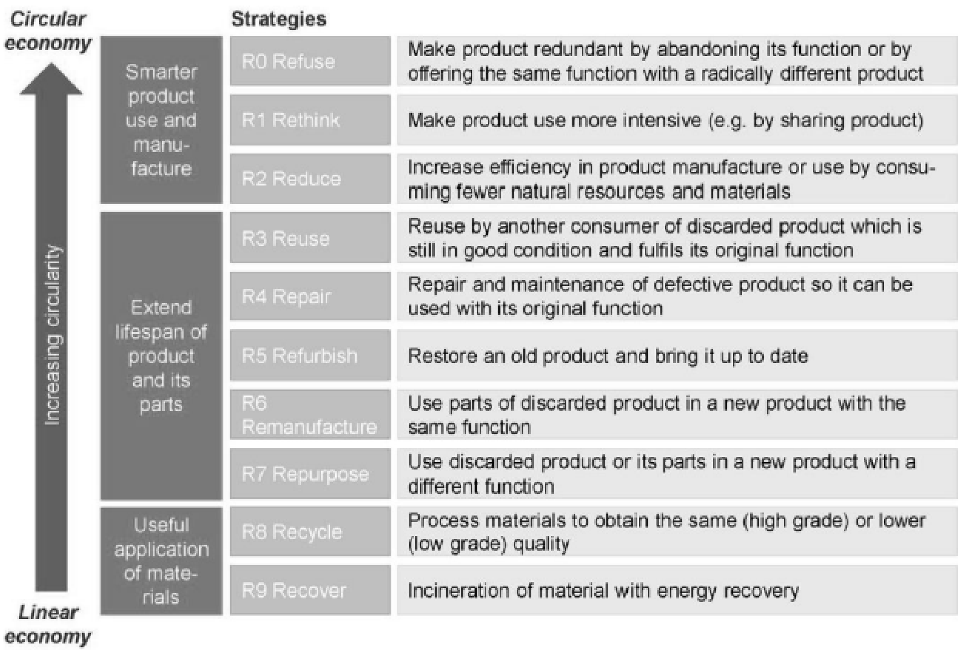


Figure 3.3 R-ladder (Cramer, 2017)

3.4. Circularity in the built environment

3.4.1. Theory of systems and layers

In the building environment circular economy approaches can be applied on different scales from material into components, buildings, neighbourhoods, cities and regions. These scales are always related to several aspects including management, technology, design, resource flows, stakeholders and economy as illustrated in Figure 3.4.

Figure 3.4 Building layers and lifespan (CBH, 2010)

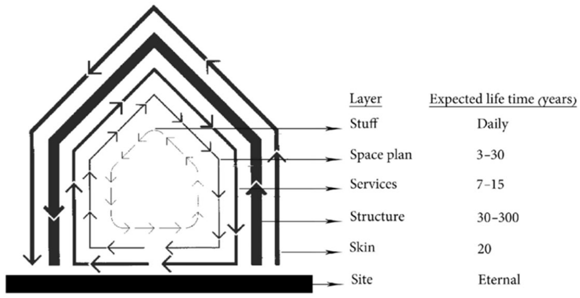


Figure 3.5 Building layers and lifespan (Durmisevic, 2010)

In order to use building components at their highest value, it is important to consider building components as a combination of parts and materials, each with their own lifespan. Brand (1994) describes the concept of 'shearing' layers as: a building which is divided in different layers with each their own lifespan which can be adapted independently as illustrated in Figure 3.5 (Durmisevic, 2010). The same principal accounts for building components as a composite of parts and materials with different lifespans.

In this concept building services have a relatively low lifespan of 7-15 years and are sometimes deeply embedded within other layers with a longer lifespan, such as the structure. Therefore it is important that layers with a low lifespan should be designed independently of the layers with a long lifespan, to allow easy access and replacements, and avoid unnecessary demolition of components, Figure 3.6 (Croxford, et al., 2018).

	SITE	• Fixed location of the building, whose boundaries and context outlast generations of ephemeral buildings. • "Site is eternal." (Brand, 1994)
	STRUCTURE	• The foundation and load-bearing elements are enduring elements. Buildings can completely change their appearance and use without changing their structure. • Replacement every **30-300 years**
	SKIN	• The external envelope can change to adapt to aesthetics, new technology, better daylight, energy efficiency or repair. On occasions, façade replacement can reduce operational carbon to the extent of outweighing the extra embodied carbon incurred. • Replacement every **~20 years**
	SERVICES	• Includes all systems that that operate the building: communications wiring, electrical wiring, plumbing, fire sprinkler systems, HVAC (heating, ventilating, and air conditioning), and moving parts like elevators and escalators • Replacement every **7-15 years**
	SPACE	• The Interior layout affecting the location of partitions, ceilings, floors and doors • Commercial space can change every **3 years**. Homes can extend to **30 years**
	STUFF	• Furniture, appliances, fixtures, etc. It can be moveable or fixed • This changes from a **daily to monthly basis**

Figure 3.6 Building layers elaboration (Croxford, et al., 2018).

Understanding the principal of different types of lifespan is important to slow and close loops efficiently. Lifespan can be divided into three types: technical, functional and economic lifespan. The technical lifespan is the maximum durability period which it can physically perform. The functional lifespan is influenced by the user needs and regulations. Lastly, the economic lifespan is the period when the benefits cover or outweigh the initial costs (van Stijn et al., 2021). In addition, the building layers can be further divided into a detailed classification. Eeckhout (2008) distinguished multiple levels by focusing on the industrial building products, differ from material to building part level:

- Material: raw materials without any adjustments or treatment.
- Standard material: intermediate products in standardized shapes
- Commercial material: specially fabricated for the purpose of a special product
- Elements: assembly of several or different commercial materials
- Sub-component: assembly of elements with a (functional) purpose
- Component: independent functional building part, usually assembled in off site and transported to the building site.
- Building part: collection of elements and components with similar (technical) function

Beurskens & Bakx (2015) combined both described concepts of Brand and Eeckhout into one circular approach. Therefore four sheared layers are applied: structure, skin, service and space plan. These layers are divided into system level (S), sub-system level (SS), component level (C), element level (E) and material level (M). Each step of this approach goes along with circular principles to achieve circularity in the different levels, including applicability of design for disassembly, design for adaptability and the applicability of sustainable materials as illustrated in Figure 3.7 (Berskens & Bakx, 2015).

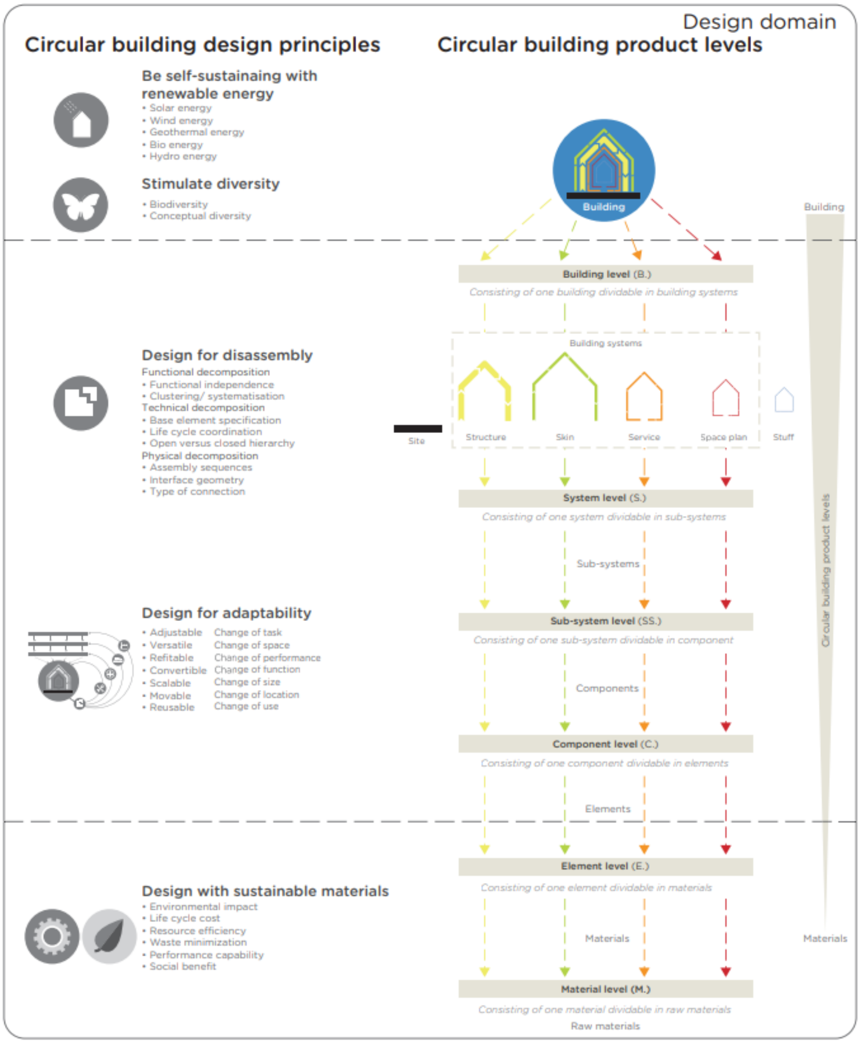


Figure 3.7 Design domain - Circular building design principles related to the circular building product levels (Beurskens & Bakx, 2015).

Next Beurskens & Bakx (2015) introduced an circular building construction model, which is a combination of earlier mentioned circular strategies as the Butterfly model and the 10 R-framework. By applying these strategies to the circular building construction model it shows that the model is able to operate in a circular way. The model illustrates the re-life options translated to different cycles after the components of the building lose their value and how this can be restored as illustrated in Figure 3.8.

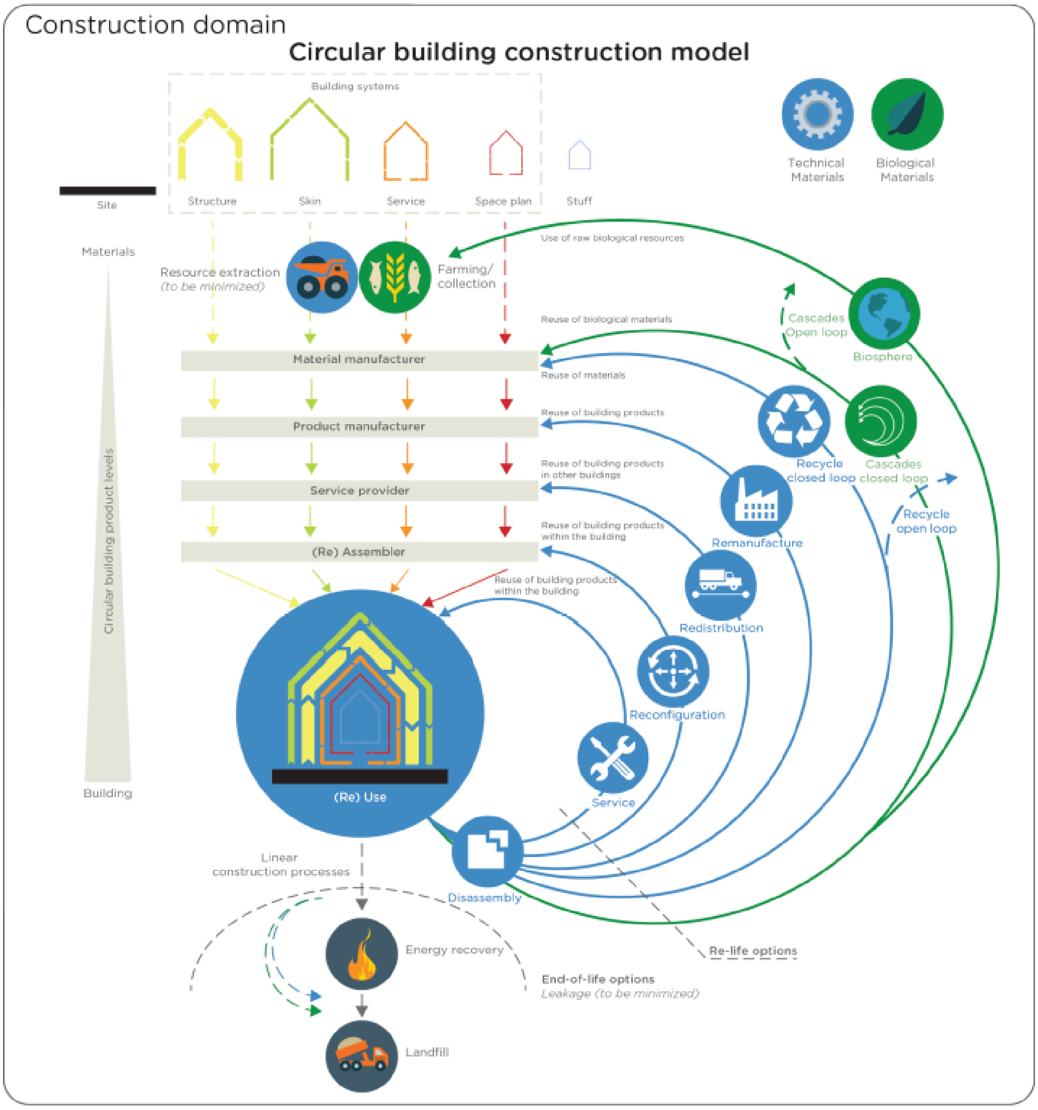


Figure 3.8 Construction domain – Circular building construction model (Beurskens & Bakx, 2015).

3.5. Circular strategy for building services

In the context of the transition to circular buildings TVVL (2020) developed a circularity strategy for building services, inspired by the Trias Energetica and analysis of current circularity approaches.

In the next years buildings have to become more comfortable, safer and more energy efficient, in this development building services play an important role. The introduced circular tool for building services is a combination of two existing circular models. Firstly the 10 R-model, which is reduced to a 4 R-model: Rethink, Reuse, Remanufacture and Recycle. Furthermore, there are 8 parameters applied which are used by GPR, BCI and Madaster, including convertibility, adaptability, connection method, replaceability, releasability, source, lifespan and maintenance. Designing for circular building services is challenging, since most of the installations consist of many components. This makes it often difficult to measure the most circular option. The circularity disk is an tool that gives structure to the design of building services in a circular way. It helps the experts to ask themselves the right questions and to search for suitable solutions during the conceptual design phase (Gerritsen, 2019).

The disk distinguishes three steps which are indicated with different colours. The first step (blue) is related to the lifecycle of the building, it is important to go through every step of the circular design tool for each building cycle in order to design a circular building installation. In the second step (green) focus on reducing the environmental impact of the used materials, the greener the colour the higher the impact on a circular design. The last step (orange) explores the circular potential of the used materials and components for the future as stated in Figure 3.9 and 3.10 (TVVL, 2020).

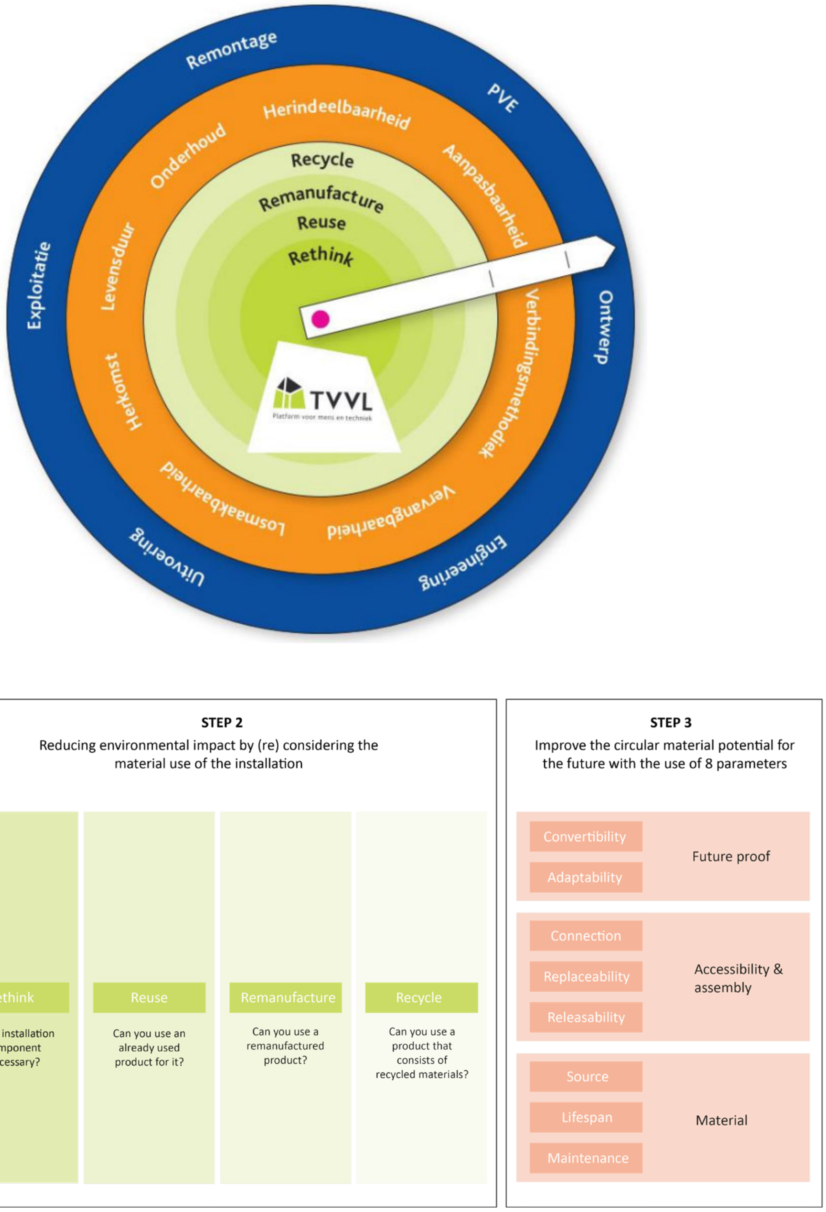


Figure 3.9 and 3.10 Circularity disk for building services (TVVL, 2020).

3.6. Conclusion

The transition from a linear to circular economy is important to have the maximum benefit of the used resources by maintaining their value as long as possible. Overtime this went along with the development of circular strategies including resource loops, The Butterfly diagram and the R-framework.

In the building environment the circularity approaches are related to different scales and layers with each their own lifespan with the possibility to adapt independently. The lifespan of a building layer, component or material can be divided into a technical, functional and economic lifespan. This is important to understand to slow and close the resource loops.

In the future buildings need to be more sustainable, therefore building services play an important role. TVVL (2020) introduced a circularity tool by mean of a disk. The disk distinguished three steps to apply circulair decisions into the building services industry including air ducts. This relates to the buildings lifecycle, limiting carbon footprint of applied materials and circularity potential of materials and components for future changes. This include important aspects including adaptability, replaceability, lifespan and maintance.

4.

BIO-BASED MATERIALS

This chapter describes the definition of bio-based materials aswell the categorization of different types of bio-based materials and relevant manufacturing methods for the explored bio-based materials. The findings give background information of the available bio-based materials and manufacturing methods to answer the following research question later in this research in chapter 6:

- Which bio-based materials are suitable for the fabrication of air ducts?
- What are appropriate manufacturing methods for the selected suitable bio-based materials?

4.1. Bio-based material definition

Different definitions are found in literature for bio-based materials. The European standard NEN-EN defined bio-based as materials that are produced fully or partially from biomass. Mentioning that "the biomass can be processes physically, mechanically, chemically or biologically, resulting in bio-based materials, which can be processed with or without materials of other origins (e.g. fossil, mineral) resulting in bio-based products" NEN-EN 16575 (2014). Biomass is a renewable material from biological origin mainly from trees, plants and animals.

In addition to the definition, bio-based materials are in most cases biodegradable, but rarely non-biodegradable. Biodegradable materials can be broken down by microorganisms into biomass, water, methane (CH_4) and carbon dioxide (CO_2). This is hardly dependent on environmental conditions: temperature, microorganisms, oxygen and water.

4.2. Classification of bio-based materials

Materials are divided into a classification, according Kula, Ternaux, & Hirsinger (2014) several main classification can be distinguished: metals, plastics, wood, ceramics, composites, wood, cardboard, leather, textiles (natural fibres), stone and concrete. Where celullose fibres and fungi are added as an additional category. The selection of a suitable bio-based material is based on the ability to be produced locally in the Netherlands. From these categories metals, ceramics, leather, stone and concrete are eliminated since to material is either not renewable, not bio-based, high density or the material (leather) is not developed enough to be applicable yet. This resulting in the following categories to be further explored:

- Textiles - Natural fibres
- Celullose fibres
- Bio-plastics
- Bio-composites
- Wood
- Cardboard
- Fungi

4.2.1. Textiles natural fibres

Natural fibres, are the most rich and renewable bio-based materials source derived from nature. Their origin can be obtained from several biological sources, including plants, animals or minerals. The natural fibres are classified according to their origin as shown in Figure 4.1 (Persson, Ramamoorthy, & Skrifvars, 2015).

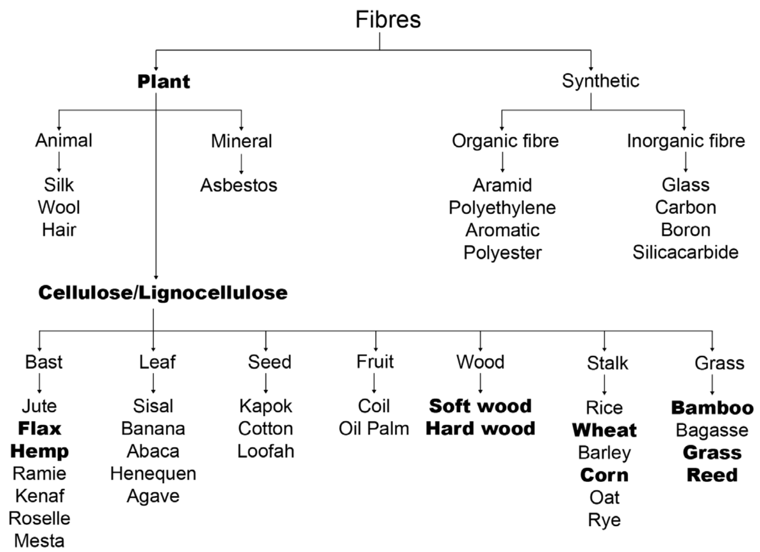


Figure 4.1 Natural fibres selection based on local production in the Netherlands (Persson, Ramamoorthy, & Skrifvars, 2015)

The properties of the natural fibres varies largly and depend on several aspects. In fact, natural fibres are a kind of biopolymers, consisting of cellulose, hemicellulose, lignin, pectin and waxes in different proportions. The content of the three main components for the selected natural fibres are tabled in Table 1. These polymers are the basic components in a cell wall and determine the physical and chemical properties of the natural fibres, such as moisture content, biodegradability, flammability, thermoplasticity and degradability caused by uv light, acids and bases (Venkateshappa, 2011).

Cellulose

The main component of the plant fibres is cellulose and plays an important role to keep the structure of the cell walls stable, in this way the stiffness and strength is maintained. There fibres with a higher percentage of cellulose have a better structural quality.

Hemicellulose

This component helps to bond the lignin and cellulose together, hemicellulose is related to the water absorbency, swelling and elasticy of the fibre.

Lignin

Lignin adds rigity to the cell walls, aswell offer protection against pests. Often lignin is extracted from plant fibres to improve their mechanical properties.

Table 1 Natural fibres chemical composition.

Natural fibres	Cellulose (wt%)	Hemicellulose (wt%)	Lignin (wt%)	Reference
Flax	71,0	18,6	2,2	(Persson et al., 2015)
Hemp	70,2	17,9	3,9	(Persson et al., 2015)
Wheat	39,0	15,0	13,0	(Persson et al., 2015)
Corn	44,5	19,7	25,5	(Buranov & Mazza, 2008)
Bamboo	26,0	30,0	21,0	(Persson et al., 2015)
Grass	33,0	27,0	17,0	(Rowell et al, 1997)
Reed	31,0	29,2	25,3	(Si et al., 2015)

Plant fibres have different origins such as bast, leaf, seed, fruit, wood, stalk and grass, which greatly affect the mechanical properties of the fibres, as a result of the long fibres derived from the stem. Therefore it can be noticed that bast fibres, including flax and hemp, have better mechanical properties in terms of strength and stiffness compared to the other origins as stated in Table 2. The tensile strenght indicates the resistance of the fibre against breaking under tension. The young’s modulus relates to the bending force it can manage when the material is under tension or compression, indicating the stiffness of the material. The higher these values the better the resistance under a specific force.

Table 2 Mechanical properties natural fibres.

Natural fibres	Density (g/cm3)	Tensile strenght (Mpa)	Young's modulus (Gpa)	Reference
Flax	1,4	345 - 1100	27,6	(Persson et al., 2015)
Hemp	1,5	690,0	30,0	(Persson et al., 2015)
Wheat	1,6	273,0	5 - 7	(O'Dogherty et al., 2015)
Bamboo	0,6 - 1,1	140 - 230	43,0	(Persson et al., 2015)

Fibre selection

From Table 1 and 2 the chemical and mechanical properties of the fibres are stated, as mentioned flax and hemp have significant better properties compared to the other fibres. The cellulosic content plays an significant role, since this component is responsible for the structural abilities of the cell walls in terms of strength and stiffness. When looking to the tensile strength the flax fibres have an significant advantage over hemp fibres, where the young’s modulus is nearly similar. Nevertheless, it can be stated that the flax fibres have the best properties overall.

