SUSTAINABLE AUTOMOTIVE DESIGN: A HOLISTIC STRATEGY FOR SUSTAINABLE PRODUCT AND MATERIALS DEVELOPMENT

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Summary

The manufacture of cars has a significant impact on the environment. Car manufacturing companies are focused on how to make cars more efficient, they are introducing composites into their manufacturing processes. This thesis discusses the literature surrounding sustainable design, sustainability in car design, the current state of car manufacture and the composite materials that could be used to create a sustainable vehicle.

This study uses a novel Materials/Design/Manufacture approach - using a holistic strategy to develop the material, design and manufacture of a sustainable product.

This project leads to the conclusion that natural fibre reinforced composites could be used to create a car which is fully sustainable. However, the material needs to be designed with the application in mind, will need to be applied in a new manner, and manufacturing processes need developing for this to become a viable prospect.

The programme of how this will be achieved is set out as series of experiments, prototypes and materials tests. Finally, a process has been developed resulting in a novel material and manufacturing process for a front wishbone component on a sustainably designed urban passenger car, this represents a step forward in the use of natural fibres in composites**.**

Key words: automotive, compression moulding, hot press, Cradle to Cradle, holistic design.

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Contents

Definitions and abbreviations

Sustainability - can be defined as "development which meets the needs of the present without compromising the ability of future generations to meet their own needs." (The World Commission on Environment and Development 1987) The United States Environmental Protection Agency suggests that "Everything that we need for our survival and well-being depends, either directly or indirectly, on our natural environment. Sustainability creates and maintains the conditions under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic and other requirements of present and future generations." (www.epa.gov) The meaning of sustainability has been discussed at length by Morelli (2011)

Cradle to cradle - design approach whereby products are designed to provide nourishment for something new at the end of their ‘useful lives’, as described by Braungart and McDonough (2009).

Biodegradable – where materials are broken down by biological action.

Natural fibres - fibres sourced from biological sources, fibres sourced from plant material can be described as lignocellulosic due to their structure - strands of cellulose crystals coated in lignen.

Bio-Composite - Also referred to as *Eco-composites* and *Sustainable Composites*. A composite material with an amount of natural material included, typically this will be a natural fibre reinforcement, but increasingly the resin matrix is sourced from plants.

Closed loop system - system mimicking natural processes whereby "waste is food", and all components can be used as "nutrients" for reuse. No resources are lost.

Greenwashing - practice whereby companies use marketing to imply that their practices are more environmentally friendly than they actually are.

VW - Volkswagen

EV - Electric Vehicle

NFRP - Natural Fibre Reinforced Plastic

FRP - Fibre Reinforced Plastic, usually referring to carbon fibre (*CFRP*), glass fibre (*GFRP*) or aramid

ISO - International Standards Organisation

LCA - Life Cycle Assessment

LCI – Life Cycle Inventory

CSR - Corporate Social Responsibility

RTM - Resin Transfer Moulding

SEM - Shell Ecomarathon, an international competition organised by Shell where teams of students build fuel efficient vehicles.

PP - Polypropalene.

PLA - In reference to Polylactic acid bioplastic.

TPS – Thermoplastic Starch

Aston EcoCar - between 2011 and 2013 Aston University ran a project for students to build a hydrogen powered wooden car to enter into the Shell Ecomarathon competition.

M/D/M - Materials/Design/Manufacture - A methodology developed during this project as a strategy to manufacture sustainable products using the Cradle to cradle approach to sustainability.

Veneer/Biome - Biocomposite formulated during this research. veneer refers to birch veneer natural fibres and Biome refers to Biome HT90 biodegradable plastic (for Biome data sheet see appendix A).

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Chapter 1 - Introduction

It is widely accepted that the actions of humans are changing the climate of the planet, resources are becoming increasingly expensive to extract, and consumption is predicted to increase. In 2011 a United Nations Environment Program (UNEP) report stated that "by 2050, humanity could consume an estimated 140 billion tons of minerals, ores, fossil fuels and biomass per year – three times its current appetite – unless the economic growth rate is "decoupled" from the rate of natural resource consumption" (Fischer-Kowalski et. al, 2011). Decoupling is one of the UNEP's key concepts of improving sustainability, this will be achieved by separating human well-being from consumption of resources.

Governments, researchers and industry have a role to play in reducing the impact people have on the planet by reducing the consumption of materials, reducing emissions and embracing a more sustainable model of development. The importance of developing sustainable technologies is paramount to safeguard our future.

The motor car plays a significant role in the consumption of minerals, ores and fossil fuels - 90 million cars were produced in 2015 (International Organization of Motor Vehicle Manufacturers, 2016). The emissions and waste created during manufacture are in addition to the emissions during use and waste during disposal. A study into designing green cars (Mildenberger & Khare 2000) suggests the materials and manufacture are an important environmental issue. Part of the solution to developing environmentally sustainable vehicles is to rethink the way cars are manufactured, used and disposed of.

This research is a design focused study, applying a holistic approach to the design, manufacture and materials of cars. A successful sustainable design strategy could then be used in other applications.

1.1 Research question

How can the motor car be developed to be more environmentally sustainable?

The question is considered by:

- Investigating how cars affect the environment.
- Exploring what needs to change to improve the sustainability of cars.

- Proposing a new philosophy for sustainably focused vehicle development.
- Applying design principles (such as prototyping, needs analysis and benchmarking) - considering the materials, design and manufacture - to a new sustainable car.

The design focused research is applied to automotive manufacturing, however, the process developed can be applied to other products.

1.2 Strategy

Figure 1.1 outlines the structure of the project.

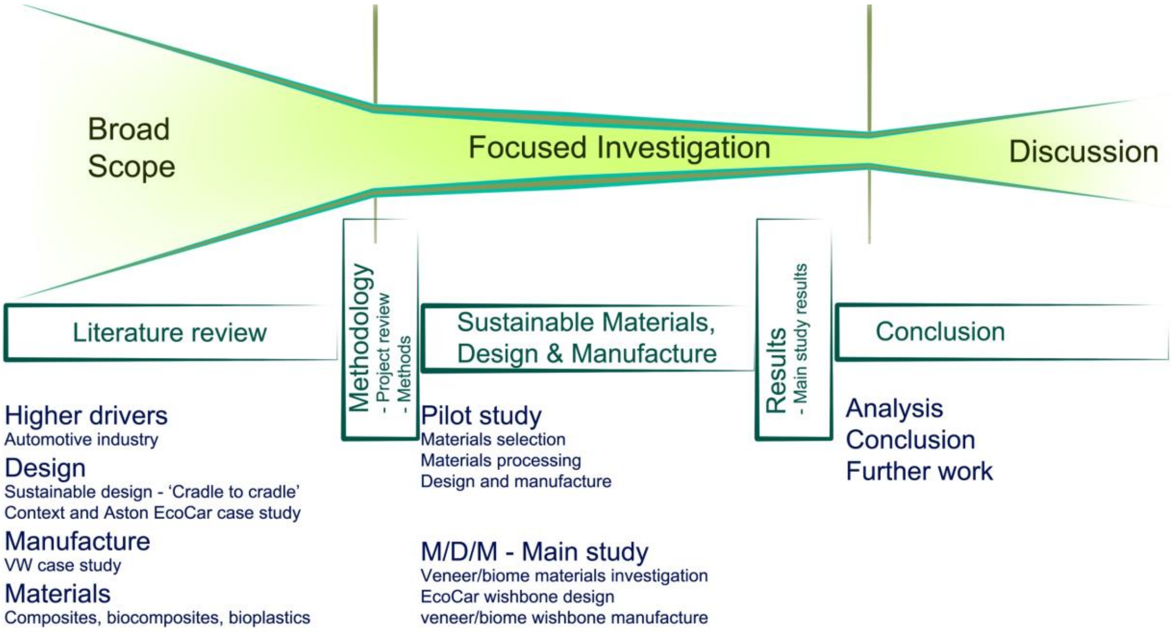

Figure 1.1, Research project structure.

A review of the literature provides a deeper understanding of the environmental issues surrounding the automotive industry. The design, materials and manufacturing factors are then analysed.

The literature review provides the background to the research topic. This is followed by a review to establish the aim and objectives of the proposed research program - to design a sustainable car. The methods to be used are set out before a focused practical investigation into the materials, design and manufacture of a sustainable product/component.

The results of this are then analysed and discussed before considering how the research can be taken further.

1.3 Philosophy

The lack of sustainability in car manufacture requires a fresh approach. This research uses product design methods to develop new environmentally focused approach to automotive materials, design and manufacture.

The research project is carried out from three distinct directions:

- Materials - developed to meet the sustainable and functional needs
- Design - Using the material properties to design a functional product
- Manufacture - allowing the design and materials to come to fruition

This Materials/Design/Manufacture approach to the project - displayed in figure 1.2 - provides an original result by considering the perspective of design when developing materials.