In addition, flax and hemp can be spun into fabrics, however for flax there is a larger amount of fabric arrangements possible compared to hemp, increasing the design freedom. Persson et al. (2015) the fabric arangement can be divided into three types including knitted, woven (textiles) and non-woven fabrics (fibre mat), all developed by weaving yarns into the specific arangement.

4.2.2. Cellulose fibres

ECOR developed a fully bio-based and recycable raw material for the building industry, based on waste materials from mainly the agriculture industry, forest and urban life. Examples of these materials are grass, reed, cellulose, but also jeans, coffee or brewer's grain as left over from production. The manufacturing process only uses heat, pressure and water to press the extracted cellulose fibres into the desired panels without the use of adhesives as illustrated in Figure 4.2 (ECOR, n.d.).

Casestudy A: ECOR panels

Manufacturer
ECOR

Location
Venlo, Netherlands

Manufacturing technology
Compression molding using heat, pressure and water

Material
Cellulose fibres from agricultural waste products

Application
Furniture, construction, displaying

Figure 4.2 ECOR moulded panels (ECOR, n.d.).

Description
The waste gathering process starts by diverting usefull raw materials before they enter the original disposal. They are sorted, processed and stored for till the raw materials are used based on the specific fiber composition required for the panel. The raw materials are processed into a usefull resource via a pulping process to achieve the right properties. Then the pulp is dispersed in water at a close tolerance to achieve a chemical reaction. This reaction occurs on cellular level between cellulose, hemicellulose, lignin, proteins and amino acids, where lignin has a binding function aswell increasing mechanical strenght properties. By using the right amount of heat and pressure, the lignin and hemicellulose become realigned and cross-bonded on the cellulose molecules creating a strong interlocking of fibers.

By creating a circular alternative based on balanced systems of inputs and outputs, all applied materials have a residual value due to the recycability and CO_2 reduction. In order to achieve an optimal en-of-life scenario of the product, circularity and recycability are key aspects during the design phase. Wooden products often use petroleum chemicals making them impossible to recycle due to the applied toxic adhesives. ECOR contains no toxic adhesives, formaldehyde to produce zero volatile organic compounds.

By creating a scalable closed-loop supply chain solution, waste fibers from large consumer brands have been up-cycled into raw materials. In this way a valuable product is fabricated for the same brand from waste. ECOR proved that valuable resources from waste should never end up in landfill, and could become a reliable and CO_2 efficient resource for raw materials (ECOR, n.d.).

4.2.3 Bio-plastics

Bio-plastics are developed from renewable resources and living organisms such as plants and animals: starch, cellulose and protein. Bio-based polymers can also be produced from plant oils such as PLA, PHA and PBS. In addition, not all bio-plastics are biodegradable examples are PE, PP, PET and PA which can also be produced from bio-based materials. The biodegradability of the bio-plastic relates to the chanche of chemical structure when it reacts with the biological environment. This results that bioplastics can be divided into several categories based on their bio-based content and biodegradability as illustrated in Figure 4.3 (European Bioplastics, n.d.):

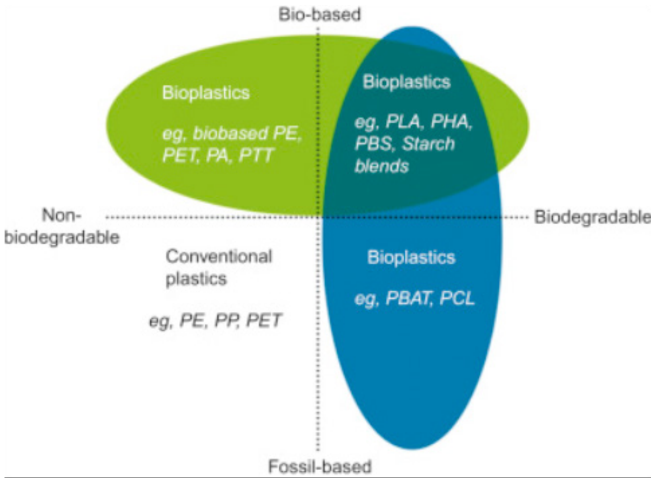


Figure 4.3 Bio-plastics overview (European Bioplastics, n.d.).

When looking at plastics two main divisions can be made including thermosets and thermoplastics, which act different when exposed to heat. The main difference is that thermoplastics can be reheated and remelted in the original state examples are PLA, PP and PE. Thermosets on the other hand remain solid once they hardened which makes it an irreversable material with exposed to heat such as PET, PVA and PVC (Osborne, n.d.). The difference in material properties also effects consequently the recycability of the plastic, thermoplastics are easier to recycle to its lower melting point. Thermosettings on the other hand are more challenging especially if its applied as resin or binder in a bio-composite.

4.2.4 Bio-composites

Bio-composites are created by combining atleast two materials with different material properties. Atleast one of these materials, the reinforcement, is derived from biological sources, including natural fibers such as flax, hemp, corn waste or grass. The matrix within the bio-composite consists of a (natural) polymer, resulting in a composite material with better material properties than the original separate materials. In terms of strength and resistance against rough environment: for instance water or moisture.

The application of bio-composites can be found in the automotive, furniture, construction and packaging industries, due to the increased climate awareness and the depletion of non-renewable resources leading to the development of cost-effective renewable products.

Reinforcement

The reinforcement of the bio-composite can be classified in three main types based on the form of their structural components: fibre, particles and laminate based reinforcements as visualised in Figure 4.4ab (Hodzic and Shanks, 2014). A fiber-reinforced layer consists of many fibres implemented in a matrix material. The fibres can be orientated in different directions either continious or discontinious, by combining different layers into a laminate the desired stiffness and thickness can be achieved. In general, natural fibres are mostly applied for bio-composites due to their ease of seperation compared to the other options, aswell the ability to combine several layers into a laminate. low costs, low weight and high toughness against impact:

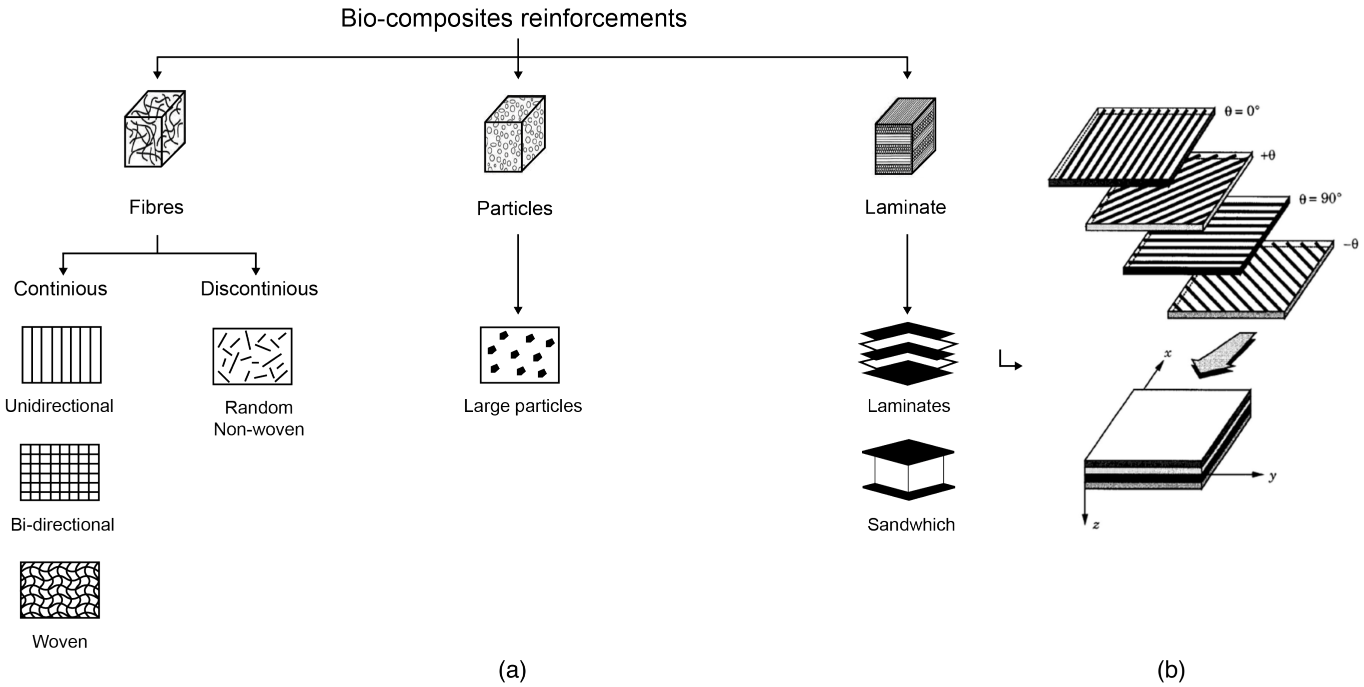


Figure 4.4 Reinforcements overview (Hodzic and Shanks, 2014).

(a) unidirectional flax fibre (b) flax fibre cloth (c) 200g non-wovenl flax fibre mat

Figure 4.5 Overview reinforcements flax fibres (Easy composites, n.d.).

Matrix

The matrix, known as resins, is the other component in the bio-composite, which can be either a inorganic material, natural polymer or synthetic resin (Hodric and Shanks, 2014). Matrices can be distinguished in two types, thermoplastics and thermo-settings, already explained in the bio-plastics section 4.3.

According to current literature the production of a fully bio-based matrix, 100%, is still a challenge. Bio-resins or bio-plastics have several limitations, therefore small amounts of petroleum based resins are combined with bio-based resins to achieve a cost-effective solution with higher performance for products. Therefore either thermosets or thermplastics are applied as matrix.

Casestudy B: Hemp chair 100% bio-based

Manufacturer

Vepa

Location

Hoogeveen, Netherlands

Manufacturing method

Compression moulding

Material

Non-woven hemp and 100% bio-based resin

Application

Furniture - chairs

Figure 4.6 Hemp chair materials used (Vepa, n.d.).

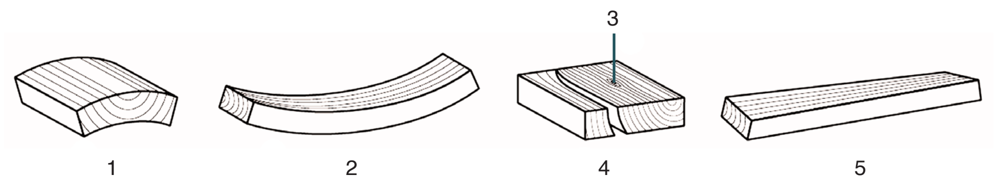
Description

The Hemp Fine is the first chair which is manufactured from an unique bio-based material, the used materials hemp and resin are plant-based and recyclable. Restproducts from the hemp industry are used after being processed into non-woven hemp mats, which is the base material for the chair. In order to create a strong chair, a bonding is applied in cooperation with Plantics. This developed resin is unique in a sense that it is 100% bio-based and able to be recycled.The components in the chair are designed in such a way that its possible to seperate and reuse them at the end-of-life stage. The materials are biodegradable, however the materials are grinded and pressed together again without losing quality (Vepa, n.d.).

4.2.5. Wood

Wood is an unique and natural material derived from trees, which has a large range of thousands species available throughout the planet. Every tree varies in density, mechanical properties, aesthetics and durability depending on the place the species grow. In general two large families can be distinguished, hard-wood and soft-wood. Hard-wood are usually slow growing trees taking up an average of 120 - 200 years to grow. Softwoods are known as fast-growing trees taking around 60 - 80 years to grow. Hardwood are often applied in the construction industry, known for their hardness and heavy-weight. Softwoods can be manufactured into layered sheets, such as plywood and fibreboard, where they are applied in the furniture industry (Kula et al, 2014). In addition, Kula et al. (2014) describe three aspects indicating the difficult material workability of wood caused by external factors such as temperature and humidity, aswell illustrated in Figure 4.7.

- Shrinkage - when drying wood is shrinking and parts of wood have the tendency to deform unevenly.
- Defects - wood may present several defects, some caused by shrinkage such as curling, warping and splitting. Knots and cracks are irregularities which can occur, making wood a difficult material to work with.
- Drying - wood is constantly changing, when it dries out it shrinks and when it gets wet it expands. Therefore drying is important to remove the water in the wood to stabilise its behaviour.



1. curling
2. bending
3. knot
4. crack
5. warping

Figure 4.7 Wood defects (Kula et al., 2014).

Veneer
This type of wood is selected due to the relative easy material workability compared to other wood types, due to its thin layers which makes it easier to bend into round shapes. The thickness of one sheet can vary from tenths of a milimeter upto a few milimeters. In addition multiple layers can be bonded together with glue to achieve thicker layers and a less fragile sheet.

4.2.6. Cardboard

Cardboard can be described as a heavy paper and is made from fibres derived from trees, recycled paper or natural fibres such as flax. In fact it is celullose as main component of the fibres, which makes it possible to produce cardboard. Due to its ease of production, cardboard is widely available in different industries in a variety of cardboard types and sizing.

Corrugated cardboard
This type of cardboard consists of two cardboard sheets with a corrugated or fluted core, a sandwhich material. The flutes gives the cardboard its rigidity, which makes it possible to withstand impacts. The corrugated cardboard is constructed in a way that the flute is of lower weight than the surrounding surfaces. There are many variations available of corrugated cardboard in terms of flute size, amount of layers such as two or three flutes and three or four sheets, aswell length and width. Their main applicability can be found in the packaging and advertising industry (Kula et al., 2014).

Cardboard tubes
This type of cardboard consists of several layers of paper and an adhesive, when winding them together on a mandrel the round shape is achieved. In this way the cardboard tubes are produced in a large variety of diameters and thicknesses, aswell specific lengths.

Casestudy C: Cardboard duct

Figure 4.8 Hemp chair materials used (Gatorduct, 2018).

Manufacturer
GatorDuct

Location
Manchester, United Kingdom

Manufacturing method
Corrugated cardboard laminating

Material
Corrugated cardboard and steel components

Application
Air ducts, mainly rectangular

Description
Currently, GatorDuct is the only duct which applied bio-based materials in the design by using cardboard as a product from trees. However, for reinforcement and connections between ducts metal components and bolts are applied, which makes the design not fully bio-based. The duct is fully recycable since the metal parts and the Tri-Wall are demountable. No data is available about the performance of the duct, with makes it difficult to compare the actual quality of the duct.

The duct is made from Tri-Wall, a lightweight cardboard panel including three liminated sheets of cardboard with a triangular structure to add stiffness. Combining the Tri-Wall with a multi layered coating made the duct fire retardant, moisture resistant, vapour resistant and water repellent. CNC cutting machinery is used to fabricate the GatorDuct, which easily is adaptable to make any duct shape: circular, rectangular and square. Due to its lightweight the duct is easy to install and transport to the building site reducing significant amount of space for transportation (GatorDuct, 2018).

4.2.7. Fungi

In the direction of material research fungi is an unique material source. Fungi are living organisms and can be classified into one of the categories of organisms, where fungi belong to the eukaryotes. The category of fungi is large and divers, where mycelium is the most well known and interesting one in its category.

Mycelium
Mycelium has the capability to produce large and complex organic structures compared to other fungi. A mycelium is a network of fungal threads also known as hyphen, which are primarly used to grow mushrooms.
In addition, mycelium consists of two characteristics to create mycelium based materials, septa and anastomose. A septum is an intern wall to split the cells of the fungi from each other. They have an opening which closes when an interruption occurs, resulting in a minimum lose of nutrients. The second important characteristic, anastomose, which is the ability of two hyphen to fuse together when they run into eachother. Anastomose is crucial to produce fast growing mycelium and results in a stronger mycelium components, since all hyphen are connected the overall mass is more consistent. It is possible to develop mycelium composites by combining a natural substrate such as flax or hemp with a binder, in this case mycelium (Tazelaar, 2017).

4.3. Coating as barrier material

The importance of a coating lies in the creation of a protective layer for the base material. In terms of bio-based air ducts this mainly includes the barrier against moisture. In order to maintain the quality of the bio-based material of the air duct in terms of potential humidity, it may be beneficial to add an coating to prevent molding of the material. There are multiple possibilities to apply a coating depending on the type of material, either sprayed or applied manually as a thin plastic film.

4.4. Manufacturing methods

Next to the potential bio-based materials, the manufacturing methods are researched. This is crucial in order to analyse later in this research the best manufacturing per material, aswell the best manufacturing method per type of component.

4.4.1. Manufacturing for natural fibres

Woven and non-woven
Natural fibres can be manufactured into several types of materials to create textiles or bio-composites as illustrated in Figure 4.9 (Graupner and Müssig, 2010). The length of natural fibres, long fibres such as hemp, jute and flax, is not endless therefore they have to be converted into yarns. From yarns they can be woven into ropes, textiles, knitted products and knotted nets. Another approach is non-woven by mechanical laying of the shorter fibres, into wadding, fleece and felt. These mentioned products can also be used as reinforcement for composite products.

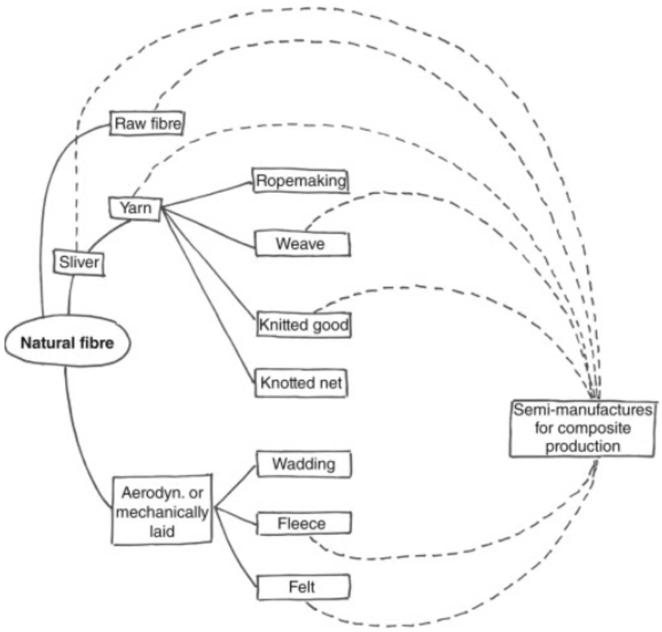


Figure 4.9 Different uses of natural fibres in textile and composite applications (Graupner and Müssig, 2010).

Compression moulding - water, heat, pressure
This manufacturing process is developed by ECOR, who developed a fully bio-based and recycable raw material for panels and other products based on diverted waste from mainly the agriculture industry, forest and urban life. The manufacturing process only uses heat, pressure and water, no adhesives are applied to create their products.

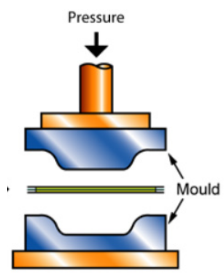
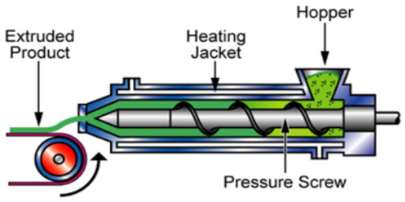


Figure 4.9 Compression moulding (Ansys Granta EduPack, 2022)

4.4.2. Manufacturing for (bio-)plastics

Extrusion

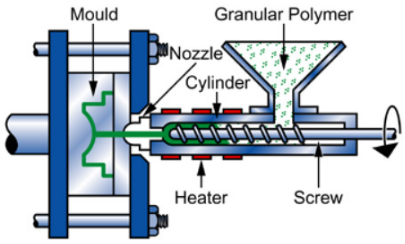
Polymer granulate is placed in a hopper and processed by a rotating screw through a heated jacket and forced through a shaped die. The material is cooled right away as it leaves the die. This process makes it possible to create different types of shapes, sizes and lengths based on the die on a relative fast pace.



(a)

Injection moulding

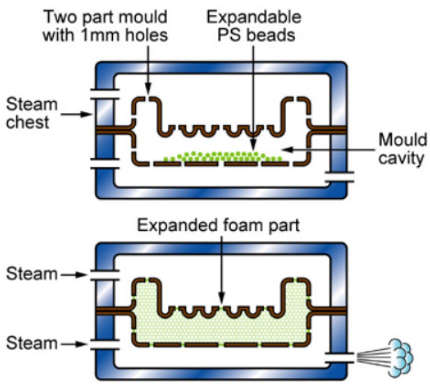
During this process molten polymer is injected into a steel mold under high pressure. The injected polymer solidifies under the pressure and the mold is dismounted. Injection moulding is possible with several methods, however the most common method is the reciprocating screw as illustrated in Figure 4.10b. This production method is often used for large volume production for either small, large and more complex objects.



(b)

Expanded foam moulding

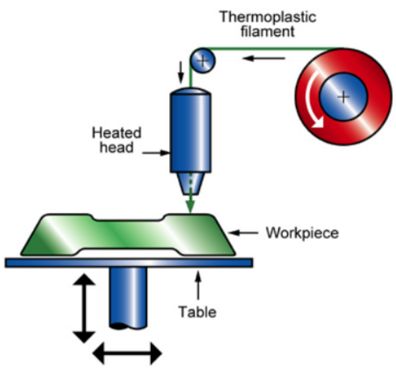
This process is often used for the packaging industry, by using low pressure and cheap moulds. Polymer granulates, containing a foaming agent that releases CO_2 when heated, which are softened and expanded by steam-heated under pressure. Next the soft particles are transferred into moulds and steam-heated at higher pressure. Which causes the particles to expand 20 times their original volume and are merged together, filling in the mould and the desired shape.



(c)

Additive manufacturing - material extrusion

This additive manufacturing technique is suitable for a thermoplastic filament or bioplastic filament. The printer uses a dual axis heated head to melt the filament, aswell move around the object The plastic material is extruded and deposited layer by layer starting at the base, building the object in vertical direction.



(d)

Figure 4.10 Manufacturing for bio-plastics (Ansys Granta EduPack, 2022)

4.4.3. Manufacturing for bio-composites

Hand lay-up

This process is a simple technique to make large components using relative cheap moulds. As today the most applied production technique for composite products. In the mould a gel coating is applied to prevent the reinforced fibres stick to the mould. The reinforced fibres are placed in the mould by hand and the resin is applied with a brush for every layer untill the required thickness. The mould is left untill the reinforcement and the added resin is cured.

Spray up technique

This technique is similar as the hand lay-up technique, however instead of using a brush manually, a spray applied by using a spraygun is used to applied the resin on the reinforced material inside the mould layer per layer. The mould is left untill the reinforcement and the added resin is cured.

Vacuum bagging

The reinforcement and resin are placed and processed as the hand lay-up or spray up technique. The material is placed inside a vacuum bag to increase the curing process. Through the use of vacuum bags and vacuum an uniform pressure and force is applied into the mould, resulting in a compact composite component.

Pultrusion

In pultrusion, the reinforced fibres are impregnated with a resin and pulled through a series of dies, where the final die is heated to cure the resin. The final cross-section of the profile can be round, rectangular or almost any other shape and cut in the desired length.