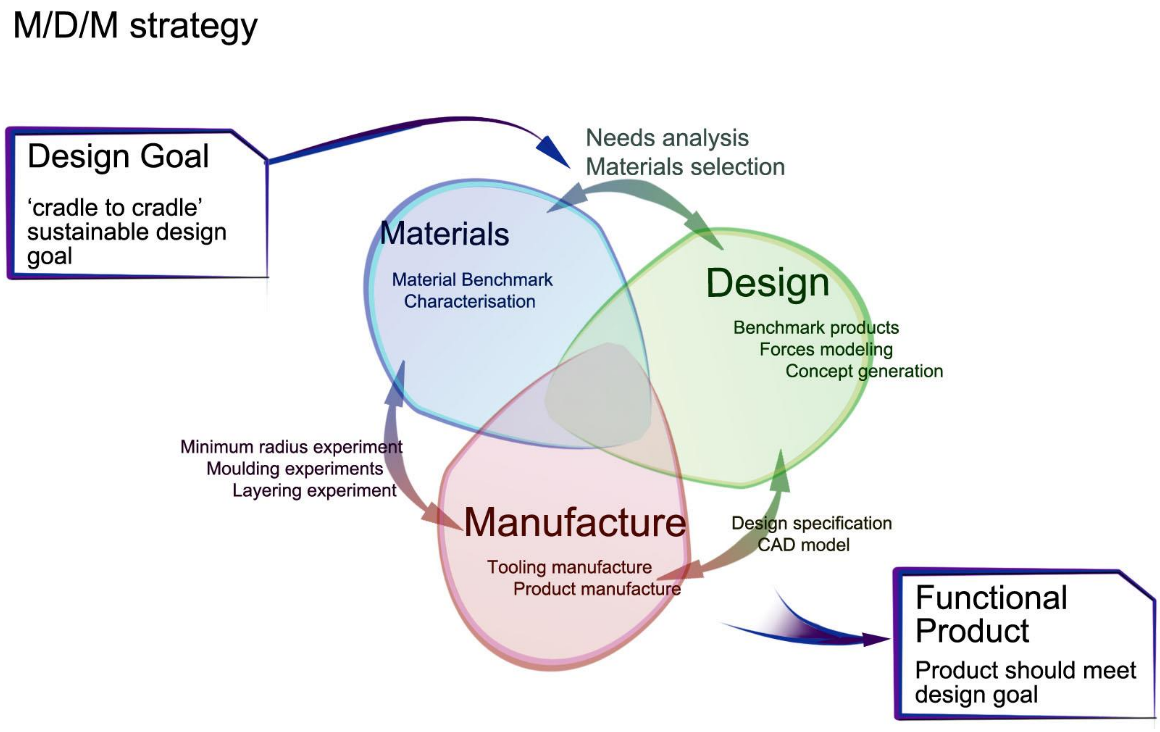

Figure 1.2, Holistic M/D/M design methodology as applied to the main research study.

1.4 Aim and objectives

Aim

Investigate the current manufacture of cars to suggest a new design approach to improve the 'sustainability' of the car. Test the new approach on a sustainable vehicle.

Objectives

1. Explore the manufacture of automobiles with regard to sustainability. Investigating the influence of various socioeconomic drivers.
2. Put the research question into a context – a case study of a typical production car (Volkswagen Golf).
3. Explore how materials, design and manufacture can solve car sustainability.
4. Develop a holistic methodology.
5. Test the feasibility of this methodology - Pilot study - tested at the Shell Ecomarathon (SEM) competition.
6. Develop a material to improve car sustainability.
7. Proof of principle - design a sustainable car component – tested at SEM competition.

Chapter 2: Literature review

2.1 Introduction

The aim of this literature review is to examine the sustainability of automotive production in the context of the issues concerning the automotive industry. The need and feasibility of developing sustainable materials for automotive applications will then be investigated.

This will be carried out by evaluating the current research in this field:

1. **Higher Drivers** - Examining the broader context of sustainability within the automotive industry and explore higher drivers affecting change within the sector. This will establish the context of the project.
2. **Design** - Explore the potential of sustainable design practises to resolve issues with current car manufacture.
3. **Manufacture** - Investigate the current production innovations used in automotive manufacture.
4. **Materials** - Discuss the advances being made in regard to sustainable materials.

Figure 2.1 displays the structure used to review the literature:

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Figure 2.1, Literature review map.

Presenting the problem in this context will provide a platform for developing an 'Environmental Car Design' philosophy.

2.2 Higher Drivers

For a broad perspective on car manufacture this section will look at the general factors driving the automotive industry. A detailed examination of these factors will be assessed in a case study. The case study will use the example of a typical car - the VW Golf, described as the “definitive family hatchback” (Calne, 2016) to explore trends in this industry with a focus on investigating environmental sustainability.

2.2.1 The automotive industry globally

Manufacturing cars remains a substantial and successful global industry. In Europe alone "the turnover generated by the automotive sector represents 6.5% of EU GDP" (European Automobile Manufacturers Association, n.d.a). The sector also employs "12.2 million people - or 5.6% of the EU workforce." Table 2.1 demonstrates the size of the industry.

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Table 2.1, Key industry figures (European Automobile manufacturers association, n.d.b)

The cars the industry manufactures are relied upon by people across the planet. The car industry is entrenched in employment, tax revenues, exports and investment of nations and as such, car manufacturers are important socially and economically. “The automotive industry is a key EU employer. Due to its strong economic links to many other industrial sectors, it has an important multiplier effect in the economy.” (European Commission, n. d. a). This position allows automotive manufacturers to influence public policy.

There are nine major companies in the sector globally, known as the '3 big 3': three companies in the American market - Ford, Chrysler and GM; three German -BMW, VW and Mercedes; and the main Japanese manufacturers - Nissan, Honda and Toyota. All nine employ thousands of people across the world. The automotive industry is important to economies locally and globally, and as such, in depth analysis of the motor car industry has been written about at length. Strategic management specialist Grant presents a case study on the position of the Ford motor company within the automotive industry (Grant, 2010: p.534-550). As a leading business within the global market, Ford is representative of the automotive industry generally, and Grant discusses the following key points:

- homogenised product.
- high cost and scale of manufacture.
- over supply of cars.
- 3 markets - Asia, Europe and America.
- environmental issues.
- regulation.

These factors can be put into macro-level models in order to identify and gauge the impact of higher drivers affecting the automotive industry. In a report analysing the BMW business Cun Hwee (2015) uses two standard models - a PESTEL analysis and a Porter's 5 forces model to provide an overall assessment of the BMW strategic position. Although the 5-forces model is short of detail it provides an overview of the drivers within the industry. A PESTEL analysis considers the Political, Economic, Social, Technical, Environmental and Legal business environment.