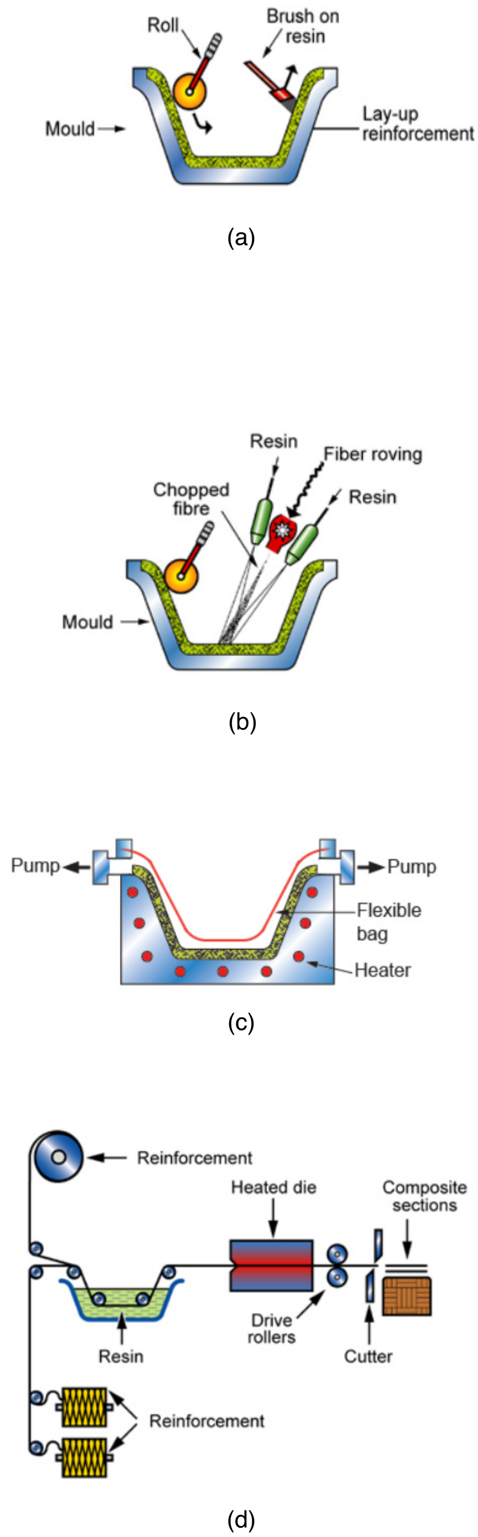
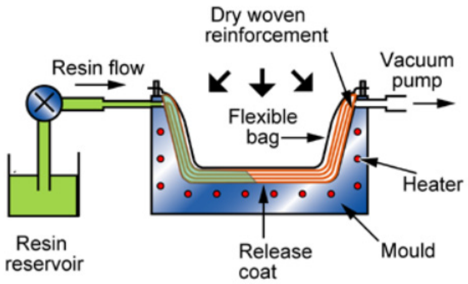


Figure 4.11 Manufacturing for bio-composites
(Ansys Granta EduPack, 2022)

Vacuum infusion

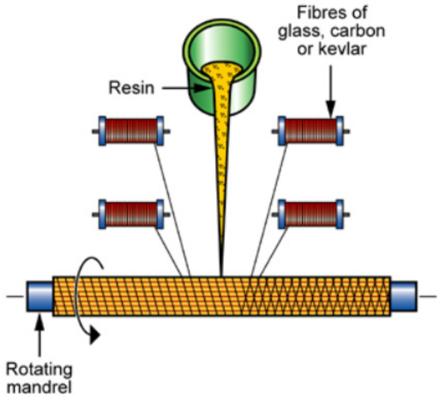
The vacuum infusion production technique uses vacuum pressure to inject a resin into the reinforced fibre, which is placed into a mould. The vacuum is applied before the resin is infiltrated into the fibre, once the vacuum is applied the resin will bind into the fibre resulting into a strong composite component. Just like the vacuum bag technique, both techniques are suitable for large components.



(e)

Filament winding

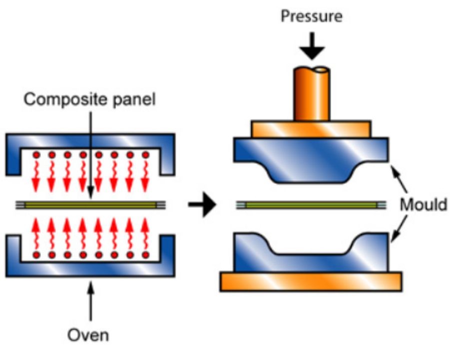
The process for filament winding is a production technique for the development of large hollow structures such as pipes, pressure vessels or masts. During the process filaments are winded over a mandrel or a specific mould, where the mandrel rotates while a carriage moves in horizontal direction to guide the fibres in the correct pattern after moving trough the resin bath. The process continues till the mandrel is covered with the required thickness of fibres. Next the mandrel is removed, resulting in a hollow product.



(f)

Compression moulding

The composite panel, including the reinforcement fibres, can be shaped by using compression moulding for small and medium components. The composite sheet is heated in an oven to the suitable processing temperature and placed into a press. Next the composite sheet is compression moulded into the desired shape based on the mould. Lastly the composite compressed object is cooled, instead of the oven the mould can contain heating to reach the processing temperature.



(g)

Figure 4.12 Manufacturing for bio-composites (Ansys Granta EduPack, 2022)

4.4.4. Manufacturing for wood

Rotary cutting

This is the most common and industrialised technique to manufacture veneer. Tree trunks are mounted on a lathe machine and cut by a blade while the tree trunk is rotating. This will result in long sheets of veneer which is cut in the desired length, aswell specific thicknesses as illustrated in Figure 4.13v (Lenderink technologies, 2022).

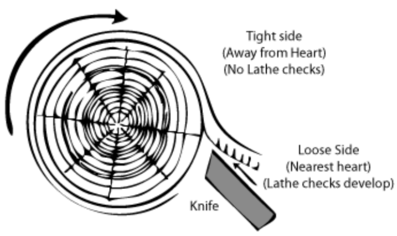


Figure 4.13 Rotary cutting (Lenderink technologies, 2022).

4.4.5. Manufacturing for cardboard

Cardboard tube spiral winding

This manufacturing technique is applied for cardboard tubes as illustrated in Figure 4.14 (Wang et al, 1995). Multiple paper layers are pulled through an adhesive bath onto a winding mandrel to shape a continues spiral cardboard tube with a desired thickness and diameter. The final tube is then cut into the required length.

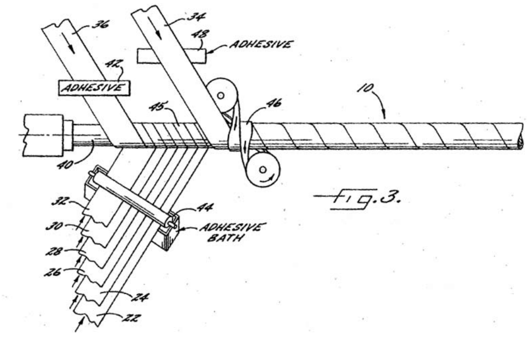


Figure 4.14 Cardboard tube spiral winding (Wang et al, 1995).

Corrugated cardboard production

The production of corrugated cardboard consists of multiple steps. In the first step, the liner (cardboard sheet) and the medium (cardboard flute) are pre-processed with steam to be flexible enough for manufacturing. The medium is fluted by being pushed trough rolls with a pattern matching the desired flute pattern. Next an adhesive is applied to one side to bond the flute and the cardboard sheet together into a single face board. Lastly, the single face board is flipped, in order to apply an adhesive on the other side of the flute, where its bonded together with a second liner as illustrated in Figure 4.15 (Watkins, 2012).

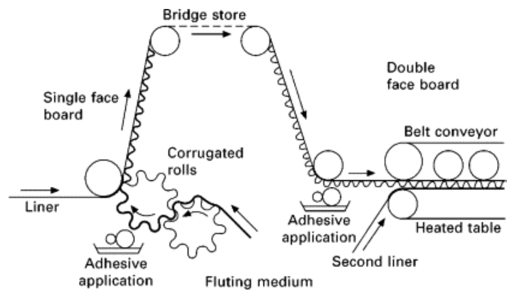


Figure 4.15 Corrugating machinery (Watkins, 2012).

4.5. Conclusion

Biobased materials can be described as derived from biomass, renewable and often biodegradable. The materials found their origin from bacteria, fungi, animals or plants. Materials can be classified into categories according Kula et al. (2014), resulting in a selection of potential suitable bio-based materials including textiles, bio-plastics, bio-composites, wood and cardboard. Cellulose fibres and fungi were added as additional categories. The selected materials are all existing and locally produced to reduce the carbon footprint.

In addition, the possible manufacturing methods per material were explored. Resulting in an overview of possible manufacturing methods, this gives an indication of how efficient a potential bio-based duct component could be manufactured in terms of production quantity, manufacturing time which relates to the extend of automation and costs. In this chapter a final selection of a suitable bio-based material and corresponding manufacturing method was not yet selected, the literature review is a first step for an analysis conducted and further elaborated in chapter 6.

5.
DESIGN REQUIREMENTS

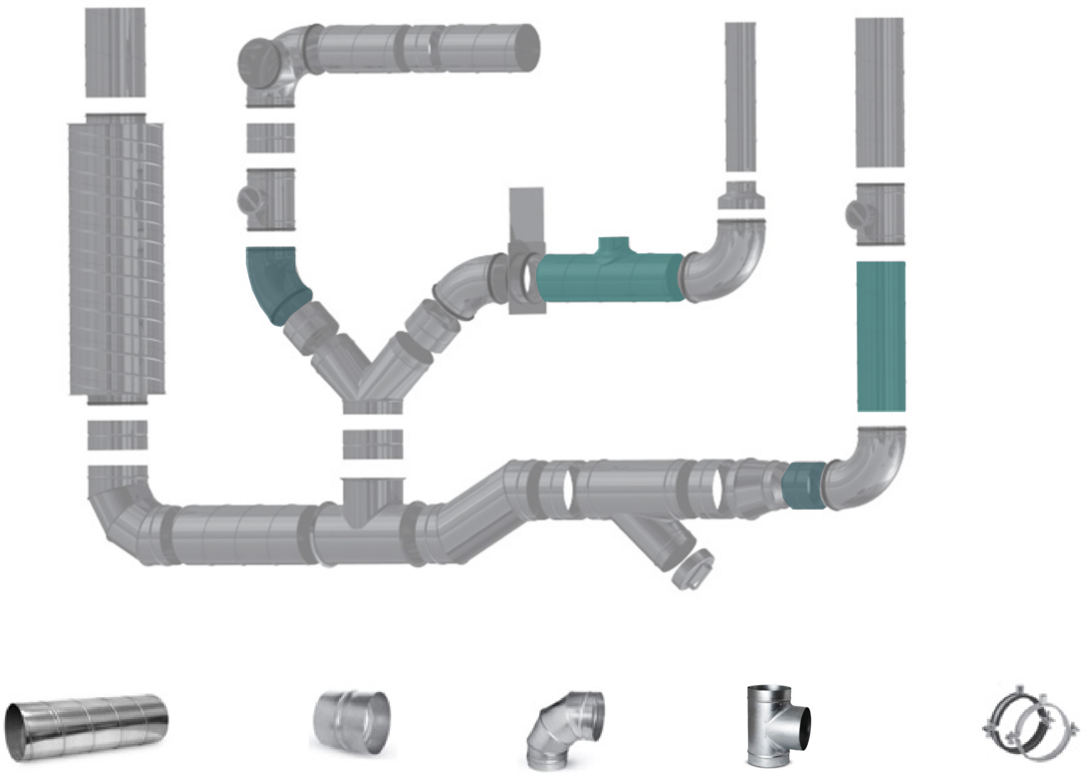
In this chapter the design goal is described leading to the design requirements which are formulated to evaluate the design decisions. In addition, boundary conditions are set up to select a suitable material and manufacturing method. For the regular requirements a weight is defined to distinguish the importance per requirement. The following research question will be answered by giving an overview of the requirements a final selection is made in chapter 6.

- What are important requirements when designing for air ducts?

5.1. Design goal

This project aims to research the potential of bio-based materials in their applicability for round air ducts. Since ductwork consists of many components a selection of the most important components is made, which together in complexity represent the overall ductwork. In addition, this approach validates which components can be designed from bio-based materials. These components include: a linear component, joint, bend, t-component and hanging products as shown in Figure 5.1a. Which are ordered based on their priority in the design process from b to f as illustrated in Figure 5.1bcdef. The priority of the selected components depends on the quantity of the component in the total ductwork system, amount of material used and size. Therefore the linear component has the highest priority, due to the mentioned aspects.

a) Ductwork overview



(b) Linear component (c) Joint (d) Bend (e) T-component (f) (Hanging products)

Figure 5.1 Priority of components for design process (Alnor, n.d.)

5.2 Design boundary conditions

In order to narrow the scope of the research several boundary conditions are established. The development of the bio-based air duct focuses on the most efficient round geometry. The spiral sheet metal duct is chosen as benchmark based on the literature research. As mentioned in section 5.1 a selection of the most important components is established: linear component, joint, bend, t-component and hanging products.

In addition, the focus on the suitable bio-based materials lies in the use of existing materials rather than developing new materials. Exploring the type of material as mentioned in section 4.2 and their workability has the priority. This same principal accounts for the manufacturing methods, design decisions are based on existing manufacturing methods.

Finally, detailed components including diffusers and grills are not taken into account into this research, thus not integrated in the design process.

5.3. Design criteria

The design criteria are established to evaluate the design problems and serve as standards. Boundary conditions are formulated, which are strict criteria the material and manufacturing should be succeed. The boundary conditions are applied to the selected suitable materials and corresponding manufacturing method in the beginning of the process in section 6.2.

In addition, regular criteria have been set up regarding five different categories. Every criteria is rated from 1 to 3 to weight the importance of the different criteria since some criteria are more important than others. In addition every criteria can score a value between 0 and 3, where a value of 3 is classified as high or good. Next, every score of the criteria is multiplied with the weight of the criteria to get a final value. By adding up all these values a final score is achieved to compare with the different concepts per design problem, the design problems are further explained in chapter 7. The criteria can differ per design problem and only the most relevant and important criteria will be applied.

Boundary conditions for manufacturing method and suitable material

●○ ●●	Geometry	relates to the shape of the duct round and rigid
●○ ●●●	Mass production	relates to the scalability in diameter and length with the manufacturing method in a relative fast manufacturing time
●○ ●●●	Renewability	relates to the end-of-life scenario, reusability and/or recycability of the material

Functional

●	Weight / density	< 7,8 g/m^3 density steel
●●	Airtightness	Class C
●	Installation noise	30 dB
●●●	Moisture resistance	Very high
●●	Chemical emission	Class A
●●	Fire resistance	> Class E, no specific requirement for fire safety of ducts.
●	Aesthetics	Preferably for linear components

Circularity

●●	Local production	Local (reused or recycled) materials accounts for all components.
●●●	Carbon footprint	< sheet metal
●●	Ease of dis(assembly)	Demountable connections for future changes or maintenance.

Manufacturing

●	Material costs	Costs of the used material.
●●	Manufacturing costs	Costs of the manufacturing process.
●●	Ease of production	The components are produced in a relative fast and easy manner.

Installation

●●●	Material workability	Material should be able to be resistant to impact.

Use

●●	Maintenance: cleaning	The material should be able to have openings to access.
●●	Adaptability	Related to furture changes in the design.

6.

ANALYSIS

This chapter describes the analysis to select suitable and efficient manufacturing methods per type of duct component. A matrix is set up to explore the possibilities per bio-based material by making models, sketches and analysing reference projects. Next an LCA is conducted to compare the cardbon footprint of the bio-based materials with sheet metal. Lastly, the bio-based materials are assessed to select a suitable material. The following sub-questions will be answered:

- What are appropriate manufacturing methods for the selected suitable bio-based materials?
- Which bio-based materials are suitable for the fabrication of air ducts?
- How feasible is the use of bio-based materials for air ducts in terms of carbon footprint compared to sheet metal?

6.1. Categorization manufacturing methods

Derived from literature an overview of manufacturing methods and bio-based materials are explored. In Figure 6.1, these manufacturing methods with corresponding bio-based material are divided into two categories of components. The first category linear components consists of the linear duct and joints, the second category consists of complex components including bends and t-components. This division is made to select suitable and efficient manufacturing methods and materials per type of component, which are crucial to select the right design concepts.

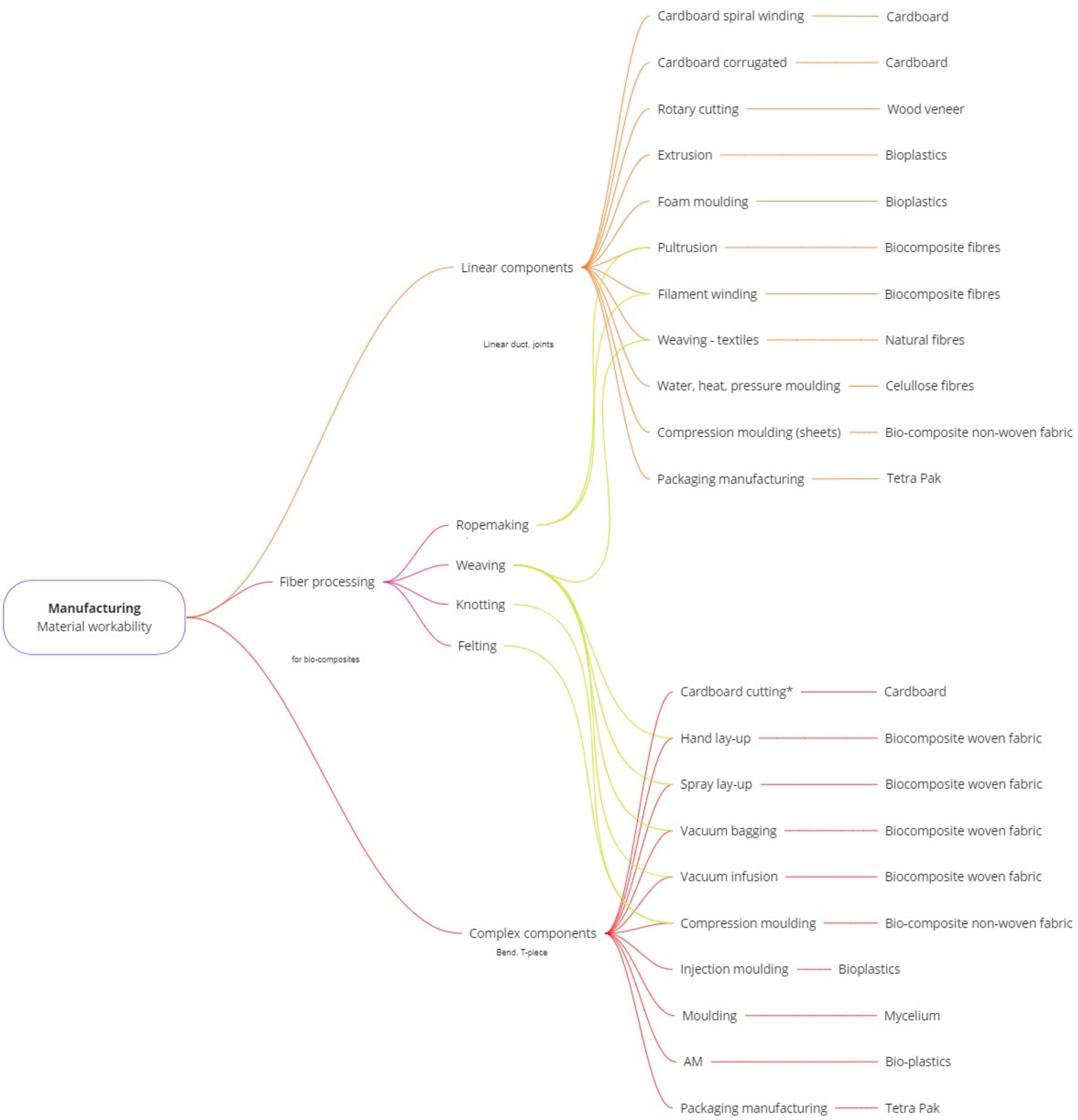


Figure 6.1 Existing manufacturing methods

6.2. Selecting suitable design direction

In order to select a suitable material, a matrix is developed with the possible manufacturing methods on one axis and the possible bio-based materials on the other axis. Different reference projects are placed to visualise the possibilities with the bio-based material and the specific production method as shown in Figure 6.2. Accordingly, for every material and manufacturing method, sketches and models are developed for the different duct components to analyse the material workability.

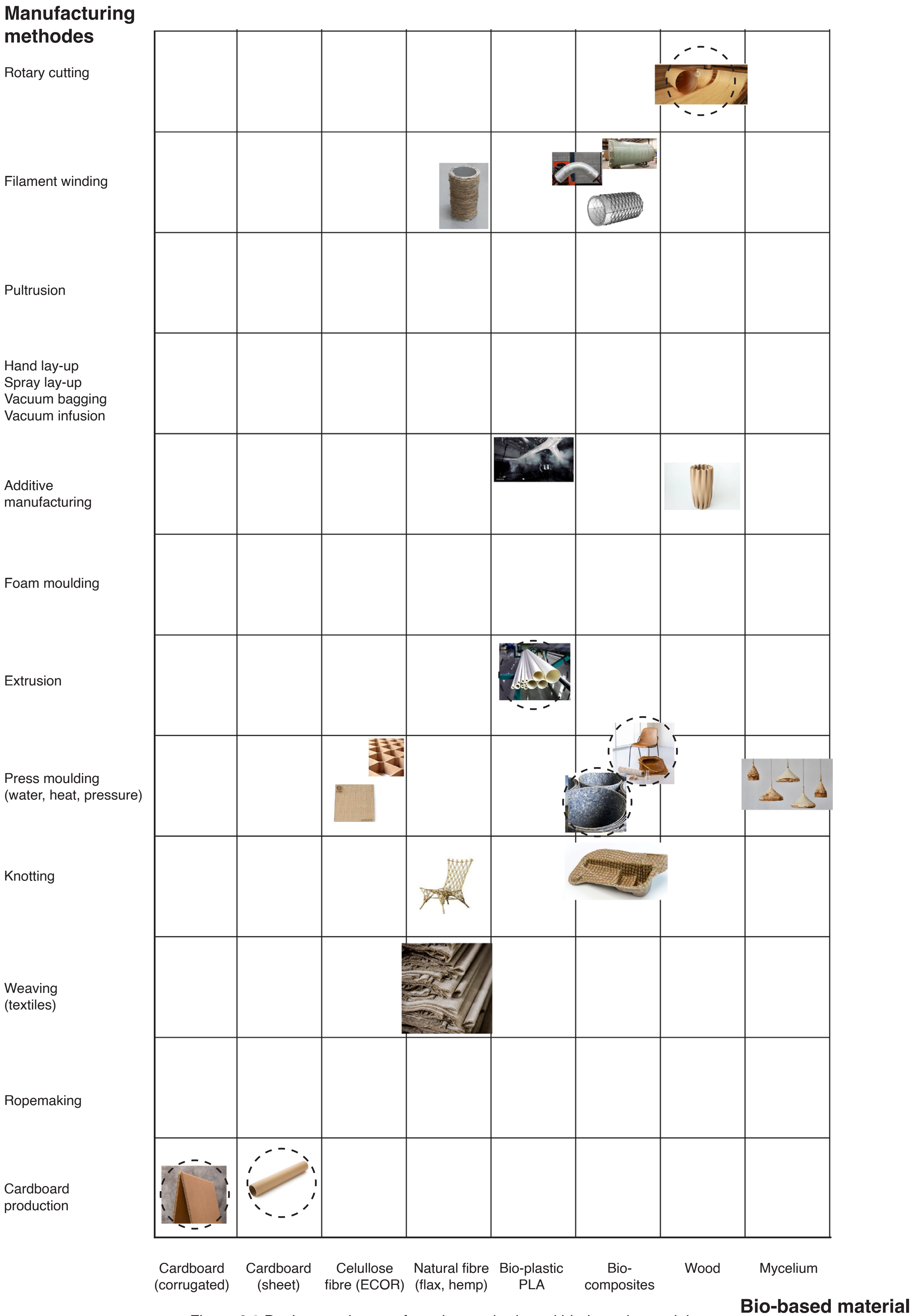


Figure 6.2 Design matrix manufacturing methods and bio-based materials.

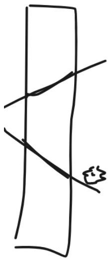
6.2.1. Corrugated cardboard

The first models from corrugated cardboard were created by cutting lines to be able to fold the cardboard in the polygonal shape as shown in Figure 6.3. The duct is constructed from a corrugated cardboard sheet and therefore both ends have to be connected, in this model tape was used. Due to its easy material workability the components are easy to construct aswell to install.

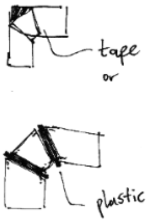
Strength and limitations
+ Very suitable for mass production for all components, no post-processing needed.
+ Moisture resistant to a certain extend.
+ Efficient transportation and possibility to construct ducts on site.

- Polygonal shape
- Less design freedom

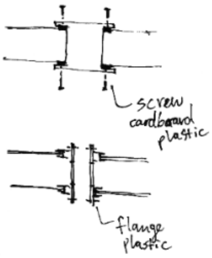
(a) Corrugated cardboard model



(b) Easily able to cut in smaller parts to construct bends.



(c) Possible to make bends.



(d) Joint connections.

Figure 6.3 Corrugated cardboard models.

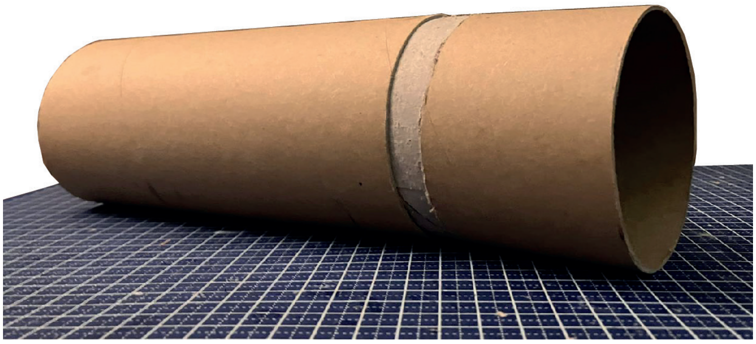
6.2.2. Cardboard tube

Besides corrugated cardboard another type of cardboard could be used, cardboard tubes often used as packaging material for posters or to store textiles. No addition changes had to be made which makes it a very easy material, for the bends and t-components the material can be adjusted with a box cutter for a small diameter and a saw for larger diameter.

Strength and limitations

+ Very suitable for mass production for all components, no post-processing needed.
+ Moisture resistant to a certain extend.

- Less effective transportation compared to corrugated cardboard, however everything is already ready to be constructed.



(a) Cardboard tube model

(b) Cardboard tube model, see Figure 6.3b

(c) Cardboard tube model

Figure 6.4 Cardboard tube.

6.2.3. Bio-plastic

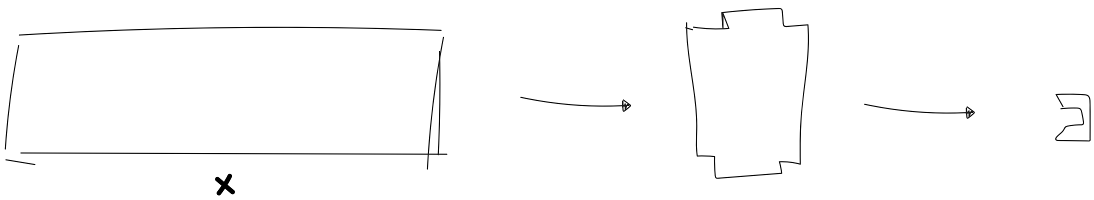
Regular plastic pipes are largely available in all types of components and sizes, for an overview of the components a building store was visited as shown in Figure 6.5a. Due to their manufacturing methodes: extrusion or injection moulding for complex components a smooth surface is achieved. In figure 6.5bcd illustration are given related to the size of acceptable duct components for bio-plastics assumming chemical emission of compounds could result in irrtant consequences due to contamined air quality. Therefore, large bio-plastic components should most likely be avoided. Smaller components can be applied such as connections within components or joints, the emission is expected to be neglectable due to its small contribution in the overall duct system.

Strength and limitations

+ Very suitable for mass production for all components, no post-processing needed.
+ Moisture resistant to a certain extend.

- Chemical emission of volotile organic compounds might occur, however using bio-plastics for the smaller components which are negligible

(a) Large product range for plastic duct components.



(a) Large (bio)-plastic components (b) Medium components c) Small components

Figure 6.5 Product range regular plastic pipes at Gamma.

6.2.4. Bio-composites

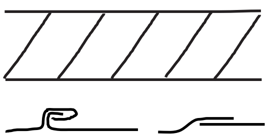
The exploration of the bio-composites asks for more detailed description due to the used equipment and material as shown in Figure 6.6. The goal of the models is to explore their rigity aswell the possibility to construct bends. As shown from the amount of equipment needed it also tells that the manufacturing process will be most likely less efficient than the previous mentioned materials, cardboard and plastics. Three types of bio-composites are explored from flax fibres, old t-shirts and jeans.

Strength and limitations

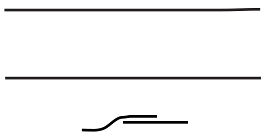
+ Aeshetically pleasing
+ Moisture resistant to a certain extend.
+ Use of waste materials and contribution to clothing waste problem.
+ Rigid geometry

- Possible chemical emission due to the used resin
- Production process might be slow and difficult for mass production.

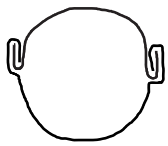
Figure 6.6 Basic tools for bio-composites making.



(a) Linear spiral component folding or overlapping.



(b) Linear component overlapping.



(c) Folding for two parts for instance bends.

Figure 6.7 Sketches bio-composites.

Process

The process of creating the bio-composite models is visualised in Figure 6.8 and starts by mixing the bioresin and hardener with a ratio of 100:27. Then the bioresin is applied on the material untill its fully impregnated. Since the resin hardens within 20 minuts the process should be relatively quick before the resin gets unusable. Lastly, the material is formed in the desired shape by moulding it around a plastic duct, Ø 125 mm. In order to prevent the impregnated bio-composite from sticking to the plastic duct a plastic film is wrapped around. The curing process takes around 24 hours, then the bio-based model can be removed from the mould.

(a) Mixing resin (b) Applying resin to non-woven flax fabric (c) Using mould

Figure 6.8 Process bio-composite ducts.

1. Flax fibres

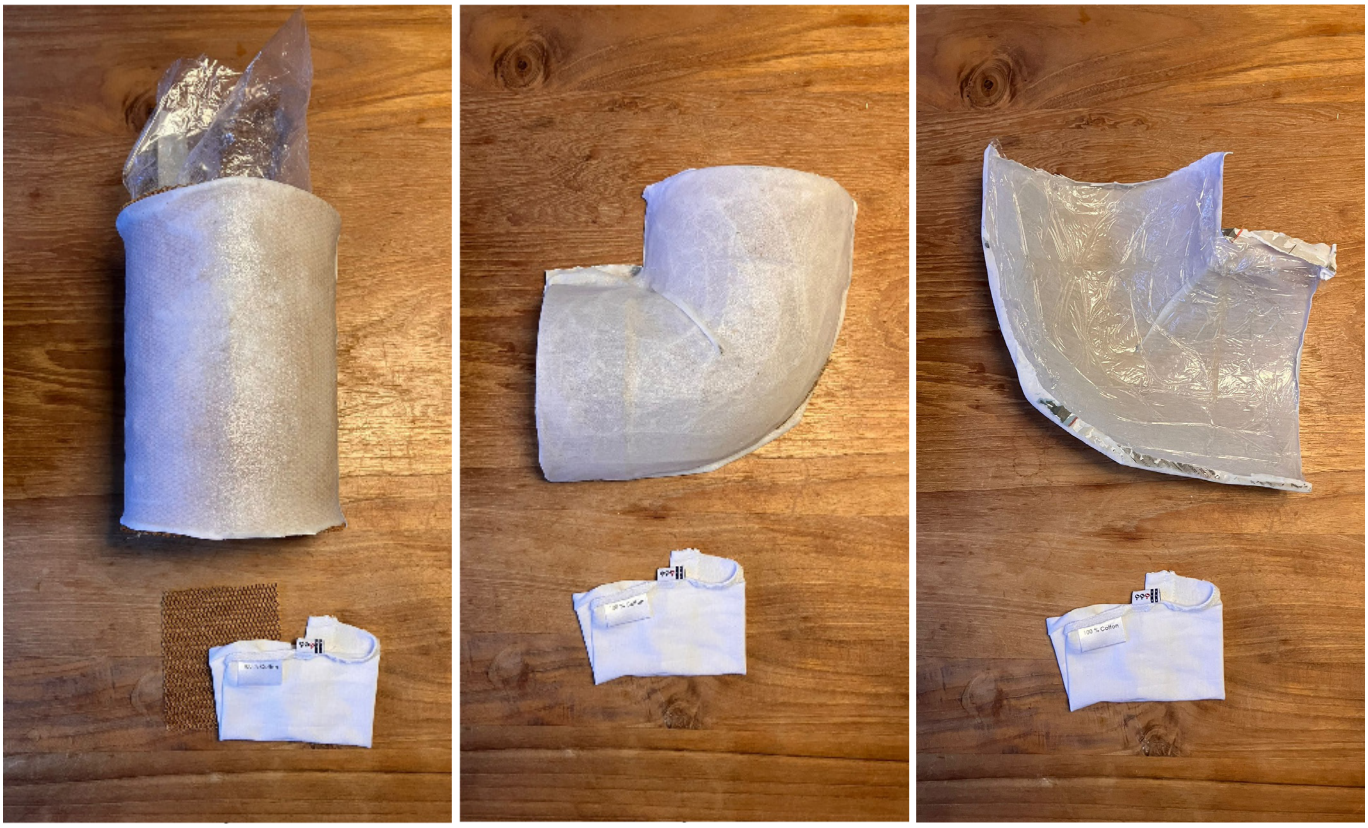
At first a bio-composite model of non-woven flax fibres was made in a round shape, therefore both sides of the material were impregnated to see the results. A second option was developed by using 100 mm strips of non-woven flax fibre and winded as a spiral around the mould, by overlapping the edges of the fabric, consequently the diameter will be larger at the end compared to the beginning. The third option is made from woven flax fabric, by winding the fabric two times around its axis. This resulting in a strong option and less material compared to the first model.

(a) Non-woven fibres (b) Non-woven fibres spiral (b) Woven fibres

Figure 6.9 Result flax fibre composites.

2. Old t-shirt 100% cotton and plastic honeycomb structure

The concept of using a t-shirt followed from the need of a thinner fabric used in the first option, resulting in the idea of using old clothing in this concept an old t-shirt made from 100% cotton. This fabric is relatively thin and therefore an additional light honeycomb structure was added made from plastic. In this concept the t-shirt is impregnated and which made it possible to stick the honeycomb plastic.



(a) Old t-shirt and honeycomb. (b) Old t-shirt bend outside. (b) Old t-shirt bend inside.

Figure 6.11 Result t-shirt clothing composites.

3. Old jeans

From the concept of using old clothing or clothing waste the idea of using old jeans as a matrix for the bio-composite arised. For this concept a reference was found where old jeans can be processed into felt which results in a similar type of materials as the non-woven flax fibre mat. In order to achieve stiffness the felt is compressed with a bioresin, resulting in thin sheets of veneer of 1000 by 3000 mm according to PlanQ (2018). Instead of rolling the sheets, the idea of creating a spiral duct from thinner

Figure 6.12 Process bio-composite ducts (PlanQ, 2022).

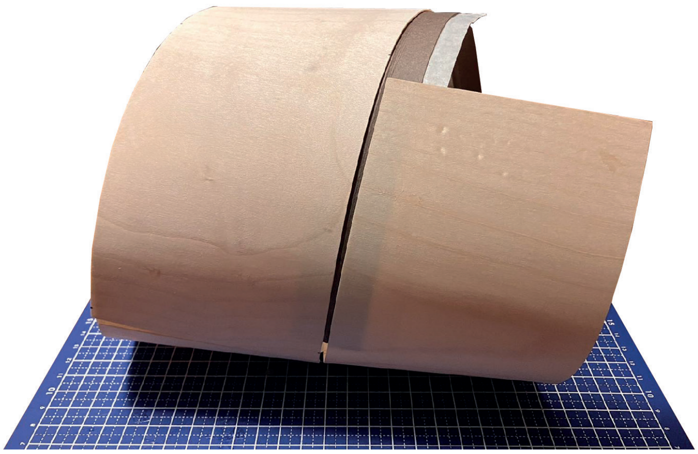
6.2.5. Veneer

For the construction of ducts from veneer two options were explored. In the first approach the veneer is constructed of two layers veneer with a thickness of 0,6, total 1,2 mm. Instead one layer of 1,5 mm could be used to prevent using an adhesive which makes it easier to disassemble at the end-of-life of the product. At first one layer of 0.6 mm was tried to be applied, however one layer would be very sensible for impact of for instance installers. In order to achieve a stiffer product it is important to bend the veneer in the opposite of the cutting direction.

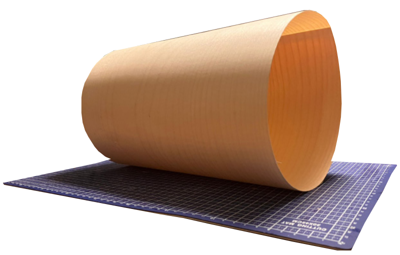
In the second approach the veneer is cut into strips and modeled into a spiral, in the model three layers can be distinguished: veneer, plastic spiral and coating. In the model the spiral is constructed out of tape, however the connection between the veneer and plastic spiral would be a challenge. This challenge lies in the stresses occuring on the veneer which could result in cracks and therefore the first concept has the preference.

Strength and limitations
+ Aesthetically pleasing
+ Lightweight

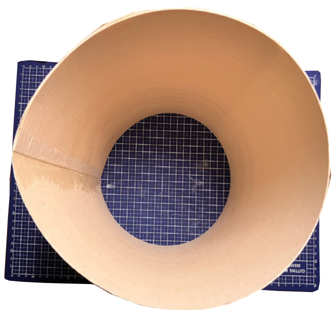
- Fragile material especially when using one sheet of veneer; 0,6 thickness
- Complicated material, material might react to temperature and humidity changes
- Not suitable for complex components: bends and t-component



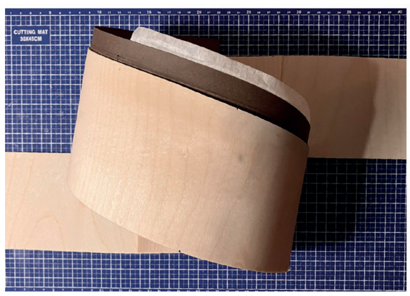
(a) Spiral veneer model.



(b) Uniform veneer model.



(c) Uniform veneer top view.



(d) Spiral veneer top view.

Figure 6.13 Development veneer models.

6.2.6. Tetra Pak

Packaging materials have the advantage of being resistant against moisture and oxygen. The packaging is produced from sheets which are winded into a coil from. ‘Dubbelfrisss’ a Dutch soda company developed a packaging which is almost fully bio-based with a 95% bio-based content and 5% aluminium. The different layers are completely recyclable after use, which could potentially be a suitable material for the construction of bio-based air ducts.

Strength and limitations

+ Moisture resistant
+ Already developed material

- Not very rigid, better applicable for smaller components for instance t-component.
- Production process might be slow and difficult for mass production.
- Damaging the edges when folding the spiral model, danger for moisture.

(a) Tetra Pak model spiral by folding edges.

(b) Tetra Pak model uniform round.

(c) Tetra Pak model spiral top view

Figure 6.14 Results Tetra Pak models.

6.2.7. Assessment per component type

The manufacturing methods and corresponding bio-based material are assessed by three boundary conditions, geometry, mass-production and renewability, as mentioned in section 5.3. These aspects are essential for the design and should all be fullfilled in order for the manufacturing methods and material to be suitable for the production of bio-based air duct components. If atleast one of the three aspects is not fulfilled, indicated with red, the concept is classified as not suitable. The assessment resulted in a narrowed down selection for both type of components as stated in Table 1.

In this assessment one exception was made for corrugated cardboard, scoring negative on the geometry aspect, due to its polygonal shape. This shape could cause problems when connecting to other components consisting of materials with a round shape, resulting in less design freedom. However, this might be preventable if all the components could be constructed from corrugated cardboard or adjust the other components to a polygonal shape, which has to be further explored.

Table 1 Assessment manufacturing method and bio-based material per type of component.

	Manufacturing method	Material	Geometry	Mass-production	Renewability
	Linear				
●	Spiral winding cardboard	Cardboard	●	●	●
○	Corrugated cardboard production	Cardboard	O	●	●
●	Rotary cutting	Wood veneer	●	●	●
●	Extrusion	Bioplastic	●	●	●
	Foam moulding	Bioplastic	●	O	●
	Filament winding	Biocomposite fibres	●	●	O
	Pultrusion	Biocomposite fibres	●	●	O
●	Compression moulding: sheets	Biocomposite woven fabric*	●	●	●
	Weaving - textiles	Natural fibres: woven fabric	O	●	●
	Celullose fibres	Celullose fibres	●	O	●
●	Packaging manufacturing	Tetra Pak	●	●	●
	Complex				
●	Cardboard cutting	Cardboard	●	●	●
●	Injection moulding	Bioplastic	●	●	●
	Hand lay-up	Biocomposite woven fabric*	●	O	O
	Spray lay-up	Biocomposite woven fabric*	●	O	O
	Vacuum bag	Biocomposite woven fabric*	●	O	O
	Vacuum infusion	Biocomposite woven fabric*	●	O	O
●	Compression moulding	Biocomposite non-woven fabric*	●	●	●
	Moulding	Mycelium	O	O	O
	AM	Bioplastic	●	O	●
●	Packaging manufacturing	Tetra Pak	●	●	●

* including clothing waste made from bio-based materials: t-shirts, jeans etc.
including bio-based fibres: non-woven flax fibres

Boundary conditions

- Geometry: relates to the shape of the duct round and rigid.
- Mass production: relates to the scalability in diameter and length with the manufacturing method in a relative fast manufacturing time
- Renewability: relates to the end-of-life scenario, reusability and/or recycability of the material.

6.3. Environmental impact analysis

The environmental impact is an important aspect and indicates the effects of the product on the environment. For this project a life cycle assessment (LCA) of the potential bio-based materials is performed. The LCA assessment is performed to verify the feasability of the bio-based materials in comparison of the sheet metal as benchmark material at the start of the design process. In order to do this relative quick a “Fast-Track” method is performed by using the database of Idemat (2022), in compliance with ISO 140040, 140044. Since performing a precise LCA is complex and therefore time consuming for potentially a similar outcome.

6.3.1. Life Cycle Assessment (LCA)

The carbon footprint of a product life cycle is assessed by calculating the impact per life cycle of the product. The life cycle consists of different phases, including production, construction, use and end-of-life phase, which are further sub-divided into specific stages according to NEN-EN 15978 (2011) as stated in Figure 6.15. In this research the environmental impact of the product chain is calculated according to the carbon dioxide equivalent emissions (kgCO_2e), known as the global warming potential (GWP). It can be considered to calculate the LCA according more indicators such as ozone depletion (kgSO_2e) and water pollution (m^3) etc., therefore the EIME software can be used to quantify the overall environmental impact. The LCA for this research includes the following phases:

- A1: Raw material supply and secondary materials processing untill it is ready for transport.
- A2: Transport from material processing location to the manufacturer.
- A3: Manufacturing of the product.
- A4: Transport manufacturer to site.
- A5: Installation of the product is neglegtable for air duct and not included for the LCA.

- B1-B7: Relates to the use stage including maintenance, repairing and energy usage. This is neglectable for air ducts as passive product and therefore not included for the LCA.

- C1: De-construction and demolition, neglectable not included for the LCA.
- C2: Transport from site to waste processing/disposal site.
- C3: Waste processing for reuse, recovery and recycling.
- C4: Waste disposal for landfill.

In terms of waste processing either phase C3 or C4 can be chosen as scenario, for this research C4 waste scenario is followed for landfill. In this way the worst case scenario is analysed since none material can be recycled and reused to benefit at the end of life.

- D: The possible benefits and loads beyond the system boundary relates to the possibilities for reuse, recovery and recycling.

Building life cycle															Supplementary information
Product			Construction		Use stage							End-of-life				Benefits and loads beyond the system boundary
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Raw materials supply	Transport	Manufacturing	Transport	Construction	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction Demolition	Transport	Waste processing	Disposal	Re-use-Recovery-Recycling-potential

Figure 6.15 Building life cycle stages according to NEN-EN 15978 (2011).

There are several boundaries for this LCA assessment due to a lack of data, therefore the following assumptions were made which are also specified in Appendix A.

- Recycling rate of recycled plastic is assumed to be 100%, not specified in the data sheet of Idemat.
- Rotary cutting process for veneer is set on 1.00 kg CO_2e per kg, no data available.
- Processing different layers of Tetra Pak is set on 0.50 kg CO_2e per kg, no data available.
- Transportation within Netherlands for bio-based materials and recycled plastics is estimated on 200 km.
- Bioresin content in bio-composites is set to 50% and the matrix (flax and jeans) as well to make it 100%, the bioresin content might be higher.
- The primary processing methods are calculated assuming the production process and post-processing of the product is neglegtable compared to the primary production process.
- Transportation within Netherlands from building site to waste disposal is estimated on 100 km.
- The landfill % is estimated based on 20% for all materials besides veneer 40%, data derived from EIME software (EIME, n.d.).

6.3.2. Results

The carbon footprint is analysed for multiple materials including sheet metal as benchmark, different bio-based materials aswell recycled plastic is added for comparison. The applied unit derived from Idemat (2022) is converted from kgCO_2e per kg to kg per meter to take into account the density of the materials. In order to compare the materials equally an air duct with an inner diameter of 180 mm, a thickness of 3 mm and length of 1 meter is taken as reference. In addition, this calculation is based on a solid uniform geometry where no other materials are taken into account which are needed to construct the air duct such as bolts, coatings or materials which improve the stiffness. According to the dimensions the weight is calculated to achieve the weight of the duct in kg per meter, this requires several steps with the following formulas and illustrations in Figure 6.16:

1. Calculate cross section area of duct (m^2).

$$A_{cross\ section} = \pi \times r_{out}^2 - \pi \times r_{in}$$

2. Calculate volume of 1 meter duct (m^3).

$$V_{linear\ duct} = A_{cross\ section} \times L_{duct}$$

3. Calculate weight of 1 meter duct (kg).

$$M_{linear\ duct,\ 1\ meter} = V_{linear\ duct} \times \rho_{material}$$

4. Calculate carbon footprint per kg/m duct (kg CO_2e per kg.m).

$$Total_{carbon\ footprint} = Data_{carbon\ footprint\ per\ kg} \times M_{linear\ duct}$$

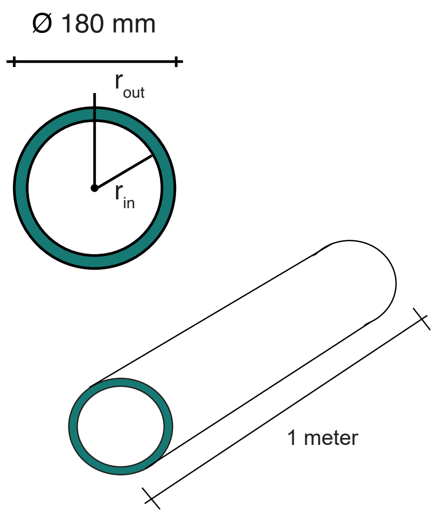


Figure 6.16 Illustrations for calculation

The results of the carbon footprint calculations are visualised in the table and graph in Table 2 and Figure 6.17. In the last step, the weight in kg/m is calculated and multiplied with the data values for the different stages for the total carbon footprint per phase. The carbon footprint calculations per phase are mentioned in Appendix A. Important to note is the secondary material use in sheet metal circular air ducts, according to Uniclima (2022) this is set to 35%, which results in 65% raw material use.

Table 2 Carbon footprint per material for an air duct with a diameter of 180 mm and length of 1 meter, landfill scenario.

Material	Unit (per meter)	Sum	A1-A3 Manufacturing	A4 Distribution	A5 Installation	B1-B7 Use	C1-C4 End of life
Sheet metal	kg CO2 eq.	8.80E+00	8.77E+00	2.00E-02	0.00E+00	0.00E+00	7.10E-3
Recycled plastic	kg CO2 eq.	1.89E+00	1.83E+00	3.00E-02	0.00E+00	0.00E+00	3.00E-2
Bio-plastic	kg CO2 eq.	8.37E+00	8.33E+00	2.00E-02	0.00E+00	0.00E+00	2.00E-2
Cardboard	kg CO2 eq.	1.62E+00	1.28E+00	1.00E-02	0.00E+00	0.00E+00	3.30E-1
Veneer	kg CO2 eq.	2.67E+00	2.04E+00	1.00E-02	0.00E+00	0.00E+00	6.24E-1
Bio-composite (flax)	kg CO2 eq.	6.15E+00	5.98E+00	3.00E-02	0.00E+00	0.00E+00	1.43E-1
Bio-composite (jeans)	kg CO2 eq.	4.35E+00	4.22E+00	2.00E-02	0.00E+00	0.00E+00	1.10E-1
Tetra Pak	kg CO2 eq.	3.25E+00	2.90E+00	2.00E-02	0.00E+00	0.00E+00	3.27E-1

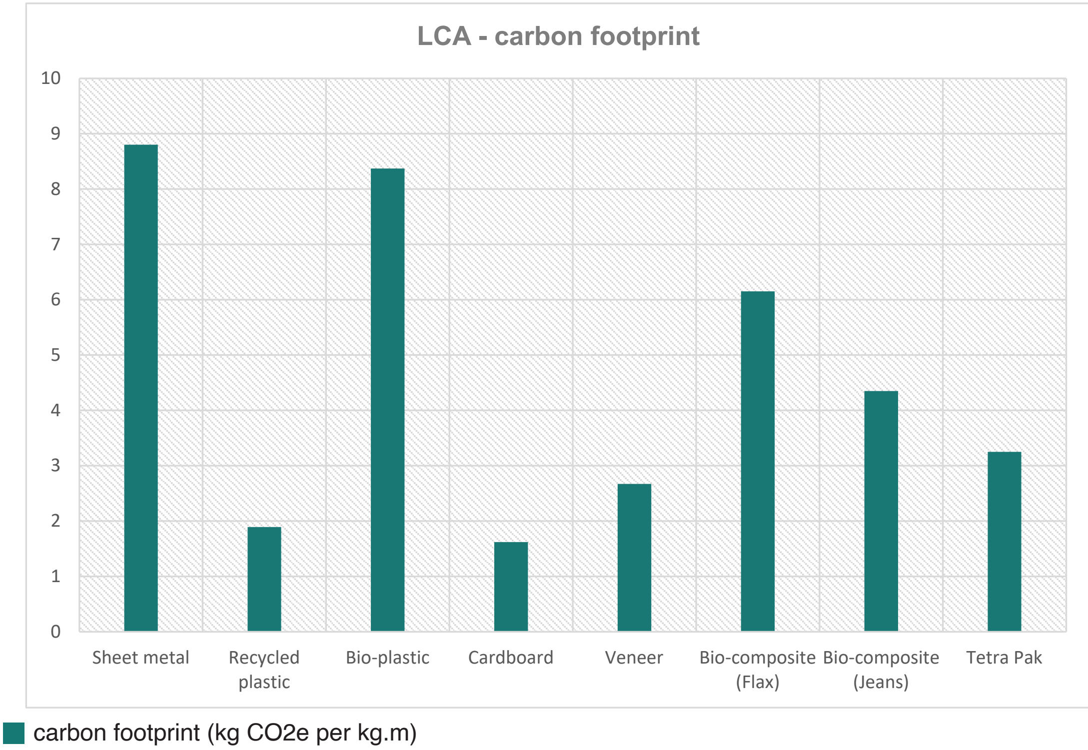


Figure 6.17 Carbon footprint assessment (LCA).