It is recognised that the forces at play in the automotive industry are complex, and sustainability is one of many pressures. However, BMW have to: make cars that meet the transport needs of consumers; maintain a technological advantage over competitors; increase market share and improve the BMW brand. These key factors are identified by Cun Hwee, and concludes "Educating consumers on the benefits of sustainable vehicles can help improve BMW’s brand value." (Cun Hwee, 2015: p.41).

Over the past century the global car market has stabilised. The products have converged to a point where the technologies are similar - front engine, steel monocoque, four wheeled vehicles. A recent KPMG industry forecast (KPMG, 2015) surveyed 200 senior figures from within the automotive industry globally. The report generally predicts no great change in the car industry. The product is largely homogenised and this limits the technological advantage. The car companies aim to increase their market share largely through branding. Customers ranked environmental friendliness in the top 5 considerations when purchasing a car (KPMG, 2015: p.11).

A survey measuring the effectiveness of green marketing concluded “consumers perceive green marketing application favourably, and are capable of perceiving it as one of the primary factors influencing their purchase decision. This trend is particularly evident for the automotive industry, which is characterised precisely by its significant impact on the environment.” (Krizanova. A, et. al, 2013).

2.2.2 Environmental marketing

Greenwashing is a term defined by Delmas & Burbano (2011) as companies “misleading consumers about their environmental performance or the environmental benefits of a product or service.” BP are one of the largest producers of fossil fuels - an industry that is instrumental in global warming - but if through 'greenwashing' they are perceived as being the most environmentally sound big oil company it will increase their brands eco-credentials in an industry responsible for a number of environmental disasters. This contradiction was heavily criticised following the Deep Water Horizon disaster (Cherry & Sneirson, 2011).

As well as being a leading automotive manufacturer, Toyota are also “the most sustainable company in the world” (Stoker, 2016). In figure 2.2 Toyota advertise that their cars are eco-friendly and that the company are “developing eco-technology for the world.” (Toyota, n.d., a)

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Figure 2.2, Toyota advert in Singapore (Source: Toyota).

The environment plays a clear role in the company’s marketing strategy, however Toyota have previously overstated their green credentials. In a 2007 advertising campaign for the Prius, Toyota “made the claim that the hybrid car ‘emits up to one tonne less CO_2 per year than an equivalent family vehicle with a diesel engine’” (Sweney, 2007). The advert was banned by the Advertising Standards Authority for being inaccurate. Pearce (2008) describes Toyota’s claims of being ‘good for the planet’ as being ‘greenwash’.

Environmental marketing is an issue that concerns the automotive industry generally. Pearce (2008) describes Land Rover’s "fragile Earth commitment" to reduce their impact on the environment as failing to address the problem of “what comes out of the exhaust pipe.” (Pearce, 2008)

Car manufacturers are interested in making cars, selling cars, building brands and increasing profits. The importance of environmental sustainability is positioned in the branding, corporate ethics and industry governance. Legislation is needed “to reinforce the industry’s competitiveness and address climate, environmental, and societal challenges” (European Commission, n. d., a) which is why “the European Commission adopted the CARS 2020 Action Plan in 2012” (European Commission, n. d., a) as current policy.

2.2.3 Cars and the Environment

Globally the motorcar is very useful for the personal transport both within and between cities. The proliferation of cars generally is the cause of numerous issues:

1. Industry - manufacturing cars accounts for a significant amount of emissions and raw materials.
2. Climate change - cars generate large quantities of greenhouse gas emissions.
3. Congestion - There are too many cars and they are too large.
4. Pollution - fumes from vehicles affect the health of residents especially NO_x fumes.
5. Safety - fatal road accidents in urban centres are likely to involve car collisions with pedestrians and cyclists.
6. Parking - inner city space is at a premium.
7. Linked factors – such as increases in road building and light pollution from street lighting.

Over the years, governments have developed a number of strategies to combat the environmental issues cars cause. A global effort to reduce CO_2 emissions to below 1990 levels was agreed by most nations at the 1992 UN 'Earth summit' in Rio. In Europe, a series of increasingly strict emissions standards have been introduced. At a national level, government initiatives include: scrappage schemes to remove older, more polluting vehicles from the road; subsidies for vehicles free of exhaust emissions (EVs for example) and limiting the number of cars entering large cities.

These initiatives generally focus on the emissions cars produce rather than taking a broader 'lifecycle' view to include the resources, manufacturing and end of life scenario of cars.

2.2.4 The Volkswagen Golf case study

2.2.4.1 Introduction

The manufacture, use and disposal of motorcars has an abject impact on the environment. This case study reviews the environmental impact of the automotive industry by examining the development of a vehicle manufactured by one of the largest makers of cars - the Volkswagen (VW) Golf. The longevity of the VW Golf allows trends to be identified. Conducting this study will improve understanding of the effect cars in general have on the environment and how these factors influence automotive manufacture.

To conduct this study, the VW Golf has been selected as the model that epitomises current car manufacture. This model of "typical family car"(Robbins 2004) provides a picture of how the car industry has developed their commercial, mass market product over the past 40 years. The Golf has been one of the best ever selling models of car since it was first put into production in 1974, with VW having sold over 29 million units (Autocar, n.d.). This case study will be presented in a number of studies in the review of the literature (in sections 2.2.4 and 2.5.2).