When comparing the carbon footprint of sheet metal with different bio-based materials it visualises that the difference with several materials is limited, such as bio-plastic and bio-composite (non-woven flax fibres and bioresin). This is explained by the use of 35% secondary materials in circular sheet metal ducts. The recycling rate of steel can be up to 95%, which makes it likely that the secondary materials use in other circular air ducts might be higher than mentioned. If this is the case the carbon footprint will be lower as stated in Figure 6.17, which potentially make these mentioned bio-based materials a worse outcome in terms of environmental impact.

Interesting is the impact of recycled plastic, despite it is not a bio-based material it shows the comparison with bio-plastics and the other bio-based materials. The emission of recycled plastic is 4 times lower than bio-plastics, which makes it more likely to apply recycled plastics rather than bio-plastics. Especially when looking to other important criteria such as moisture resistance which is questionable for bio-plastics.

The bio-based materials which show a significant difference with sheet metal are cardboard and veneer, respectively a factor 5 and 3 lower. In terms of environmental impact these would be the most likely to be applied, as long as the air ducts can be constructed from the materials and fulfill in the other important criteria.

Besides stage A-C, the benefits and loads beyond the system boundary are described as stage D. This includes three scenarios reuse, recover and recycling after the end-of-life stage which relates to the impact prevented by using one of the mentioned strategies. Reuse and recycle are preffered to its potential benefits forthe manufacturing stage of a second generation products. Recovery is the last option where energy is recovered by burning the waste materials when reuse and recycling are no option anymore. Table 3 shows which scenarios are relevant for each material specified that the material was applied to an air duct component, indicated with a cross.

When comparing the bio-based materials with sheet metal it becomes clear that no material most likely has the potential to be reused knowing the end-of-life condition of the materials assuming they were applied for air duct components. Recycability is crucial to prevent impact for a next generation of products. In terms of recycability all materials have to possibility to be recycled besides bio-plastics and veneer. Which are difficult to recycle, making them less appealing materials to use for a circular approach.

Table 3 Benefits and loads beyond the system boundary possibilities for recovery, reuse and recycling according stage D.

Material	**Recover**	**Reuse**	**Recycle**	**Description**
Sheet metal	x	x	x	Sheet metal is known for recycling purposes. Often een smalll percentage is lost during the recycling process therefore the recycling rate will at maximum be 95%. If the quality would be maintained sheet metal is also suitable for reuse purposes.
Recycled plastic	x		x	Recycled plastic (thermoplasts) has the possibility to be recycled again however there are limitations since it will lose its function after being recycled multiple times. In that case the plastics can be burned in an oven with energy recovery also a part will end up in landfill.
Bio-plastic	x			Bio-plastics are often biodegradable due to its different properties compared with regular plastics they usually not used or combined for recycling since it will result in lower quality plastics. Bio-plastics can also be used for landfill or burned with energy recovery.
Cardboard	x		x	Cardboard is easy to be recycled in good condition by shredding it and pulping, after drying it is pressed into new sheets of cardboard. If the condition is poor it can be decided to burn the waste product for energy recovery.
Veneer	x			Veneer as an organic material is most likely not recycable especially after serving as a material for air ducts. Therefore the veneer will be burned with energy recovery.
Bio-composite (flax)	x		x	The bio-composite as a whole can in good condition be recycled into other products by shredding the product in smaller particles. They can be used as secondary material for the production of furniture by heat compression moulding. Recycling the fabric and bio-resin seperately is possible but quality of the materials will be lost, which makes shredding more
Bio-composite (jeans)	x		x	The bio-composite as a whole can in good condition be recycled into other products by shredding the product in smaller particles. They can be used as secondary material for the production of furniture by heat compression moulding. Recycling the fabric and bio-resin seperately is possible but quality of the materials will be lost, which makes shredding more
Tetra Pak	x		x	Tetra Pak consists of 100% recyclable material, the different layers where the packaging material consists of cardboard, aluminium and plastic. Every material will be recycled in their own manner. Aswell having the possibility to end up as waste material for recovery.

In terms of feasability it is important to compare the lifespan of the bio-based materials with sheet metal, however the lifespan for the bio-based products are unknown. Instead, an estimated lifespan is calculated based on the carbon footprint in the production phase (A1-A3). Assuming a expected lifespan of 40 years for a sheet metal duct, the bio-based materials should have the following minimum lifespan as stated in Figure 6.18. Derived from the amount of times it can be replaced within 40 years before it exceeds the lifespan of the sheet metal duct. This indicates that materials such as bio-plastic and bio-composites (Flax+bioresin) should last atleast 40 years and can only be replaced once, which might be challenging. Materials with a lower impact can be replaced many times before the lifespan of the sheet metal duct ends, such as cardboard and veneer. However this is just an indication for the minimum lifespan based on the carbon footprint, in reality the lifespan of these materials will most likely be higher.

Material	Minimum lifespan
Sheet metal	40 years
Recycled plastic	5 years
Bio-plastic	40 years
Cardboard	3 years 4 months
Veneer	5 years 9 months
Bio-composite (Flax+bioresin)	40 years
Bio-composite (Jeans+PLA)	13 years 3 months
Tetra Pak	8 years

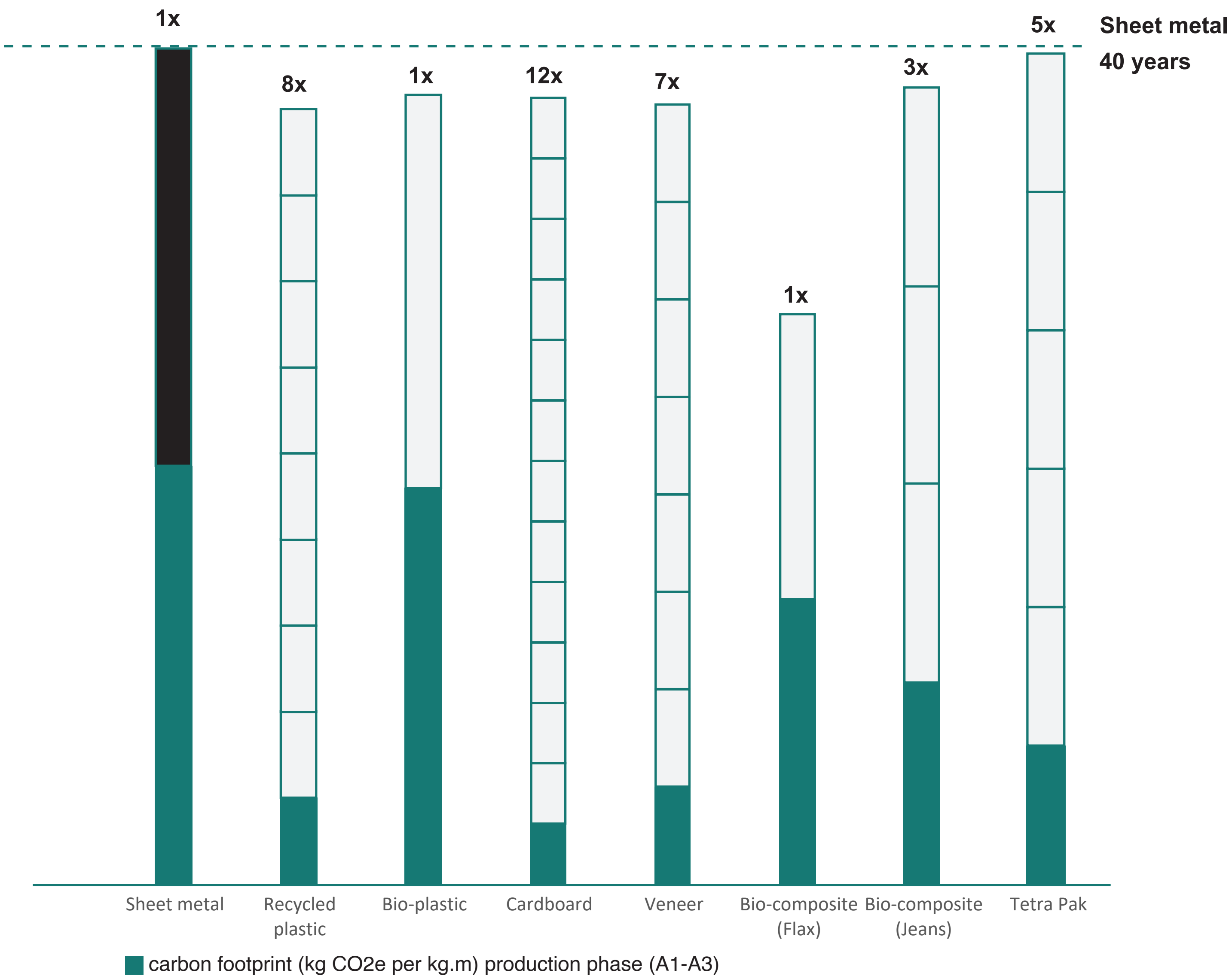


Figure 6.18 Minimum lifespan based in carbon footprint in production phase.

6.4. Suitable bio-based materials

When looking to the different criteria in section 5.3 a selection of the most important criteria is made which are critical for the bio-based material to fulfill. The assessment is made based on the material exploration in section 6.1 and 6.2 aswell the LCA assessment in section 6.3. Therefore the scoring system from chapter 5 is followed, the criteria can score between 0 and 3 where 3 is related to most positive and 0 most negative. The following criteria are assessed for sheet metal as benchmark and the bio-based materials:

- Moisture resistance

- key aspect which can determine to the lifespan of the product
- Chemical emission

- relates to the health and comfort of the occupants
- Carbon footprint

- relates to the environmental impact
- Renewability

- relates to the end-of-life scenario
- Material workability

- relates to the installation and material weight
- Mass-production

- relates to the ease of scalability in relative fast pace

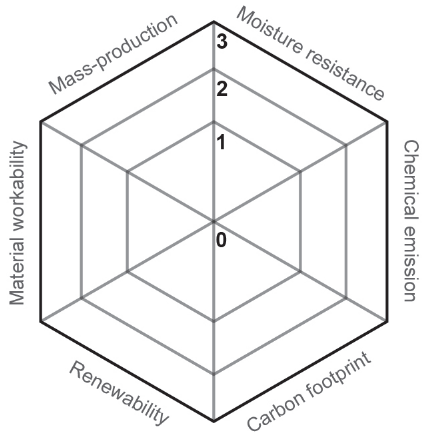


Figure 6.19 Assessment criteria

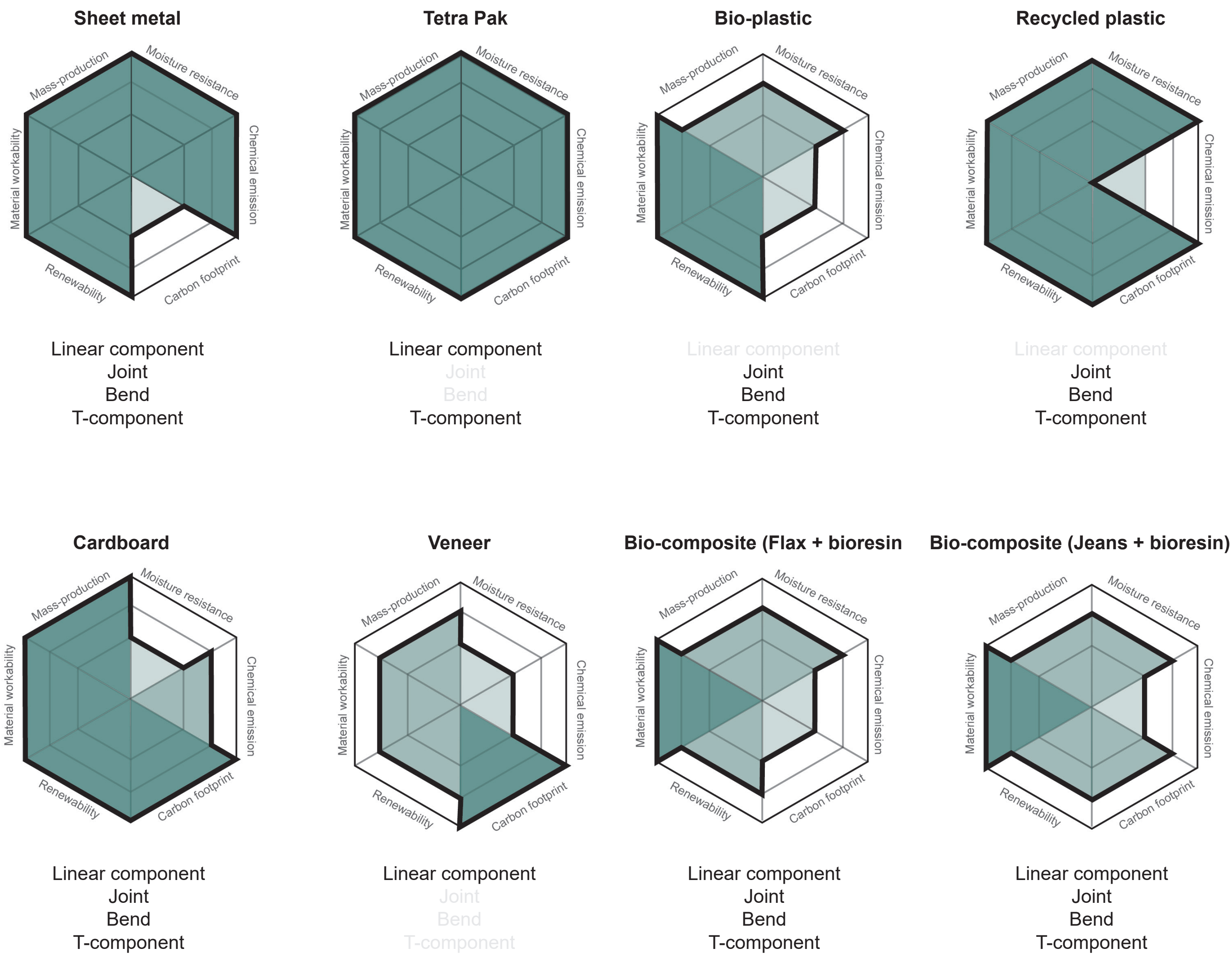


Figure 6.20 Selecting suitable material per component based on assessment.

6.5. Conclusion

According to the analysis conducted, using different materials for specific components have proven to be beneficial, resulting in multiple suitable production methods depending on the component. The common aspect of these manufacturing methods is their scalability. The possibility to produce the component in a relative fast pace by producing different sizes and or lengths of the component. For linear components this include cutting and folding corrugated cardboard, spiral cardboard winding, rotary cutting for veneer, compression moulding sheets of bio-composites and extrusion for plastics. For complex components this include cutting cardboard, injection moulding for plastics and compression moulding for bio-composites. In addition, packaging manufacturing method to produce sheets of Tetra Pak are beneficial for both type of components.

The assessment of the different materials resulted in an overview of the main problems of the analysed bio-based materials, as can been seen from the diagrams. The moisture resistance and chemical emission score relatively low for most materials. In comparison to sheet metal, one material can be seen as directly suitable for the construction of bio-based air ducts which is Tetra Pak. Aswell recycled plastic and recycled plastic as replacement for bio-based plastics. This does not mean that all the other materials are not suitable, for many materials it is possible to construct the air duct components. However the quality can not fully be archieved.

In terms of carbon footprint not all analysed bio-based materials materials are feasible to be applied for the construction of air ducts. There are materials such as veneer, cardboard and Tetra Pak which have a relative low carbon footprint up to a factor 3 difference. However bio-plastics and bio-composites resulting to have a relative high carbon footprint, where bio-plastics showed almost similar results as sheet metal. Taking into account that the lifespan of potential bio-based air ducts might be challenging which increases the carbon footprint overall due to the increase of replacements and therefore the overall environmental impact could in reality be higher than sheet metal.

7.

DESIGN PROCESS

This chapter describes the development and selection of the most suitable concept per design problem related to geometry of the component, connection between components and coating. Several concepts are developed per design problem which are assessed according a multi criteria analysis based on the set up criteria and corresponding weight factors to indicate their importance. The chapter results in a selection of a final design concept which will be further developed into a final design.

7.1. Design problems

Now the selection of suitable materials is finalised, a suitable concept can be chosen. This follows by solving different design problems in order to design the final duct components. The design problems are assessed according the set-up criteria in chapter 5 the selection of criteria per design problem varies depending on the importance of certain criteria. The assessment include the folllowing design problems:

- Geometry: linear component, joint, bend and t-component
- Connection between components
- Coating

7.2. Linear component

The design concepts for the linear component are divided into two categories, ducts which are easy and efficient to produce for low costs and another categorie is less efficient to produce and focus more on the aeshetic aspect for higher costs. For both categories two potential options are assessed according to the set-up criteria in chapter 5, for this assessment a set of criteria is selected.

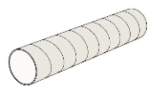
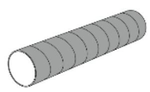
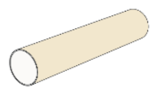
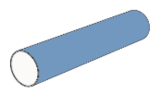
		Efficient, lower costs		Aeshetic, higher costs	
					
Criteria	Factor	Cardboard	Tetra Pak 75% bio-based	Veneer	Bio-composite (Jeans and bioresin)
Airtightness	●●	3	3	3	3
Moisture resistance	●●●	1	3	1	2
Chemical emission	●●	2	2	1	1
Aesthetics	●	1	2	3	2
Renewability	●●●	3	3	2	2
Carbon footprint	●●●	2	2	3	1
Ease of dis(assembly)	●●	3	3	2	2
Mass production	●●●	3	3	2	1
Material costs	●	3	2	1	1
Material workability	●●	3	3	2	3
Total		53	59	44	39

Figure 7.1 Selection concept for linear component

Concept 1: Spiral cardboard.
The first concept is a duct made from spiral winded cardboard, due to the efficient production method this type of duct is very suitable for scalability in different diameters and lengths.

Concept 2: Tetra Pak
This concept follows from the moisture resistance aspect, which is problematic for many bio-based materials, Tetra Pak include around 75% paperboard and uses plastic and aluminium to make their packaging moisture resistant. Tetra Pak is folded from sheets, which makes it a potentially good material for bio-based air ducts, due to the mass-production and mainly moisture resistance.

Concept 3: Veneer.
This concept follows from an aeshetic aspect, sheets of 3 mm first concept is a duct made- from spiral winded cardboard, due to the efficient production method this type of duct is very suitable for scalability in different diameters and lengths.

Concept 4: Bio-composite from jeans and bioresin.
The concept of using old waste jeans as matrix for bio-composites derived from the large clothing waste globally. Instead of transporting the clothing to the other side of the world such as Africa or South-America, the jeans could be remanufactured into a bio-based air duct. By doing so it contributes to several problems: the use of renewable resources, no transport to other side of the world, and using a waste product.

7.3. Joint

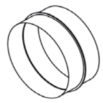
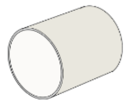
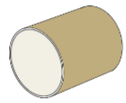
Criteria	Factor	 Recycled plastic	 Cardboard	 Bio-composite (Flax and bioresin)	
Airtightness	●●	3	3	3	
Moisture resistance	●●●	2	1	2	
Chemical emission	●●	1	2	1	
Renewability	●●●	3	3	2	
Carbon footprint	●●●	3	3	1	
Ease of dis(assembly)	●●	3	2	2	
Mass production	●●●	3	3	2	
Material costs	●	3	3	1	
Material workability	●●	3	3	2	
Total		56	53	38	

Figure 7.2 Selection concept for joint

1: Recycled plastic joint.
Injection moulding

The first concept is based on using recycled plastic as replacement for bio-plastic, due to its lower environmental impact, However, the chemical emission of TVOC might increase therefore it is applied to a small component compared to other components in the ductwork system. The joint fits in the inside of the joining duct components, meaning that if the inner diameter of the component is similar the thickness could differ which might be the case if the overall system consists of different materials.

Concept 2: Cardboard joint.
Cardboard cutting

This concept is a duct made from spiral winded cardboard, due to the efficient production method this type of duct is very easy to produce by cutting the original cardboard tube. This connection will be placed around the outter diameter of the incomming duct, which might limit the design freedom since different materials will need to have the same thickness.

3: (Bio)-composite joint.
Compression moulding

The bio-composite variation is constructed by impregnating non-woven flax fibre with bio-resin and placed around a mold to cure. However, the production is quite complex compared to the other options. Also carbon footprint of resins is high, which explains the lower score compared to the other concepts.

7.4. Bend

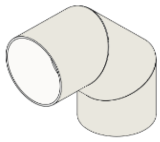
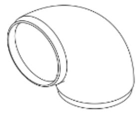
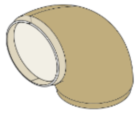
Criteria	Factor	 Cardboard	 Recycled plastic	 Bio-composite (Flax + bioresin)	
Airtightness	●●	3	3	3	
Moisture resistance	●●●	1	3	2	
Chemical emission	●●	2	1	1	
Renewability	●●●	3	3	2	
Carbon footprint	●●●	3	3	1	
Ease of dis(assembly)	●●	3	3	2	
Mass production	●●●	3	3	2	
Material costs	●	3	3	2	
Material workability	●●	2	3	3	
Total		53	59	41	

Figure 7.3 Selection concept for bend

1: Cardboard 90 degree bend.
The concept of a cardboard bend follows by cutting three seperate parts from the linear spiral winded cardboard duct, However, by using three different components the amount of sealant increases, which increases the potential chanches on pressure loss. Nevertheless, the components can be easily mounted together with for instance tape.

2: Recycled plastic bend.
The use of recycled plastic derived from the ease of production by injection moulding, thus makes it possible to manufacture the piece relative fast. The component scores low on chemical emission, assuming this would be critical due the use of plastics. However since bends are less applied in the overall duct system, the amount of emission could be neglegtable.

3: Bio-composite (non-woven Flax fibre and bioresin).
The last concept is a bend manufacturing from a bio-composite from a non-woven flax fibre mat combined with a bio-resin. The disadvantage is that the component has to be produced from two mirrored parts, which makes it less suitable for mass production. The two components have to be joined which could be achieved with an overlapping layer of flax fibre mat to make an airtight connection.

7.5. T-component

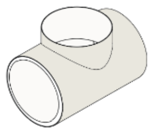
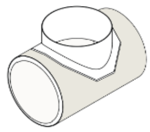
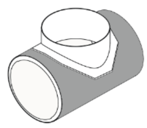
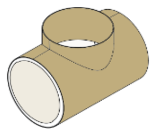
Criteria	Factor	 Cardboard	 Cardboard + recycled plastic	 Tetra pack + recycled plastic	 Bio-composite (Flax + bioresin)
Airtightness	●●	2	3	3	3
Moisture resistance	●●●	1	2	3	2
Chemical emission	●●	2	1	2	1
Renewability	●●●	3	3	3	2
Carbon footprint	●●●	3	3	2	1
Ease of dis(assembly)	●●	3	3	3	1
Mass production	●●●	3	3	3	1
Material costs	●	3	3	3	2
Material workability	●●	2	3	3	2
Total		49	57	58	34

Figure 7.4 Selection concept for t-component

1: Cardboard 90 degree bend.
The first concept is completely constructed from cardboard and consists of two components, which can be joined by taping the parts together. However, by using two different components where the smaller component potentially has to the amount of sealant increases, which increases the potential chanches on pressure loss. Nevertheless, the components can be easily mounted together with for instance tape.

2: Cardboard and recycled plastic.
This concept is an improvement of the first option where a recycled plastic component is chosen. The advantage of using this material ability to have more surface to connect both components to eachother, resulting in a stronger connection.

3: Tetra Pak and recycled plastic.
This concept makes use of Tetra Pak, the advantage of this material is the already applied moisture resistant layer combined with recycled plastic component which makes it a moisture resistant product. In addition, it is relatively easy to manufacture from sheets of Tetra Pak bended into a circular shape.

4: Bio-composite (non-woven Flax fibre and bioresin).
The last concept manufacturing from a bio-composite from a non-woven flax fibre mat combined with a bio-resin. The disadvantage is that the component has to be produced from two mirrored parts, which makes it less suitable for mass production similar as the bend in section 7.4 The two components have to be joined which could be achieved with an overlapping layer of flax fibre mat to make an airtight connection.