By investigating trends in the VW Golf as a benchmark product, the extent to which mass manufacture of cars has progressed over the past few decades can be mapped out.

2.2.4.2 Case study aim and objectives.

<u>Aim</u>

Examine how car manufacturers are developing their products to meet the current environmental challenges - using the VW Golf as an example.

<u>Objectives</u>

1. Investigate how the VW golf has changed over time.
2. Study how industry pressures have affected the golf.
3. Review VW environmental policy and how the Golf has changed as a result.
4. Relate the Golf to the wider automotive industry.
5. Compare the Golf to a sustainable car design.

<u>Method - Case study</u>

There are five components to case studies - A study's questions, propositions, how it is measured (unit), logic linking data to the proposition and interpretation of the findings (Yin, 1994: p.20)

The Case study is split into two sections:

1. Golf chronology - Investigate how the Golf has changed over time with regard to the wider pressures the industry faces.
2. Environmental performance - explore how VW environmental policy has progressed. The Golf is then studied for evidence of sustainable manufacturing practices.

This will expose trends in car manufacture, revealing how committed car makers are with regards to environmental issues. The Golf investigation will be used to assess whether current car manufacture is fit-for-purpose and will be used to inform further study.

2.2.4.3 Limitations of the study

<u>Narrow view</u> This study can only provide a representation of a single model of car, however the Volkswagen Golf is an enduring and successful design. An advantage of studying a specific model is the added depth to the investigation, allowing more detailed comparisons to be drawn.

The factors effecting how the Golf has developed are complex and numerous. This case study will discuss major drivers, however, not all factors can be discussed.

Bias The investigation is heavily reliant on information from VW. It is recognised that VW will not provide the most objective view of their own practices and products - in 2015 VW were exposed in an emissions scandal (chu, 2016). “Volkswagen has suffered a shocking loss of credibility after conspiring to violate US pollution laws and dupe customers on a systemic scale.” (Evans-Prichard, 2015). Objective sources have been sought where possible, however many published articles will source their information from VW.

2.2.4.4 The Volkswagen Golf

The current VW range in the UK consists of 21 cars (Volkswagen AG, n.d.). These vary from the Up and the Polo - the smallest cars in the range, to the Sharan and Taureg – the largest cars in the range. A third of the cars in the VW range fall under the Golf brand. The standard Golf being one of the smaller 'family cars' in the range – through to the larger Golf Estate.

The VW Golf is an iconic product of the last 40 years (Roberts, 2014). It is the ideal choice for a case study on the influences on design and manufacture of automobiles. Examining the VW Golf in this study will aid towards picturing current practices and projecting future trends in the car industry.

Over 40 years seven different iterations of the Golf have been in production as shown in figure 2.3.

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Figure 2.3, The seven iterations of the VW Golf (source: magazine.volkswagen.com.au).

The first 1974 model is referred to as the ‘Mk.1’ with the launch of subsequent replacements referred to as Mk.2, Mk.3, Mk.4, Mk.5, Mk.6 and Mk.7. The changes to the vehicle between each generation can indicate:

- The effect of legislation.
- Adoption of new technology.
- Trends in consumer expectations.

The Golf was designed in the early seventies by Giorgetto Giugiaro as a replacement for the VW Beetle. “One of the keys to the Golf’s success lies in its continuity", says Walter de Silva, VW’s Head of Design. Taylor (2012) agrees: “There are a handful of cars with a design that, like the Golf’s, has been refined, tweaked and enhanced down the decades and thus become timeless.”

Over time there have been many different variants of the Golf, from soft-top convertibles to an 'estate' version. Because this case study is concerned with ‘small family cars’, there will be a focus on the 3-door hatchback with the smallest engine available.

2.2.5 Case study 1 - Golf chronology

To understand how the automotive industry has changed over this time, this case study will investigate the chronology of the Golf. Figure 2.4 displays the weight, size and time gap between the launch of each model of the VW Golf as it has changed over the years.

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Figure 2.4, Golf chronology. Data source: Model release dates (Taylor, 2014), Weight of Golf Mk.1 and Mk.2 (Enright, 2005), further Golf size and weight statistics from Parkers (n.d.)

Figure 2.4 clearly shows several trends. The Golf has increased in both size and weight. “A spokesman for the Society of Motor Manufacturers and Traders (SMMT) said: ‘Cars are getting bigger. In line with customer demand, vehicle manufacturers have dramatically enhanced the safety, comfort and convenience features of modern cars – often adding extra width and weight” (Massey, 2014). In the last decade the weight has decreased marginally “to improve fuel economy” (Tuttle, 2012). The rate of releasing new models also increases.

Since 1970 people's expectations of comfort, and driver experience have changed - for example, immobilisers have improved security and satellite navigation systems are now integrated into the vehicle dash. In 1974 safety standards were such that seatbelts were not required in the UK. Improvements such as air bags and the anti-lock braking systems have reduced fatalities on the road.

2.2.5.1 Industry pressures

This study will explore how industry pressures affect the end product, in this case the car. This will provide a broad perspective on what wider factors influencing car manufacture are and how this affects sustainability.