7.6. Connections

The illustrations for the possible connections are self explanatory, important for connections between components is the airtightness to prevent unnecessary air leakage. In addition, for future changes or replacement of components the importance lies in the use of easy demountable connections without damaging the material, which is accessed with the renewability and ease of disassembly.

Criteria	Factor	 Adhesive	 Tape, 1 side	 Tape, 2 sides	 Bolted
Airtightness	●●	3	3	3	2
Aeshetics	●	3	2	3	3
Renewability	●●●	1	2	2	3
Ease of dis(assembly)	●●	1	3	1	3
Total		14	20	17	22

Criteria	Factor	 Rubber / cork	 Click	 Click bolts	
Airtightness	●●	3	2	2	
Aeshetics	●	3	3	3	
Renewability	●●●	3	3	3	
Ease of dis(assembly)	●●	3	3	1	
Total		24	22	18	

Figure 7.5 Selection concept for connections

7.7. Coating

Most bio-based materials are not moisture resistance which makes it a challenge overtime, therefore a coating could be applied in the table below two different options are elaborated.

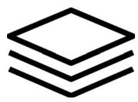
Criteria	Factor	 Liquid	 Thin film		
Airtightness	●●	3	3		
Renewability	●●●	1	2		
Ease of dis(assembly)	●●	1	2		
Chemical emission	●●	2	2		
Total		15	20		

Figure 7.6 Selection coating

7.8. Final concept

The final concept is a mix of different materials based on the most suitable manufacturing method and criteria per component. This resulting in a concept with a linear component made from Tetra Pak aswell a t-component with a recycled plastic part. The joint and bend are constructed from recycling plastic. This includes two type of connections: bolts and/or tape. Coating could be applied for materials to be moisture resistant in this case the linear component made of veneer.

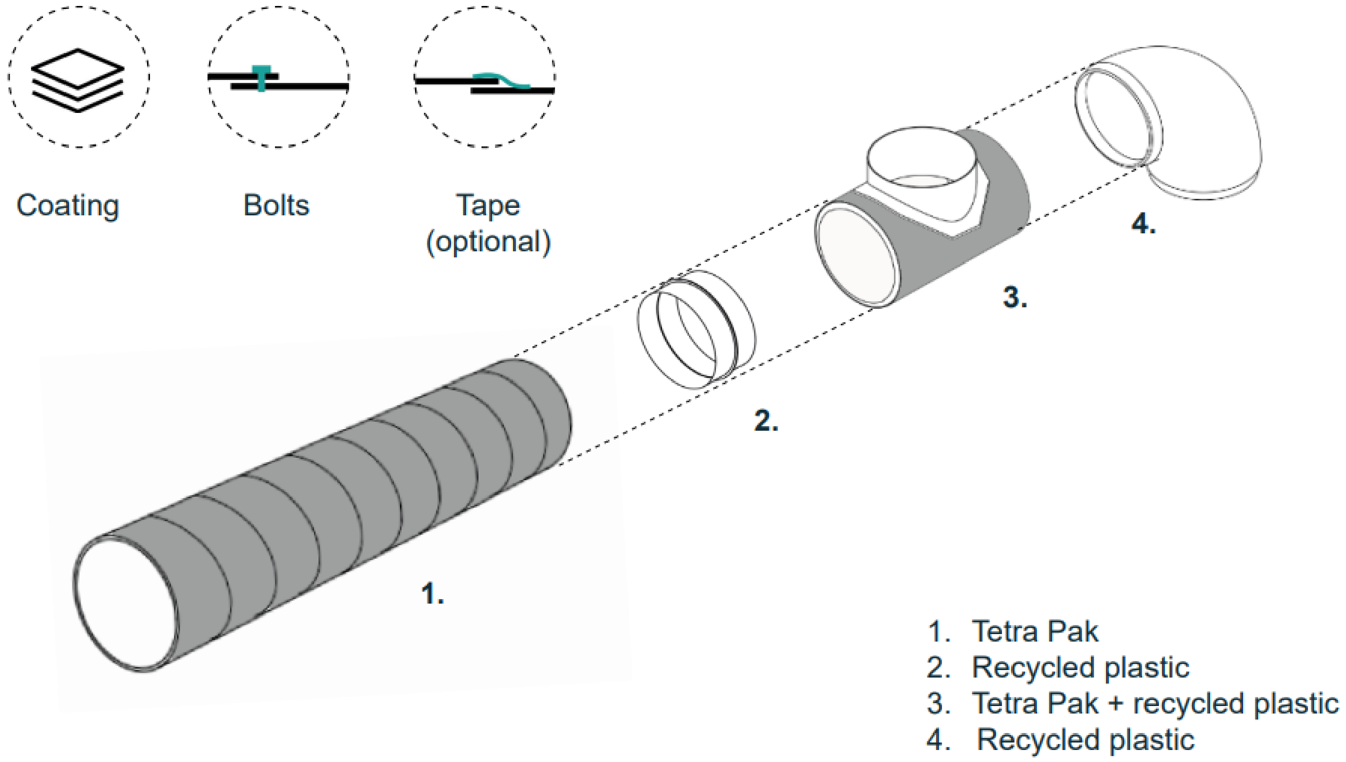


Figure 7.7 Final concept

8.

FINAL DESIGN

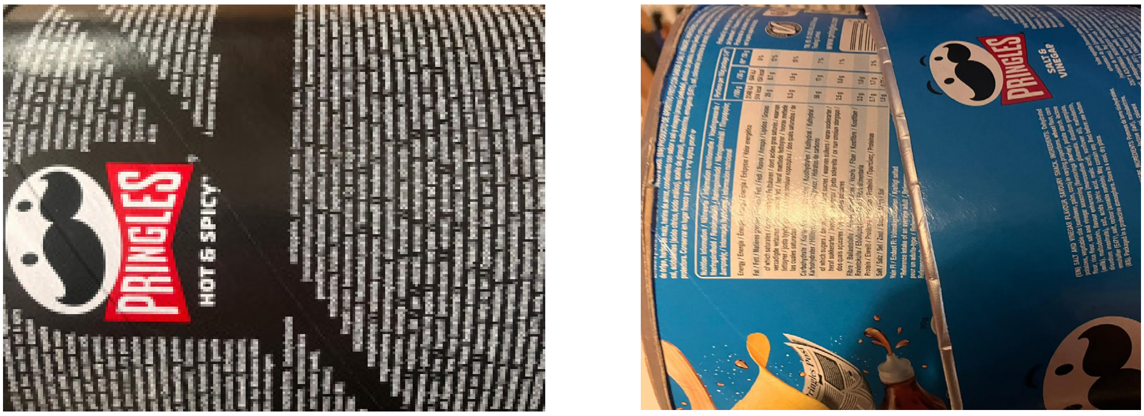
In this chapter the final design of bio-based duct components is illustrated, including the applied materials per duct component, dimensions and assembly sequence if relevant. The design is proved with a final prototype for the linear duct and bend component.

8.1. Linear component

The linear component is constructed from the principal which Tetra Pak uses for packaging. The material consists of an interior layer of aluminium and thin plastic aswell an outerlayer of thin plastic, making the material potentially moisture resistant. The design for this component can be achieved in several ways, as an uniform spiral or as a spiral consisting of strips of Tetra Pak connected together by folding.

For the construction of the linear component two directions were explored. The first option is an uniform spiral winded as cardboard tubes and layered with aluminium inside. The second option is three ways as an uniform spiral or as a spiral consisting of strips of Tetra Pak connected together. The use of the first option has several advantages:

+ Easier to produce, manufacturing method has been proven to work on smaller scale for packaging
+ Less chanche on damaging the material
+ Airtightness
+ Stiffness

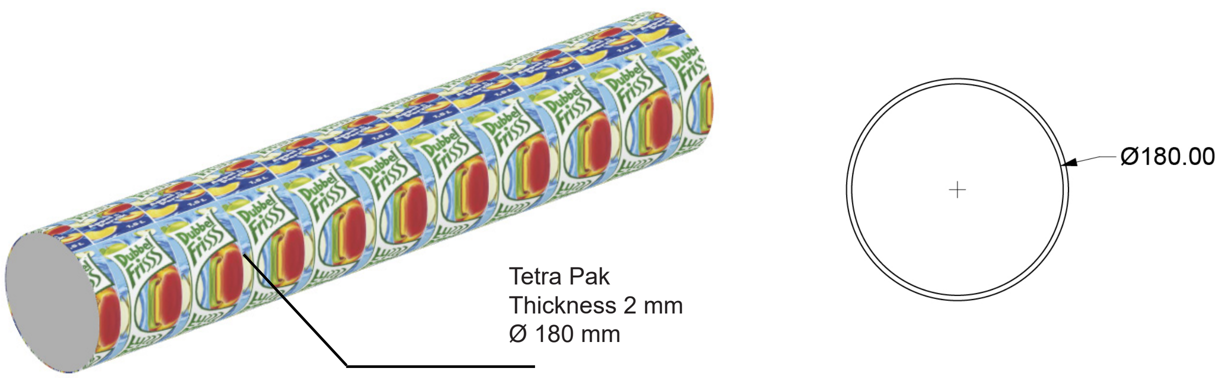


a) Uniform spiral.

b) Folded into spiral.

Figure 8.1 Linear component design approach.

Because of the ease of manufacturing and potential of damage when folding the Tetra Pak, the uniformed spiral winded packaging was further developed. This is a similar approach as how Pringles packaging is produced consisting of cardboard and a aluminium inner layer, therefore the manufacturing method is mainly similar as the cardboard spiral winded tubes.



a) 3D impression.

b) Section dimensions.

Figure 8.2 Linear component drawings.

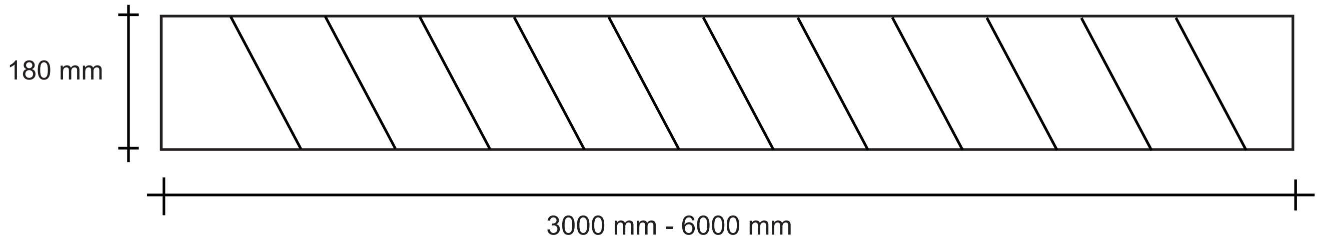


Figure 8.3 dimensions length.

8.2. Joint

The recycled plastic is used to produce joint components in a relatively fast pace by the means of injection moulding. The reason for recycled plastic is the complexity of its component, which is relative hard to achieve with a bio-based material. Aswell the high environmental impact of bio-plastics and poor recycling possibilities made bio-plastics not a suitable material for this purpose.

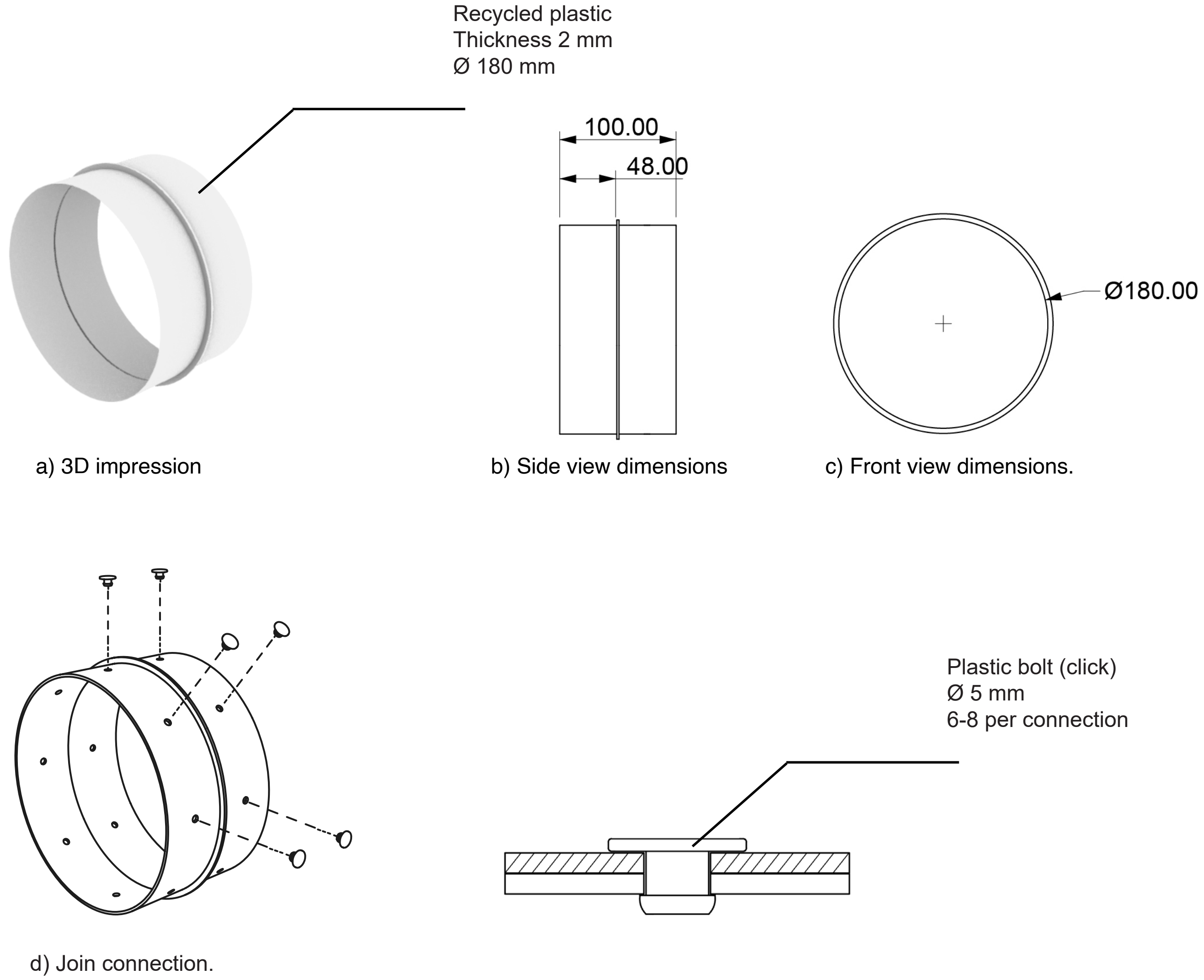
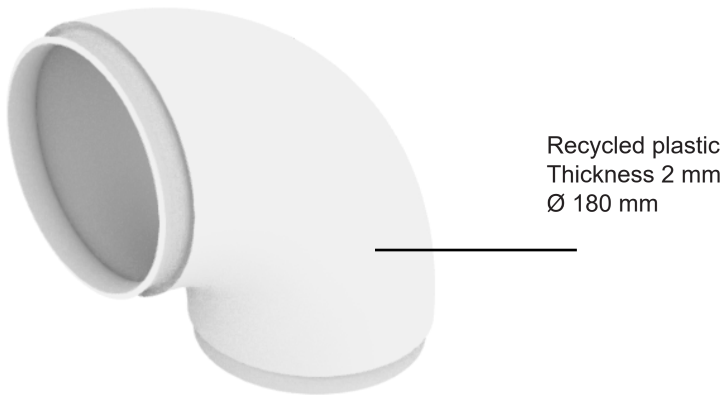


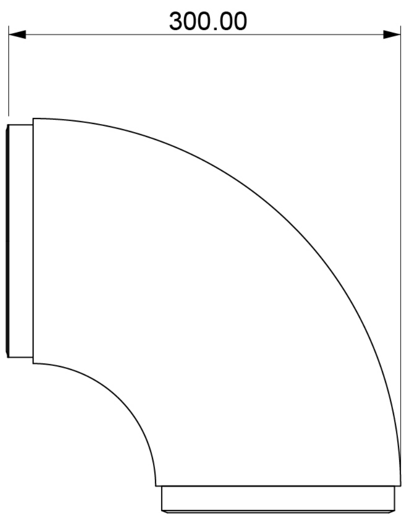
Figure 8.4 Joint design and drawings.

8.3. Bend

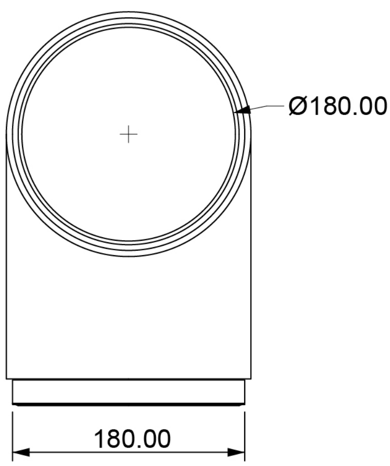
The recycled plastic is used to produce the bend components in a relatively fast pace by the means of injection moulding. The reason for recycled plastic is similar as for the joint component. The bend is designed in such a way that an extra joint is prevented due to the smaller inner diameter the duct components can fit around the section, where they are connected with plastic bolts as explained in section 8.3.



a) 3D impression bend.



b) Side view.

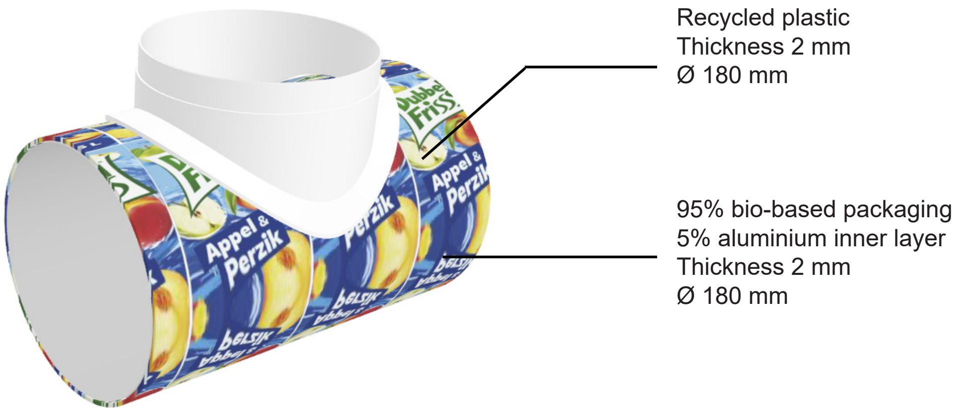


c) Front view.

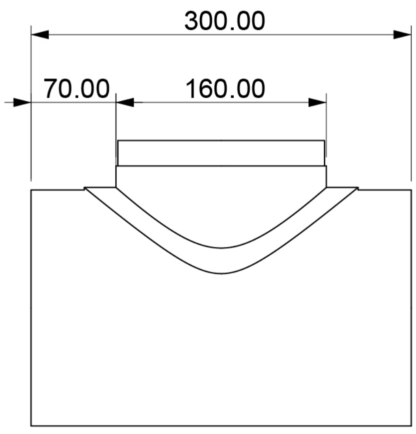
Figure 8.5 Bend design and drawings.

8.4. T-component

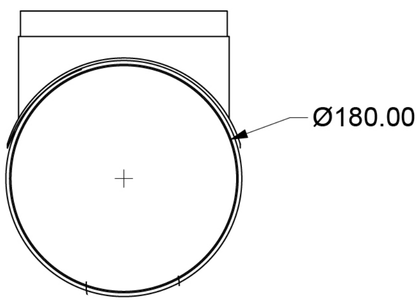
The t-component is constructed out of two main materials including Tetra Pak and recycled plastic to connect with an incomming duct. The Tetra Pak component is constructed in the same manner as the linear component. An hole is made in the duct so the incomming part can connect. The connection between the two components is achieved by heating a plastic film to stick the recycled plastic component together with the surface of the Tetra Pak. This solution is chosen because openings or holes in the packaging material could make the potential moisture enter in this openings till it reaches the cardboard, where it has the potential to spread further leading to molding overtime.



a) T-component 3D impression.



b) Side view.



c) Front view.

Figure 8.6 T-component design and drawings.

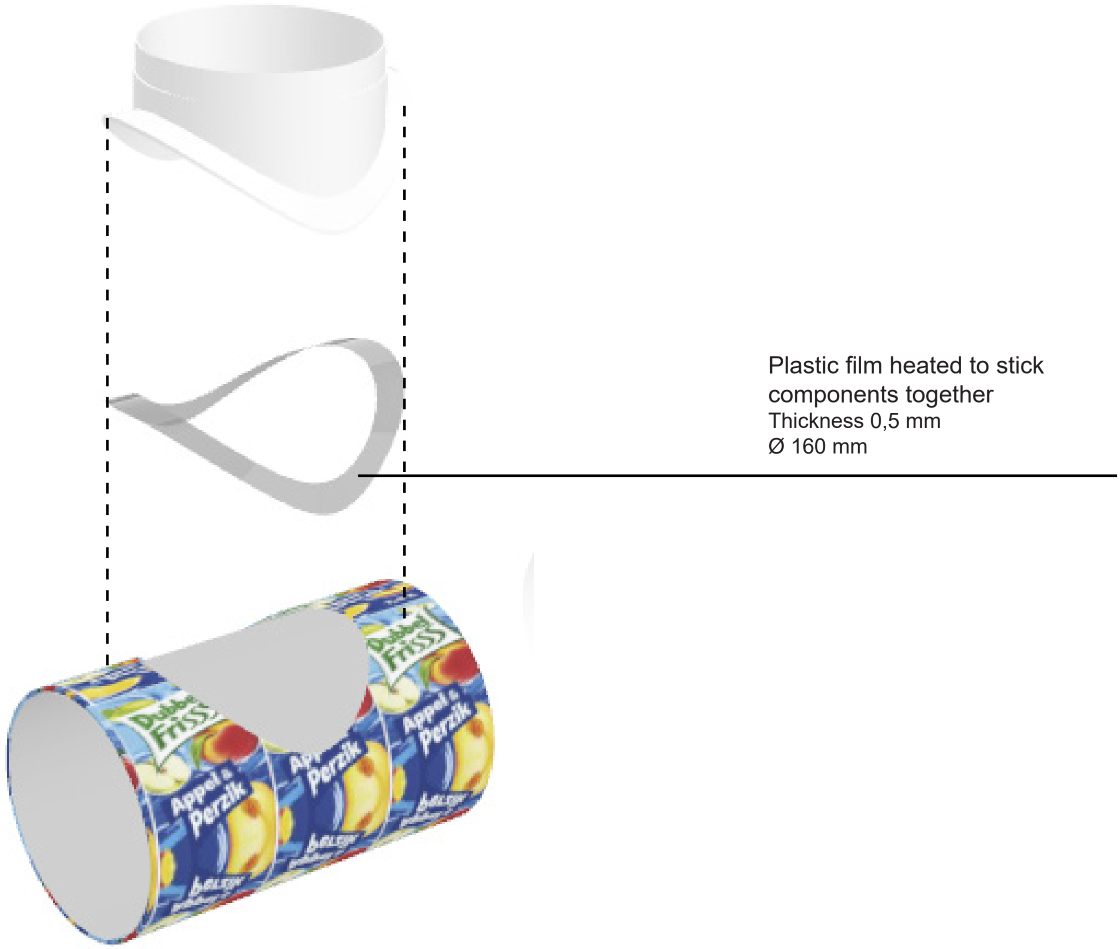
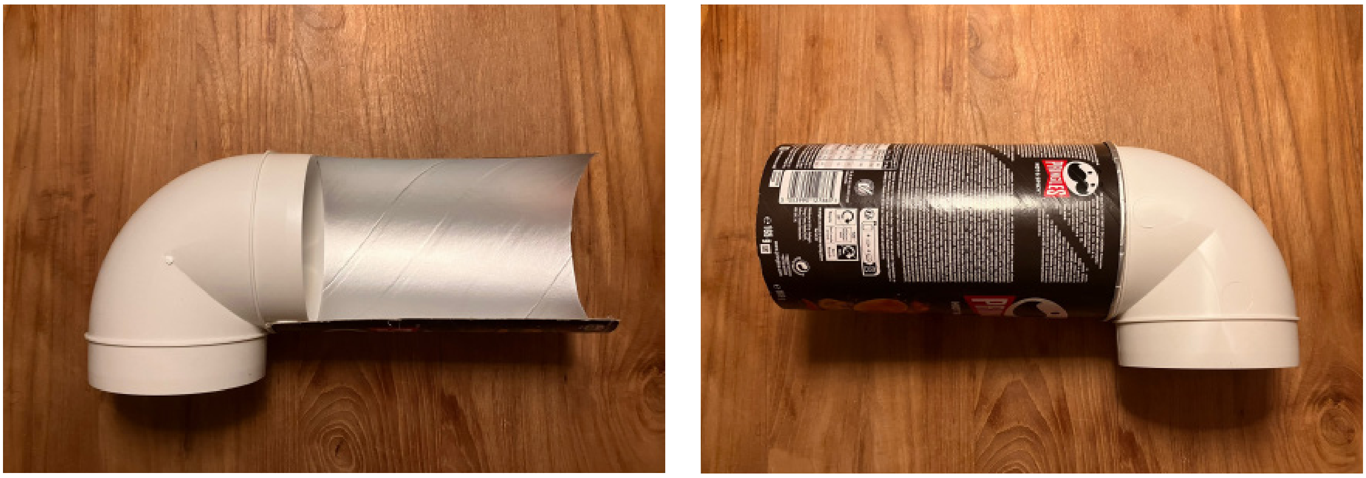


Figure 8.7 Assembly t-component.

8.5. Prototyping

A simplified prototype was constructed for a linear component and bend component, constructed from packaging material and plastic to represent Tetra Pak and recycled plastic. In terms of connection, while constructing the prototype it was concluded that plastic bolts or rivets are a danger for bio-based materials in terms of moisture resistant, since the bolt will penetrate trough the material. This could increase the risk of molding overtime and spread troughout the whole material. Therefore an alternative was explored in this case double sided tape for smaller size duct components, which in terms of moisture resistance would be a better alternative. However, for larger diameters the double sided tape most likely will not be strong enough to hold the weight of the duct components and therefore an other type of connection should be explored.



a) Inside view: aluminium layer

b) Outside view

Figure 8.8 Simplified prototyping linear and bend component.

9.

PERFORMANCE EVALUATION

In this chapter evaluation methods for important performance criteria are established to evaluate the final design. This include the evaluation of the moisture resistance and the chemical emission of the applied bio-based materials. Resulting in a validation of the final design. Therefore, the following sub-research question will be answered.

- How can performance criteria of bio-based air ducts be evaluated?

9.1. Bio-based material evaluation methods

For this research the performance evaluation methods are described for the final design, not conducted. However this can also be conducted at an earlier stage of the process to make and evaluate design decisions. The evaluation of the applied bio-based materials is important in order for the bio-based air duct components to be suitable as a potential market product. Therefore important characteristics of bio-based materials are identified this includes moisture resistance and chemical emission of bio-based materials. The bio-based materials are compared with sheet metal as reference material indicating the benchmark quality of current air duct components.

9.2. Moisture resistance

The aim of the moisture resistance evaluation is to investigate the potential of moisture and mold growth in bio-based material. Since moisture and fungi could affect the mechanical properties of the material resulting degradation of the material and durability of the material and component. In order to evaluate these criteria two tests were conducted.

Firstly, due to the hydrophylic characteristic of bio-based materials the materials are tested on their water repellency, therefore a water absorption test is performed to analyse the weight change over time, with and without coating depending on the material. Bio-based materials are relatively new for material evaluation therefore the guidelines for plastics accordance with NEN-EN ISO 62 guidelines, water absorption test for plastics.

In addition, bio-based materials are assumed to be sensitive for mold growth due to their material composition caused by moisture. It is important that materials used in air duct components, were the humidity is relative high or water is likely to occur, must not create a breeding ground for microorganisms. The bio-based materials are tested on potential mold growth in accordance with NEN-EN ISO 846 standards, evaluation of the action of microorganisms for plastics.

9.2.1. Water absorption

Preparation
The NEN-EN ISO 62 guidelines were used for the water absorption test orginally used for plastic materials and adjusted for this test method. For every bio-based material evaluated, three square-shaped test material samples were prepared with the dimensions of 50 x 50 mm and 2 mm thickness. In this way a more accurate result can be achieved. The materials are coded with a letter i.e. R (reference) and every sample with a number R.1, R.2 and R.3.

Equipment

- Accurate scale
- Plastic cups or glasses
- 3x sample for every bio-based material and sheet metal

Test procedure
The water absorption test indicates the amount of water absorbed by the material in a certain time. Higher water absorption rates could indirectly indicate an increased risk of molding. This is physically experimented in a mold growth test in chapter 9.2.2. The bio-based material samples are fully immersed in water for 24 hours in seperate cups at 23 °C. The amount of water absorbed by each of the three material samples is determined by weighting the change in mass with a precision scale. Before weighting the material samples are dried with a cloth to remove the left over droplets. Next the average weight difference is obtained of the three material samples and analysed. Most likely a more porous material will absorb more water in the time it is immersed in water, materials with a higher water absorption rate will have an increased risk for molding.

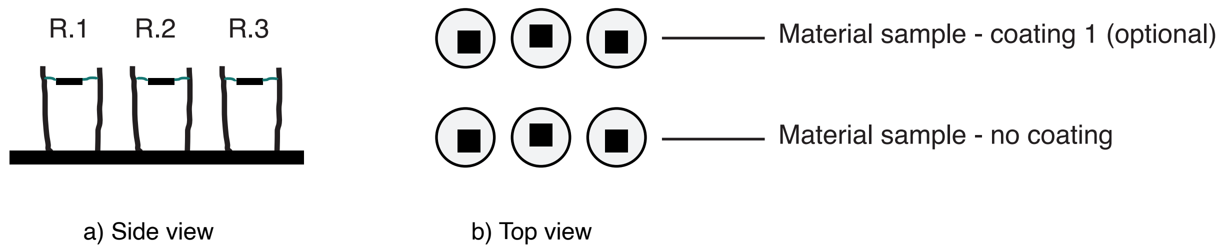


Figure 9.1 Test set-up water absorption.

Results interpretation
The weight difference overtime was tabled and analysed resulting in Table 1 as an example. By analysing and describing the findings conclusion of the results can be drawn. The weight of sheet metal most likely will not change, were an increased weight of bio-based materials is expected. A value above 0 indicates that the material sample absorbed water and there is a potential for mold growth as explained in section 9.2.2.

Table 1 Water absorption test result comparison sheet metal and bio-based materials without coating.

Material	Sample	Weight (g)	Weight after 12h (g)	Weight after 24h (g)	Weight gain (%)	Average (%)
R	R.1	50,14	50,14	50,14	0,00%	
sheet metal	R.2	50,03	50,03	50,03	0,00%	0,00%
example	R.3	51,02	51,02	51,02	0,00%	
A	A.1	14,98	15,52	16,63	11,01%	
bio-based	A.2	14,73	15,29	16,72	13,51%	12,38%
example	A.3	15,12	15,78	17,03	12,63%	

9.2.2. Mold growth

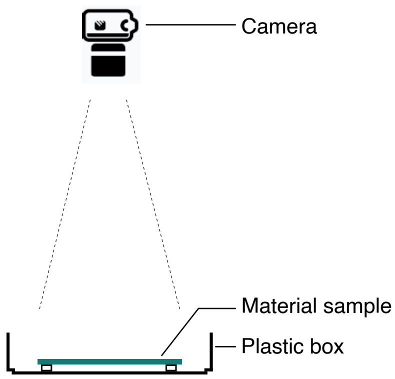
Preparation
The NEN-EN ISO 846 guidelines were used for the mold growth test method, standards for plastics were used since there is no specific standard for bio-based materials. The methodology is adjusted according to limitations of the used materials. Similarly to the water absorption test for every bio-based material evaluated, three square shaped material samples were prepared with the following dimensions 150 x 150 mm and 2 mm thickness. The materials are coded with a letter i.e. R (reference) and every sample with a number R.1- R.7.

Equipment
- Climate chamber
- Plastic boxes
- 3x sample for every bio-based material and sheet metal
- Aluminium supports to place the material samples
- Camera
- Microscope (optional)

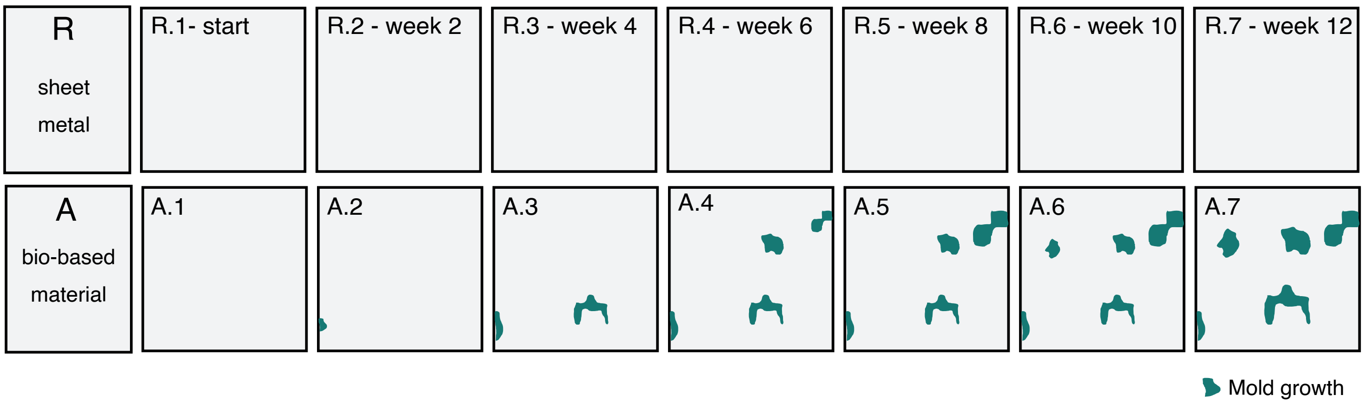
Test procedure

The bio-based materials were exposed to higher temperature and humidity levels to accelerate the aging of the materials and analyse potential mold growth, assuming these factors will accelerate the mold growth. The material samples were regularly analysed and documented. Pictures were made at the start of the test before the material samples were placed in the climate chamber to compare with the pictures made during the test. In addition, the material samples are photographed every 2 weeks to a maximum of 12 weeks. By analysing the mold growth an estimated lifespan of the bio-based material can be made under extremer conditions, temperature of 30 degrees and humidity level of 80%. If a material starts molding after 2 weeks it indicates that the lifespan of the material is limited. In addition, the materials could be coated with bio-based coatings to compare the results and to what extend these coatings will affect the mold growth. Figure 9.2 gives an indication of a possible experiment set-up (VWR, n.d.).

a) Climate chamber for 12 weeks (VWR, n.d.).



b) Photographing of material samples.

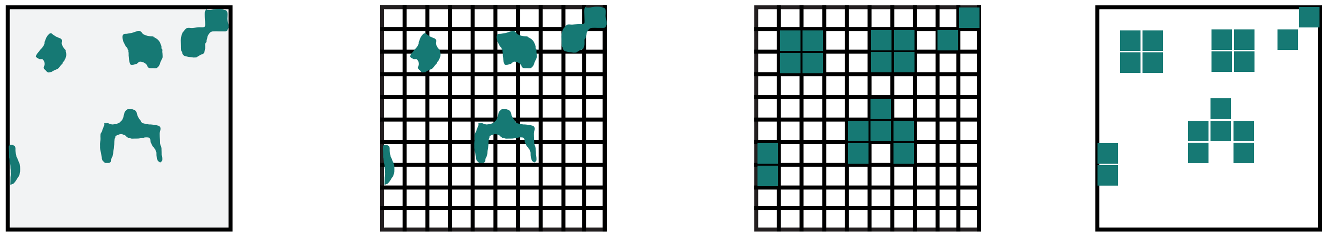


c) Documentation pictures of mold growth.

Figure 9.2 Test procedure mold growth.

Results interpretation

From the start and every two weeks till the end of the test, pictures were made of the materials to make a timeline of potential mold growth developed during the test. Finally, after 12 weeks the bio-based materials are evaluated on mold growth in a subjective manner. This is done according an evaluation scale which classifies the mold growth intensity as described in table 2. If the mold growth can be seen with the naked eye, a grid is applied on the picture or material sample. In this way every box with mold growth can be marked, the mold coverage on the test surface is calculated by adding up the boxes which are equal to 1% surface area since the grid is 10x10 as visualized in Figure 9.3. This is done for every of the three material samples and collerated to an intensity, from the three intensity values an average is calculated.



a) Sample after 12 weeks

b) 10 x 10 grid

c) Identify mold growth

d) Calculate area

18% mold growth

Intensity : 2

Acceptable: NO

Figure 9.3 Test procedure mold growth

Table 2 Evaluation scale mold growth intensity according NEN-EN ISO 846.

Mold growth intensity	**Evaluation**
0	No growth visible under the microscope.
1	No growth visible to the naked eye, but clearly visible under the microscope.
2	Growth visible to the naked eye, covering up to 25% of the test surface.
3	Growth visible to thet naked eye, covering up to 50% of the test surface.
4	Considerable growth, covering more than 50% of the test surface.
5	Intense growth visible to the eye, covering more than 75% of the test surface

In case the mold growth intensity is scored 0 or 1 a microscopic analysis should be conducted to be sure of the appearance of mold growth in the material. Therefore a sample from the bio-based material is taken and observed under a microscope, by variating the magnification between 50x and 100x a close up of the potential mold growth can be analysed, an example is shown in Figure 9.4 (Viel et al., 2019). If the value is above 0 mold growth is observed in the material sampels and therefore not acceptable as a potential bio-based material for air duct components.

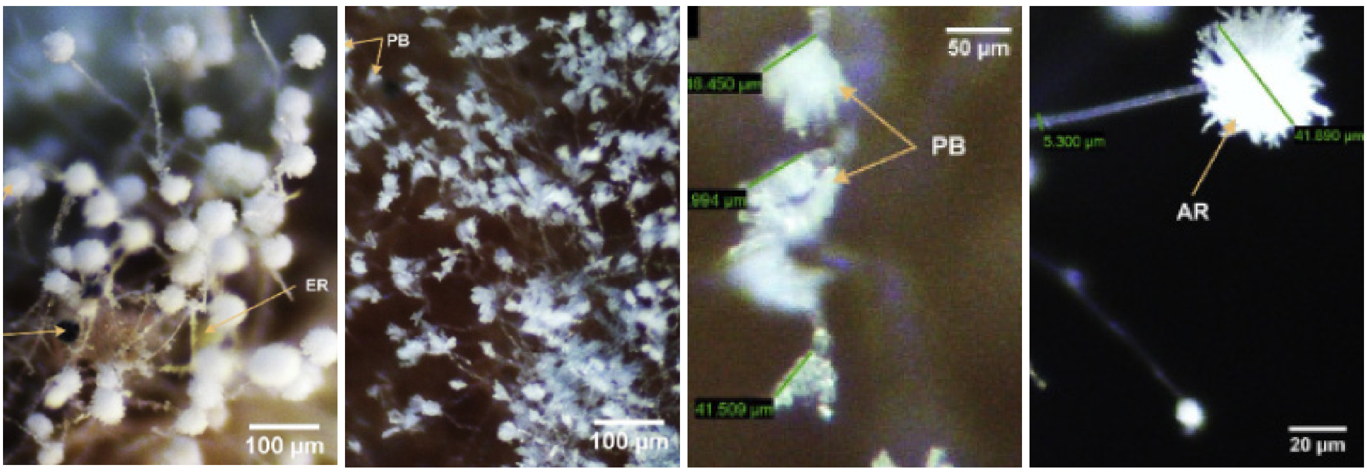


Figure 9.4 Microscope analysis of close up mold growth with different magnification (Viel et al., 2019)

9.3. Chemical emission

The chemical emission can be evaluated according the ISO 16000 standards for wood-based materials and plastics; in this research veneer, bio-plastics, bio-resins, recycled plastic and plastic coatings. Materials which could consists a harmful concentration of volatile organic compounds (VOCs) for plastics and formaldehyde concentration for wood-based materials. Since veneer is not the most suitable material the focus in the section will be on plastics and their related VOCs. Applying these types of materials for air duct components could result in contaminated air quality containing harmfull compounds, causing irritant effects for human health including unpleasant smell, problems with breathing or chronic health problems. By evaluation the materials this issues can be prevented.

Preparation

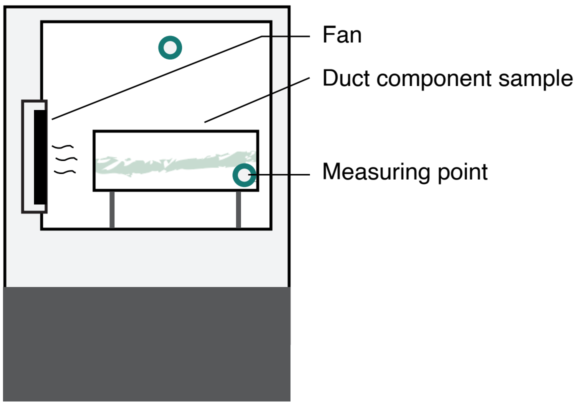
The ISO 16000 standards were partly used to be able to meassure the potential chemical emission of the above mentioned materials. For this test components of bio-based materials are prepared as well a reference component of sheet metal with similar dimensions, linear component with a length of 500 mm and Ø 125 mm.

Equipment

- Formaldehyde/VOCs meter
- Sheet metal duct components: 500 mm linear component Ø 125 mm
- Bio-based duct components: 500 mm linear component Ø 125 mm
- Aluminium supports to place the material samples
- VOC emission test chamber
- Tenax-TA sorbent
- GC-MS device

Test procedure A: Simplified VOCs evaluation.

The chemical emission of volatile organic compounds is measured by supplying air through a bio-based duct in a closed VOC emission test chamber at a temperature of 20 degrees and 50 % humidity for a period of 1 hour. The values are measured in the duct and around the duct directly after opening the test chamber, these values are measured with a formaldehyde/VOCs meter as visualized in Figure 9.5. If any values are measured a detailed evaluation of VOCs can be conducted as explained in the next section.



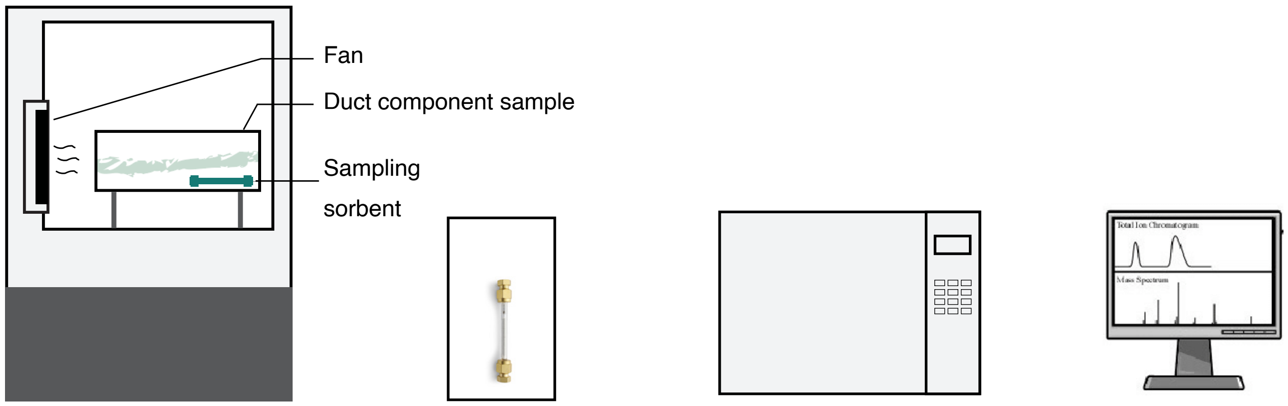
a) Test chamber set-up, section side view.

b) Measuring the chemical emission (VOCs), example bio-composite; flax fibre and bio-resin.

Figure 9.5 Simplified VOCs evaluation set-up.

Test procedure B: Detailed VOCs evaluation.

The duct component made from bio-based materials containing potential VOC's is placed in the test chamber where the temperature and humidity is set to room settings 20 °C and 50 % humidity. The duct component is place within the direction of the fan, where a Tenax-TA sorbent is placed for 24 hours. By doing so volatile organic compounds (VOCs) can be retained by the sorbent tube containing Tenax-TA sorbent. These are analysed in the laboratory by heating the sorbent tube(s) the compounds are collected and analysed by gas chromatography and mass spectroscopy (GC-MS) according ISO 16000 standards. This methodology analysis the sum of the total volatile compounds (TVOC) C6-C16, which relates to compounds containing 6 to 16 C-atoms. The different steps are visualised in Figure 9.6.



a) Test chamber set-up b) Tenax-TA sorbent c) GC-MS analysis d) Results

Figure 9.6 Experiment set-up chemical emission.

Results interpretation

The data derived from both evaluations are compared with the standards for VOCs emissions as explained in section 2.9.9., based on the results a class either A, B or C can be assigned for the applied bio-based materials and compared with sheet metal as reference material. In Table 3 a possible outcome is visualised based on the simplified experiment, where the chemical emission is measured after 1h in the test chamber. The same type of table can be made for the detailed experiment, where the emission after 24 hours per compound can be evaluated where the data is derived from the GC-MS analysis. Conclusions can be drawn based on these classifications, if the data exceeds the maximum standard values the tested bio-based material will not be acceptable for the application of air duct components.

Table 3 Results VOCs evaluation example per bio-based material following the simplified evaluation.

Material	Emission type	Emission (µg/m3) after 1h	Class	
Sheet metal	None	0	A	very good
Bio-composite	VOC	950	C	sufficient
Plastic coating	VOC	75	A	very good

9.4. Conclusion

The focus in this research is the evaluation of critical criteria related to the moisture resistance and chemical emission for the potential applied bio-based materials. The moisture resistance can be evaluated according two tests a water absorption test and mold growth test. This is achieved by placing the bio-based material samples in water and a climate chamber to respectively measure the weight change overtime and analyse the mold growth for 12 weeks. In addition the chemical emission is evaluated for plastics, bio-composites and coatings by measuring the volatile organic compound concentration after the sample is placed in the test chamber for 1 hour as simplified method. An detailed evaluation can be conducted which analysis all VOCs and related concentration in the analysed sample by GC-MS.

10.
CONCLUSION

In this chapter the main research question is answered by first answering the sub-questions. Based on the conclusion a recommendation can be formulated. In addition, aspects for future research are established which are needed to improve the development of this research.

10.1. Conclusion

In order to answer the main research question the following sub-questions are formulated:

SQ1: How are standard air ducts constructed?
Air ducts are manufactured in different materials, sizes and shapes depending on their applicability. However, the most common ducts are made from sheet metal, mainly galvanised steel, in three shapes including round, rectangular and oval. The difference in shape results in a variaty in performance, manufacturing method, installation efficiency and cost. By comparing the three different shapes the round or spiral winding sheet metal duct is the most efficient in the previous mentioned aspects. The main advantage lies in the limited material usage due to its low surface area, resulting in 30% less material than a rectangular duct resulting a significant weight reduction. In addition, the round sheet metal duct is manufactured as a spiral which makes it possible to make the air ducts more rigid resulting in longer ducts. This is achieved with lock seams by pinching and locking the metal coils together, which also function as seams to make airtight ducts.

SQ2: What are important requirements when designing for air ducts?
Requirements of air ducts either developed from sheet metal or any bio-based material are related to the following aspects: functionality, circularity, manufacturing, installation and use of the product. Derived from these categories a selection of critical criteria can be set up stated that the materials are airtight. These criteria include moisture resistance, chemical emission, carbon footprint, renewability, material workability and mass production of the air duct.

SQ3: What is circularity in the built environment?
The circularity in the built environment relates to the aspect of applying circular strategies to increase the lifecycle of applied materials. In the build environment, circularity can be applied into different layers: on material, building component, building and even regional scale.

SQ4: How can circular strategies be applied to the lifecycle of air ducts?
For building services, including air ducts, a circular strategy according TVVL is set up. This strategy helps to make an integrated circular design by taking into account the different building cycles, the simplified R-framework to reduce the environmental impact and by improving the circular material potential for the future. Due to the low lifespan of building services the need for replacement is higher, which ask for a demountable design. Thinking in systems makes it easier to apply circular strategies into products and make design decisions according the principles of re-life or renewability, according to the R-framework and Butterfly diagram.

SQ5: Which bio-based materials are suitable for the fabrication of air ducts?
In terms of fabrication of an air duct several materials are suitable divided in two type of components: linear and complex (joint, bend, t-component). The assumption is that coatings can be applied on the materials, in that way there are several suitable materials including cardboard, veneer, bioplastic, bio-composites (flax, jeans and bioresin). Currently for one material a coating is integrated in the manufacturing process for Tetra Pak since its a packaging material to make it air and moisture resistant.

SQ6: What are appropriate manufacturing methods for the selected suitable bio-based materials?
According to the research using different materials with related manufacturing methods for specific components have proven to be beneficial, resulting in multiple suitable production methods depending on the component. However, the common aspect of these manufacturing methods is their scalability. The possibility to produce the component in a relative fast pace by producing different sizes and or lengths of the component. For linear components this include cutting and folding corrugated cardboard, spiral cardboard winding, rotary cutting for veneer and compression moulding sheets of bio-composites and extrusion for plastics. For complex components this include cutting cardboard, injection moulding for plastics and compression moulding for bio-composites. In addition, packaging manufacturing method to produce sheets of Tetra Pak are beneficial for both type of components.

SQ7: How feasible is the use of bio-based materials for air ducts in terms of carbon footprint compared to sheet metal?
Based on the carbon footprint assessment of the full lifecycle of the product from manufacturing to the end-of-life phase, all the assessed bio-based materials resulted to have a lower carbon footprint than sheet metal from galvanised steel. The values vary significantly between the materials, making certain materials more feasible than others. Materials such as bio-plastics and bio-composites have a relative higher carbon footprint due to the plastic content, surprisingly bio-plastics have almost a similar carbon footprint as sheet metal. Therefore, recycled plastic was analysed resulted to have a difference of a factor 4. Other materials such as cardboard, veneer and Tetra Pak have a relative lower footprint up to a factor 3 and 5 difference.