The VW Golf will be compared with the higher forces driving the automotive industry. This will be achieved by considering the macro factors affecting the car industry (as identified in section 2.2.1) The following trends affecting the car industry have been compiled within the same time period as the Golf chronology in figure 2.4. These trends can then be analysed to determine the importance of outside influences and the effect they have on the cars produced.

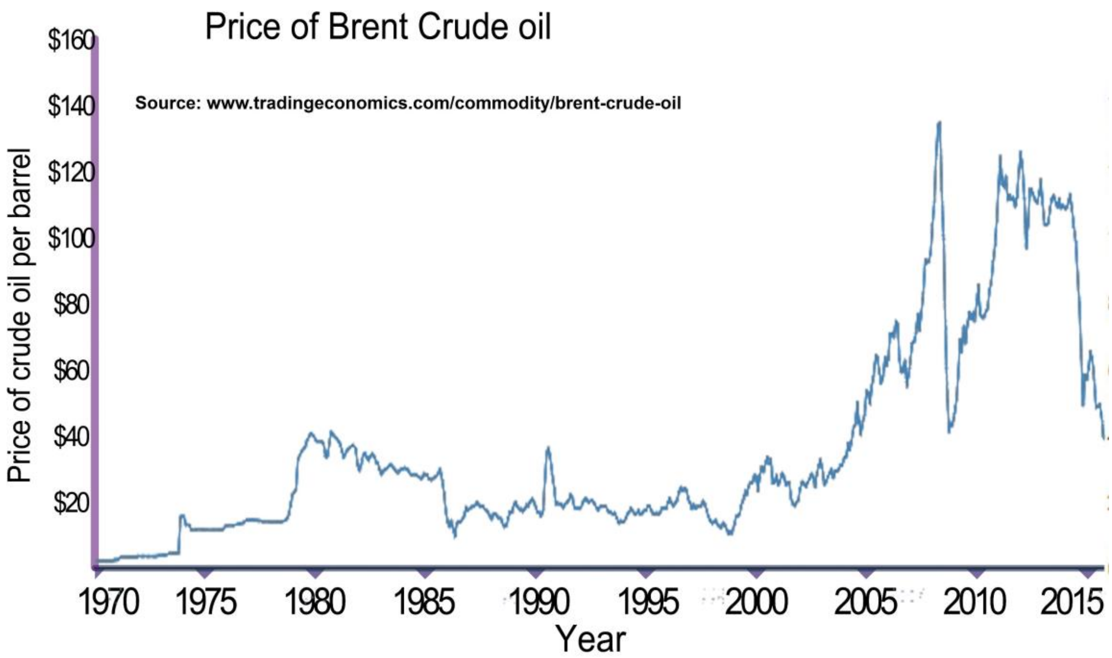

Figure 2.5, Crude oil price. Graph sourced from: Trading Economics (2017)

Commodity prices - such as the price of crude oil shown in figure 2.5 - are an important macro-economic factor for auto manufacturers. Crude oil is not only important for the Golf as a source of fuel, but is also the material to make plastics and energy to run factories. Recently the price has dropped due to the availability of shale gas, factors that affect the price include war - such as the1991 spike in price and other politically driven motives.

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Figure 2.6, Change in UK fuel prices from 1978. Data sourced from: Department for business, energy and industrial strategy (2016).

Figure 2.6 shows a general trend in the increasing consumer cost of fuel. As fuel (generally) becomes increasingly unaffordable it has an increased impact on consumers choice of car. Increases in efficiency of diesel engines have resulted in diesel cars being cheaper to run than petrol equivalents.

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Figure 2.7, Increase in global temperature. Graph sourced from: Met office (2017).

Figure 2.7 shows the increase in the global temperature, this and other factors including decrease in sea ice, increase in atmospheric CO_2 and rising sea levels have led to fears of 'climate change'. Governments have therefore tried to limit the amount of CO_2 emissions produced globally. In 1992 the European Union introduced emissions standards ‘Euro 1’, these standards have become increasingly stringent leading to the current Euro 6 (Regulation (EC) No 715/2007). The SMMT claim due to industry investment in technology “it would take 50 new cars today to produce the same amount of pollutant emissions as one vehicle built in 1970” and “over the same time, average new car CO_2 emissions have more than halved.” (SMMT, n.d.).