In terms of feasability it greatly depends on the lifespan of the product when applied as bio-based air duct component, which is currently unknown. Nevertheless, taking into account the lifespan of potential bio-based materials might be limited or challenging which increases the carbon footprint overall due to the increase of replacements. This could result in an overall carbon footprint which can be higher than sheet metal.

SQ8: How can performance criteria of bio-based air ducts be evaluated?
The moisture resistance can be evaluated according two tests a water absorption test and mold growth test. This is achieved by placing the bio-based material samples in a cup with water and a climate chamber to respectively measure the weight change overtime and analyse the mold growth for a selected period of time. In addition the chemical emission is evaluated for plastics, bio-composites and coatings by measuring the volatile organic compound concentration after the sample is placed in the test chamber for 1 hour as simplified method. A detailed evaluation can be conducted which analysis all VOCs and related concentrations in the analysed sample by GC-MS.

Main research question: What are the potential and limitations of bio-based materials to replace sheet metal for the construction of air ducts by maintaining the same quality?

This project proved realistic possibilities for mass-production for bio-based air duct components, by exploring the suitable manufacturing methods for bio-based materials per component aswell by developing models with the different materials. It can be concluded that the potential for linear bio-based components made from Tetra Pak is more advanced than complex components including joints, bends and t-components. This mainly relates to the production efficiency and the LCA of the used materials. Bio-plastics as potential material for complex components resulted in a relative high carbon footprint which made recycled plastic as non-renewable material a more realistic alternative.

Nevertheless, limitations mainly lie by achieving the quality of sheet metal in terms of moisture resistance and chemical emission. Due the porous character of most bio-based materials they are sensitive for humid environments, increasing the risk of mold growth overtime. This can be prevented with a coating which in many cases consists of volatile organic compounds (VOCs). The same accounts for wood-based materials such as veneer and plastics due to the existance of respectively formaldehyde and VOCs. High concentrations can result in irritant effects of human health and therefore should be evaluated according NEN regulations.

Furthermore, the lifespan of bio-based materials is unknown and ask for further research. The lifespan of the a product relates to the product lifecycle and the amount of replacements it needs which potentially increases the carbon footprint and therefore could exceed the carbon footprint of sheet metal components if the lifespan turns out to be relatively low.

Lastly, the connections between components is not as simple as between sheet metal components, where often bolts or rivets are applied. When applying this type of connection for bio-based materials the bolt or rivet will penetrate through the material increasing the risk of moisture and therefore could cause molding of the material overtime.

10.2. Recommendations for further research

The current design outcome in this research represents a possible suitable outcome. Due to the limited time there are still important aspects which can be further explored.

- Development of a coating, bio-resin or bio-plastic which is moisture resistant and limits the amount of chemical emission.
- Research the expected lifespan of the duct components when exposed to temperature and humidity changes as explained in section 8.3.
- Explore the scalability of the used materials, some materials have proven to be suitable for mass production for others its still an aspect to be further explored. As well the different diameters requires a different diameter thus a thicker material the optimal relation between thickness and stiffness should be achieved to prevent overdimension of materials. This will also influence the lifecycle assessment (LCA), since it will affect the amount of materials being used.
- Evaluate the mechanical properties of the applied bio-based materials when they are exposed to higher temperature and humidity rates in a climate chamber.
- Explore other materials which weren't available during this research, such as cellulose waste fibres from ECOR and Giant Bamboo as a 100% bio-based material.
- The explored components in this research represents the complexity of geometry for a ductwork system. However, that being said there are still a lot of other components to be developed.

REFERENCES

Accu duct. (2006). Duct systems & components. Retrieved from http://www.accuduct.com/pdfs/catalog.pdf

Ansys Granta EduPack. (2022). ANSYS, Inc., Cambridge, UK

Airways Partners. (2002). Source book for efficient air duct systems in Europe.

Aiva. (n.d.). Ovalizer. Retrieved from http://www.ductingmachine.com/html_products/pro-104.html

Alnor. (n.d.). Ventilation ducts and round fittings. Retrieved from https://www.ventilation-alnor.co.uk/index/products-en/ducts-and-round-fittings/

ASIEPI. (2010). Stimulation of good building and ductwork airtightness through EPBD. Retrieved from https://www.aivc.org/sites/default/files/ASIEPI_Airtightness_Technical_report_20100422.pdf

Aslani, F., Uy, B., Hicks, S., & Kang, W.-h. (2015). Spiral welded tubes. Advances in steel structures, DOI: 10.13140.

Beurskens, P., & Bakx, M. (2015). Built-to-rebuild "The development of a framework for buildings according to the circular economy concept, which will be specifed for the design of circular facades". Retrieved from Built-to-rebuild "The development of a framework for buildings according to the circular economy concept, which will be specifed for the design of circular facades".

Bhatia, A. (2014). HVAC - How to Size and Design Ducts. Retrieved from https://www.cedengineering.com/userfiles/HVAC%20-%20How%20to%20Size%20and%20Design%20Ducts%20R1.pdf

Bocken, N., Pauw, I., Bakker, C., & Grinten, B. (2016). Product design and business model strategies for a circular economy. Journal of Industrial and Production Engineering, 33, 308-320.

Brand, S. (1994). How Buildings Learn: What Happens After They're Built. London, UK: Viking Press.

Braungart, M., Bondesen, P., Kälin, A., & Gabler, B. (2008). Specific public goods for economic development: With a focus on environment. Public goods for economic development 139 (2008).

Buranov, A., Mazza, G. (2008). Lignin in straw of herbaceous crops. Industrial Crops and Products 28, 237-259.

Cao, S.-J., & Fang, Z. (2022). Handbook of Ventilation Technology for the Built Environment - Design, Control and Testing. Croydon, UK: CPI Group (UK) Ltd.

CIBSE. (2016). Ventilation and Ductwork - CIBSE Guide B2. Norwich, UK: Page Bros. (Norwich) Ltd.

Climate Construct. (n.d.). Luchttechniek. Retrieved from https://www.climaconstruct.be/documents/technische-info/05-ventilatoren.pdf

Cramer, J. (2017). The Raw Materials Transition in the Amsterdam Metropolitan Area: Added Value for the Economy, Well-Being, and the Environment. Environment: Science and Policy for Sustainable Development, 59 (3), 14-21 doi:10.1080/00139157.2017.1301167.

Croxford, B., Mendoza, R., Portal, S.-J., & Rovas, D. (2018). Circular options for building services: Case studies; 22 Gordon Street, Arup Circular Building. Retrieved from https://www.ucl.ac.uk/circular-economy-lab/sites/circular-economy-lab/files/bif_circular_economy_options_for_hvac_final_report.pdf lab/files/bif_circular_economy_options_for_hvac_final_report.pdf

Durmisevic, E. (2010). Green design and assembly of buildings and systems, design for disassembly a key to life cycle design of buildings and building products. Saarbucken, Germany: VDM Verlag Dr. Müller.

ECOR. (n.d.). Nature's Composite Providing Clean Sustainable Circular Supply Chain Solutions. Retrieved from https://ecorglobal.com/

Eekhout, M. (2008). Methodology for Product Development in Architecture. Amsterdam: IOS Press.

EIME. (n.d.). EIME LCA and Eco-design Software. Retrieved from https://codde.fr/en/our-software/eime-presentation.

Ellen MacArthur Foundation. (n.d.). What is circular economy? Retrieved from https://ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview

Ellen McArthur Foundation. (2015). Towards a circular economy: business rationale for an accelerated transition.

EMF. (2012). Towards the Circular Economy: Economic and Business Rationale for an Accelerated Transition. Retrieved from www.ellenmacarthurfoundation.org/assets/downloads/publications/

Etheridge, D., & Sandberg, M. (1996). Building ventilation - theory and measurements. Chichester, UK: John Wiley & Sons.

European Bioplastics (n.d.). Bioplastic materials. Retrieved from https://www.european-bioplastics.org/bioplastics/materials/

GatorDuct. (2018). GatorDuct® is transforming the ductwork industry across the world. Retrieved from https://www.gatorduct.com/

HVAC Global. (2022). Air Handling Unit. Retrieved from https://hvacglobal.org/air-handling-unit-manufacturers/

Idemat. (2022). Idemat and Ecoinvent and ecocosts midpoint tables. Retrieved from https://www.ecocostsvalue.com/data/

Kenniskaarten. (2016). How do materials circulate in a circular economy? Retrieved from https://kenniskaarten.hetgroenebrein.nl/en/knowledge-map-circular-economy/how-materials-circulate/

Klein, T., Bilow, M., Sabbe, A., Smit, M., Leclercq, E., Konstantinou, T., . . . Wandl, A. (n.d.). Circular Economy of a Sustainable Built Environment [MOOC]. Retrieved from https://online-learning.tudelft.nl/courses/circular-economy-for-a-sustainable-built-environment/

Kula, D, Ternaux, E., & Hirsinger, Q. (2014). Materiology, the creative guide to materials and technologies. Amsterdam, Netherlands: Frame Publishers. https://www.scribd.com/document/500529462/Materiology

Lenderink Technologies. (2022). Veneer cuts. Retrieved from https://lenderink.com/wood-veneer/veneer-cuts/

Malmstrom, T., & Andersson, J. (n.d.).

Nederlands Normalisatie Instituut. (1998). Ventilation for buildings - Sheet metal air ducts and fittings with rectangular cross-section - Dimensions NEN-EN 1505.

Nederlands Normalisatie Instituut. (2003). Ventilation for buildings - Ductwork - Strength and leakage of circular sheet metal ducts NEN-EN 12237.

Nederlands Normalisatie Instituut. (2006). Ventilation for Buildings - Ductwork - Requirements for ductwork components to facilitate maintenance of ductwork systems NEN-EN 12097.

Nederlands Normalisatie Instituut. (2006). Ventilation for buildings - Sheet metal air ducts with rectangular section - Requirments for strength and leakage NEN-EN 1507.

Nederlands Normalisatie Instituut. (2007). Ventilation for buildings - Sheet metal air ducts and fittings with circular cross-section – Dimensions NEN-EN 1506.

Nederlands Normalisatie Instituut. (2010). Ventilation for buildings - Ducts and ductwork components, leakage classification and testing NEN-EN 15727.

Nederlands Normalisatie Instituut. (2014). Bio-based products - Vocabulary NEN-EN 16575 .

Nederlands Normalisatie Instituut. (2019). Fire classification of construction products and building elements - Part 1: Classification using data from reaction to fire tests NEN-EN 13501-1 .

Nederlands Normalisatie Instituut. (2019). Noise control in buildings - Determination methods for performances concerning airborne sound insulation of facades, airborne sound insulation and impact sound insulation sound levels caused by technical services NEN-EN 5077.

Nederlands Normalisatie Instituut. (2008). Plastics - Determination of water absorption NEN-ISO-62.

Nederlands Normalisatie Instituut. (2019). Plastics - Evaluation of the action of microorganisms NEN-ISO-846.

Nederlands Normalisatie Instituut. (2021). Determination of organic compounds (VVOC, VOC, SVOC) in indoor and test chamber air by active sampling on sorbent tubes, thermal desorption and gas chromatography using MS or MS FID NEN-ISO-16000.

Nederlands Normalisatie Instituut. (2019). Ventilatie van gebouwen - Bepalingsmethoden voor nieuwbouw NEN 1087.

Nederlands Normalisatie Instituut. (2021). Fire classification of construction products and building elements - Part 2: Classification using data from fire resistance tests, excluding ventilation services NEN-EN 13501-2.

Nederlands Normalisatie Instituut. (2011). Sustainability of construction works - Assessment of Environmental Performance of buildings - calculation method NEN-EN 15978.

O'Dogherty, M., Hubert, A., & Marshall, J. (1995). A Study of the Physical and Mechanical Properties of Wheat Straw. Journal of Agricultural Engineering Research, 62 (2), 133-142.

Osborne. (n.d.). The Difference Between Thermoplastic and Thermosetting Plastic. Retrieved from https://cdn.thomasnet.com/ccp/01266694/296817.pdf

Persson, A., Ramamoorthy, S., & Skrifvars, M. (2015). A Review of Natural Fibers Used in Biocomposites: Plant, Animal and Regenerated Cellulose Fibers. Polymer Reviews. DOI: 10.1080/15583724.2014.971124

PlanQ. (2022). Rezign Veneer. Retrieved from https://static1.squarespace.com/static/5e4d3b2d437be343b3cb96d0/t/62dfcbb16af18e1bd3449806/1658833845115/Rezign_veneer_technical_sheet_2022_online.pdf

Preda . (n.d.). Auto Duct Line 5. Retrieved from https://www.predacnc.com/auto_duct_line_5.html

Rijksoverheid. (2016). Nederland circulair in 2050. Retrieved from http://www.rijksoverheid.nl/onderwerpen/circulaire-economie/nederland-circulair-in-2050

Rowell, R., Young, R., & Rowell, J. (1997). Paper and Composites From Agro-based Resources. New York, USA: CRC Press Inc.

R-vent. (2022). Buizen - Spiraalgefelste buizen. Retrieved from https://media.rventgroup.com/doc/view/7600/Technische_documentatie_Rvent-Buizen_CHR.pdf

Saiductfab. (2020). Indiamart. Retrieved from https://www.indiamart.com/proddetail/spiral-duct-13486306691.html

Si, S., Chen, Y., Fan, C., Hu, H., Li, Y., Huang, J., Liao, H., Hao, B., Li, Q., Peng, L., Tu, Y.,. (2015). Lignin extraction distinctively enhances biomass enzymatic saccharification in hemicelluloses-rich Miscanthus species under various alkali and acid pretreatments. Bioresource Technology 183, 248-254.

Spot. (n.d.). Spiral flat oval duct. Retrieved from https://www.spotusa.com/products/spiral-flat-oval-duct/

Stahel, R. (2016). The circular economy. Nature, 531, 435-438.

Stahel, W. (2010). The Performance Economy. Hampshire, UK: Palgrave Macmillan Hampshire.

Tazelaar, K. (2017). Bio-composieten. Ontwerpen met vezels 'bio' polymeren. Retrieved from https://www.nweurope.eu/media/17202/bio-composieten.pdf

TVVL. (2018). Programma van eisen. Gezonde Kantoren 2018. Retrieved from https://tvvlconnect.nl/?file=467&m=1542116048&action=file.download

TVVL. (2020). Community Circulaire Installaties. Retrieved from https://www.tvvl.nl/community/circulaire-installaties

Uniclima. (2020). Joint Product Environmental Profile. Metal circular air duct. Retrieved from https://register.pep-ecopassport.org/pep/consult/mbesqrsCBZbWbKJq6-kJ3jIYsnPuV99dLcXovlCp-cA/mbesqrsCBZbWbKJq6-kJ3lQmBuGvAHsLUfQU9idjOpk

van Stijn, A., Malabi Eberhardt, L., Wouterszoon Jansen, B., & Meijer, A. (2021). A Circular Economy Life Cycle Assessment (CE-LCA) model for building components. Resources, conversation & recycling 174, 105683.

Vepa. (n.d.). Hemp fine. Retrieved from https://vepa.nl/downloads/

Venkateshappa, S. (2011). Static bending and impact behaviour of areca fibers composites. Materials and Design. DOI: 10.1016/j.matdes.2010.11.020

Viel, M., Collet, F., Lecieux, Y., Francois, M., Colson, V., Lanos, C., Hussain, A., Lawrence, M. (2019). Resistance to mold development assessment of bio-based building materials. Composites Part B: Engineering,158, 406-418. doi: 10.1016/j.compositesb.2018.09.063.

VWR. (n.d.). Climate chambers, ICHeco series Retrieved from https://nl.vwr.com/store/product/25211002/climate-chambers-icheco-series

Wang, Y., McCarthy, M., Johnson, C.G. and Gerhardt, T.D. (1995). Enhanced crush strength construction multi-grade paperboard tubes. US Patent 5,393,582

Watkins, T. (2012). Packaging technology Fundamentals, Materials and Processes. Woodlead publishing. https://doi.org/10.1533/9780857095701.2.240

APPENDIX A

LCA assessment (A1-A3)

Details product

Product category

- Air ducts, circular spiral

Description

- Air ducts made with a inner diameter of 180 mm and a length of 1 meter.
- Weight varies depending on the material for sheet metal the weight is 2.44 kg/m
- For bio-based materials a similar thickness of 3 mm is used for equal comparison, makes inner diameter 180 mm and outer diameter 186 mm

The following data is required to calculate the weigh of 1 meter duct with a diameter of 180 mm in kg, where the density is derived from Ansys Granta EduPack (2022) software, unless mentioned differently.

	Sheet metal	Recycled plastic	Cardboard	Bio-plastic	Bio-composite (Old jeans + PLA)	Bio-composite (Flax + PLA)	Veneer	Tetra Pak
Density (kg/m3)	7800	1470	700	1300	1160	1500	640	850
Thickness (m)		0,003	0,003	0,003	0,003	0,003	0,003	0,003
Crossection area (m2)		0,001725	0,001725	0,001725	0,001725	0,001725	0,001725	0,001725
Length (m)		1	1	1	1	1	1	1
Volume (m3) duct 1 meter		0,001725	0,001725	0,001725	0,001725	0,001725	0,001725	0,001725
Weight (kg/m)	2,44*	2,54	1,21	2,24	2,00	2,59	1,10	1,47

*Weight sheet metal: (R-vent, 2022).

Notes transport

Sheet metal	Containership from Brazil to Rotterdam estimated kilometers
Data container ship	0,129 kg CO_2e per ton.10km (Idemat, 2022)
Distance	10000 km
Calculation	0,129 x 10000 = 1290 kg CO_2e per ton.10km = = 1,29 kg CO_2e per kg.10km = 0,13 kg CO_2e per kg.km

Bio-based materials + recycled plastic	National transport in Netherlands estimated kilometers with 24 ton truck
Data 24 ton truck	0,091 kg CO_2e per ton.km (Idemat, 2022)
Distance	200 km
Calculation	0,091 x 200 = 18,2 kg CO_2e per ton.km = = 0,02 kg CO_2e per kg.km

Assumptions

- Recycling rate of recycled plastic is assumed to be 100%, not specified in the data sheet of Idemat.
- Rotary cutting process for veneer is set on 1.00 kg CO_2e per kg, no data available.
- Processing different layers of Tetra Pak is set on 0.50 kg CO_2e per kg, no data available.
- Transportation within Netherlands for bio-based materials and recycled plastics is estimated on 200 km.
- Bioresin content in bio-composites is set to 50% and the matrix (flax and jeans) as well to make it 100%, the bioresin content might be higher.
- The primary processing methods are calculated assuming the production process and post-processing of the product is neglegtable compared to the primary production process.
- The landfill % is estimated based on 20% for all materials besides veneer 40%, data derived from EIME software.

Sheet metal
Weight: 2,44 kg/m

Phase	Explanation	Values	Carbon footprint kg CO2e / kg	Carbon footprint kg CO2e per kg/m
A1. Raw material supply	Raw material sheet metal	65%	0,65 x 3,94 = 2,56	2,56 x 2,44 = 6,25
	Recycled sheet metal	*35%	-	
A2. Transport	Container ship from Brazil	10000 km	0,13	0,13 x 2,44 = 0,32
A3. Manufacturing	Rolling steel into coils		0,90	0,90 x 2,44 = 2,20
A4. Transport	Truck 24t national	100 km	0,01	0,02
C1-C4. End of life	Landfill metal	20%	0,20 x 0,0145 = 0,0029	0,0071
Total				8,80

* According to Uniclima (2020) the weight of the air duct in their product is 4,6 kg the use of secondary material 1,3 kg (1,3/4,6)x100% = 35%

Recycled plastic
Weight: 2,54 kg/m

Phase	Explanation	Values	Carbon footprint kg CO2e / kg	Carbon footprint kg CO2e per kg/m
A1. Raw material supply	Recycled plastics	100%	0,57	1,45
A2. Transport	Truck 24t national	200 km	0,02	0,05
A3. Manufacturing	Extrusion		0,13	0,33
A4. Transport	Truck 24t national	100 km	0,01	0,03
C1-C4. End of life	Landfill plastics	20%	0,20 x 0,072 = 0,01	0,03
Total				1,89

Bio-plastic (PLA)
Weight: 2,24 kg/m

Phase	Explanation	Values	Carbon footprint kg CO2e / kg	Carbon footprint kg CO2e per kg/m
A1. Raw material supply	Bio-plastic (PLA)	100%	3,57	8,00
A2. Transport	Truck 24t national	200 km	0,02	0,04
A3. Manufacturing	Extrusion		0,13	0,29
A4. Transport	Truck 24t national	100 km	0,01	0,02
C1-C4. End of life	Landfill plastics	20%	0,20 x 0,072 = 0,01	0,02
Total				8,37

Cardboard
Weight: 1,21 kg/m

Phase	Explanation	Values	Carbon footprint kg CO2e / kg	Carbon footprint kg CO2e per kg/m
A1. Raw material supply	Cardboard	100%	0,90	1,09
A2. Transport	Truck 24t national	200 km	0,02	0,03
A3. Manufacturing	Spiral winding		0,13	0,16
A4. Transport	Truck 24t national	100 km	0,01	0,01
C1-C4. End of life	Landfill organic cardboard	20%	0,20 x 1,38 = 0,276	0,33
Total				1,62

Veneer
Weight: 1,10 kg/m

Phase	Explanation	Values	Carbon footprint kg CO2e / kg	Carbon footprint kg CO2e per kg/m
A1. Raw material supply	Veneer	100%	0,84	0,92
A2. Transport	Truck 24t national	200 km	0,02	0,02
A3. Manufacturing	Rotary cutting		1,00	1,10
A4. Transport	Truck 24t national	100 km	0,01	0,01
C1-C4. End of life	Landfill wood	40%	0,40 x 1,41 = 0,564	0,624
Total				2,67

Bio-composite (non-woven flax and bioresin)
Weight: 2,59 kg/m

Phase	Explanation	Values	Carbon footprint kg CO2e / kg	Carbon footprint kg CO2e per kg/m
A1. Raw material supply	Bio-composite	100%	1,34	3,42
	Non-woven flax	50%	0,44 x 0,5 = 0,22	
	Bioresin	50%	2,24 x 0,5 = 1,12	
A2. Transport	Truck 24t national	200 km	0,02	0,05
A3. Manufacturing	Weaving	50%	1,50 x 0,5 = 0,75	2,51
	Thermo moulding	100%	0,22	
A4. Transport	Truck 24t national	100 km	0,01	0,03
C1-C4. End of life	Landfill organic: 50%	20%	0,20 x 0,513= 0,10	0,10 x 1,295 = 0,13
	Landfill plastic: 50%	20%	0,20 x 0,072 = 0,01	0,01 x 1,295 = 0,013
	Landfill total			0,143
Total				6,15

Bio-composite (jeans and bioresin)
Weight: 2,00 kg/m

Phase	Explanation	Values	Carbon footprint kg CO2e / kg	Carbon footprint kg CO2e per kg/m
A1. Raw material supply	Bio-composite	100%	1,12	2,24
	Clothing waste jeans	50%	0 x 0.7 = 0	
	Bioresin	50%	2,24 x 0,5 = 1,12	
A2. Transport	Truck 24t national	200 km	0,02	0,04
A3. Manufacturing	Weaving (into felt)	50%	1,50 x 0,5 = 0,75	1,94
	Thermo moulding	100%	0,22	
A4. Transport	Truck 24t national	100 km	0,01	0,02
C1-C4. End of life	Landfill organic: 50%	20%	0,20 x 0,513 = 0,10	0,10 x 1,0 = 0,10
	Landfill plastic: 50%	20%	0,20 x 0,072 = 0,01	0,01 x 1,0 = 0,01
	Landfill total			0,11
Total				4,35

Tetra Pak
Weight: 1,47 kg/m

Phase	Explanation	Values	Carbon footprint kg CO2e / kg	Carbon footprint kg CO2e per kg/m
A1. Raw material supply	Tetra Pak	100%	1,45	2,13
	Cardboard	80%	0,90 x 0,8 = 0,72	
	PE plastic	15%	1,91 x 0,15 = 0,29	
	Aluminium	5%	8,84 x 0,05 = 0,44	
A2. Transport	Truck 24t national	200 km	0,02	0,03
A3. Manufacturing	Bonding different layers		0,50	0,74
A4. Transport	Truck 24t national	100 km	0,01	0,02
C1-C4. End of life	Landfill cardboard: 80%	20%	0,20 x 1,38 = 0,276	0,276 x 1,18 = 0,325
	Landfill plastic: 15%	20%	0,20 x 0,072 = 0,01	0,01 x 0,22 = 0,002
	Landfill metals: 5%	20%	0,20 x 0,0145 = 0,0029	0,0029 x 0,07 0,0002
	Landfill totaal			0,327
Total				3,25