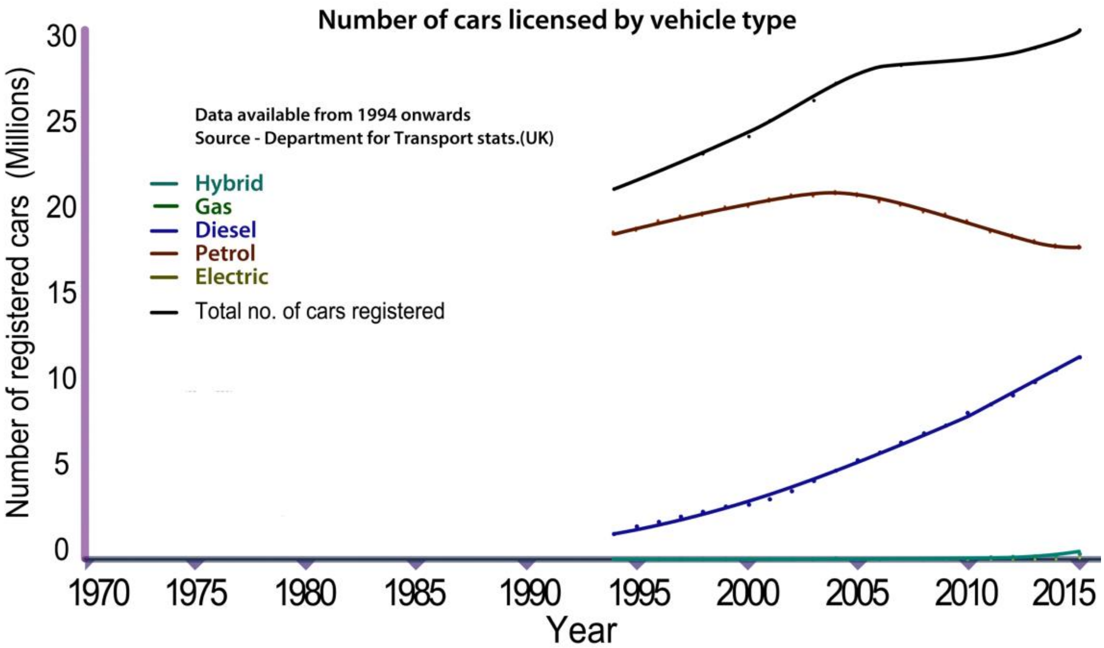

Figure 2.8, UK vehicle registrations. Data sourced from: Department for Transport (2016).

Figure 2.8 shows a trend of increasing numbers of diesel cars being registered in the UK. While the overall number of cars has increased, the number of petrol cars has decreased. Cars free of exhaust emissions represent only a small proportion of new registered vehicles on the road.

2.2.5.2 Discussion of trends

Evidence of climate change such as the global average temperature anomaly (figure 2.7) has resulted in governments agreeing to curb greenhouse gas emissions. To achieve emissions targets, car manufacturers have been encouraged - through the vehicle tax structure based on CO_2 emissions (among other factors) - to sell more diesel cars (Owen & Merrill, 2015). As diesel cars can achieve more km per litre they are less expensive to run. These 'better' more fuel-efficient diesel vehicles have led to an increase in NO_x emissions (Vidal, 2015). The consequence of the increase in diesel cars seen in figure 2.8 is directly harmful to public health. (Owen & Merrill, 2015), (Swanton et al, 2016). This demonstrates one of the difficulties in implementing an environmental agenda.

The weight of vehicles has increased dramatically from the 1970s; "When cars are made safer and more comfortable in response to customer wishes, they inevitably become heavier, leading to a rise in fuel consumption. In the case of the Golf it took a wealth of individual design measures to balance out the increases in weight and consumption." (Volkswagen AG, 1999: p.30). VW are now attempting to reduce the weight of their vehicles as lighter vehicles are more fuel efficient (less expensive to run) and also use fewer materials to construct. As petrol prices have risen, fuel efficiency is at the forefront of consumer choice. The importance of fuel efficiency is reinforced by the environmental argument that cars with lower emissions pollute less. In this way lighter, more fuel efficient Golfs can be sold as more environmentally sound (Volkswagen AG, 2010).

The above series of graphs demonstrate how the political, social and environmental impact of oil and climate policy has created pressure on Golf production. This is one facet of the wider changes that have occurred. Further trends to consider include the global steel market, safety legislation and an increase in car ownership. The changing factors affecting the Golf are numerous and complex. Generally it can be said that:

- A range of external factors have affected the automotive industry.
- The environmental impact is an increasingly important factor.

2.2.5.3 Conclusion

Assessing the macro-environment of the car industry and the impact this has on the VW Golf, it has been shown that environmental concerns about the motor car are increasingly important. Manufacturers invest billions of pounds in production plants. Communities and economies globally rely on the industry for both transport and employment. Fundamentally, the manufacture of motorcars has not changed for decades albeit with more sophisticated equipment now available.

This discussion of the higher drivers within the automotive industry has focused primarily on the use phase of the car lifecycle, the total environmental impact of the car (including Life cycle analysis) is discussed in chapter 2.5.

To improve efficiency VW have switched to diesel production and reduced the weight of their vehicles. Producing fewer, different emissions does not solve the problem of the environmental harm cars cause. With the VW emissions scandal VW may have been concerned with the perception of the cars rather than being environmentally sound (Hotten, 2015). VW have been accused by environmental group Greenpeace of "actively seeking to thwart EU plans to reduce climate-change emissions by 2020" (Hickman, 2011). Considering the prevalence of petrol and diesel cars (displayed in figure 2.8), it is not convincing that the automotive industry as a whole is committed to environmental sustainability. In a study into the reorientation of the US car manufacturers, Penna and Geels "do not expect full industry reorientation towards radical green options in the next few years, because of high risks and costs, low market demand, and because of limited policy pressure. Instead, we expect automakers to continue to hedge and develop capabilities in multiple low-carbon technologies." (Penna & Geels, 2015)

These 'low-carbon technologies' in the VW Golf product range are the electric and hybrid models. This can be seen as evidence that government incentives such as various EV grants and free charging points as well as consumer pressures can affect car makers in a positive way to develop sustainable technologies - the first Electric Golf was launched in 2014.

2.3 Design

2.3.1 Introduction

Human activity is adversely affecting the natural world. Rising sea levels, increased levels of greenhouse gases, decreased bio-diversity, drought and many other man-made phenomenon need to be curtailed if future generations are to thrive. One solution to this problem may be to use technology to develop in a sustainable manner: "Technological innovation is essential for achieving sustainable development" (Ashford & Hall, 2011: p271). This should be done strategically in the short, medium and long term for maximum effect (Weaver et al, 2000: p.66). This section will review the issues facing designers of sustainable products, the design tools used to examine and improve sustainability, and include a critical discussion of sustainability - specifically concerning the design of cars. The holistic approach used in the sustainable design of relatively simple products can also be applicable to the design and manufacture of a sustainable car.

2.3.2 Design issues

Sustainability can be used as a marketing tool in order to project an image of corporate social responsibility (CSR) - 'greenwashing'. These branding exercises create a problem with consumer perception of sustainable products as 'sustainability' has become something of an ambiguous catch-all term. Sustainable (where ‘sustainable’ is used to mean environmentally sustainable) has a variety of meanings, this and other 'eco-phrases' need to be treated with caution. Morelli (2011) explored the use of the term ‘sustainable’ and defined the concept as “meeting the resource and services needs of current and future generations without compromising the health of the ecosystems that provide them” (p.6).

A product presented as being manufactured from environmentally friendly materials is likely to have some impact on the environment. This poses the problem that as all human activity has some impact on the environment then to achieve full sustainability is unlikely. However, the current rate of global industry is unlikely to continue indefinitely and practices need to be improved.

Uptake of sustainable products can face several barriers:
<u>Price</u> - Watson (2014) suggests that sustainable materials tend to command a higher price and low volume manufacture increases the cost of products.
<u>Convention</u> – Murillo-Luna et. al. (2011) identified several factors affecting the reluctance of manufacturers in adopting environmental strategies: “difficulties that can actually prevent firms from progressing in their environmental strategy are within the firm… such as 1) limited financial capabilities for environmental investment, 2) low employee involvement in decision-making, 3) lack of technological information and communication capabilities, 4) aversion to innovation, and 5) deficient investment of resources in R&D.”
<u>Trade-offs</u> – Olsen (2013) found that consumers ‘financially value’ sustainable products, however, limited choice and reduced performance can compromise the uptake of green options.

For sustainability to affect consumer product choices, environmental issues need to factor into their decision. Governments can introduce legislation and levy 'green taxes' against products that are harmful to the environment - such as petrol. These are societal issues and it is recognised that lifestyle changes may be problematic to implement.

It is difficult to create a product which has no net impact on the environment, especially a product that requires a large amount of energy, such as a car. A car also requires the investment of a large and expensive infrastructure of factories, roads, petrol stations, car parks, traffic management and scrap yards. Added to this is a global economy based partly on crude oil, with a significant quantity of this oil fuelling motor cars. Having invested in this network, society may now have to confront the consequences of becoming accustomed to cheap personal transport. Rising fuel costs, congested roads and increased pollution are enduring issues. These challenges could be met by designing a more sustainable model (Mildenberger & Khare, 2000).

Iterative improvements can be made towards an overall goal of a sustainable transport system: there are alternative modes of transport to the car - bicycles and public transport; alternative modes of car use – car shares and car clubs; reducing commutes to work (working at home); and alternatively, less environmentally damaging modes of transport can be developed.

Electric Vehicles (EV's) are a response by automotive companies to regulation and consumer pressure to produce more sustainable cars. The EV network is growing, bringing a lifestyle change for owners of electric cars needing to plan their time and journeys around charging batteries (Richards, 2011). The petrol car has become a homogenised design of front engine, long range vehicle. The EV has brought with it a change to the range, energy usage and drive train of personal transport. These changes have effected a change in the design of road going vehicles, the short range has led to small city car designs with less constraints - designs without the consumers preconceived demands such as 4 seats, engine performance and aesthetics. New breeds of urban vehicles such as the Toyota i-Road concept displayed in figure 2.9 can be short and narrow, providing “positive solutions to future congestion and environmental pressures” (Toyota, n.d., b).

Figure 2.9: Toyota i-Road electric city vehicle concept launched in 2013 (Source: Toyota-europe.com)

The build method can be changed as an internal combustion engine no longer needs to be accommodated. These developments may fundamentally change the design and manufacture of road cars.

These changes to the design of cars are aimed at addressing the exhaust emissions of petrol cars, however - even with all the innovation surrounding car design - vast quantities of non-renewable resources are used during manufacture. Even if it is subsequently recycled, this material can not be used for the same high grade components as before (Braungart & McDonough, 2009: p.56). A different approach to the design of cars could be used to develop a sustainable transport network.

2.3.3 Design approach

<u>Cradle to Cradle (Braungart & McDonough, 2009)</u>

'Cradle to Cradle' is a design philosophy where by a 'closed loop' system is devised when sourcing materials, manufacturing, using and disposing of products. This approach is in response to the standard 'cradle to grave' life cycle of many products where by products are manufactured using finite resources, the products are used before being disposed of in landfill. The book describes two key methods of achieving closed loop systems: the first is a cycle of technical nutrients - where materials can be re-used without losing performance; the second is to use the biological cycle to effectively break down and re-grow the materials needed for manufacture. This holistic approach to sustainable design is an effort to mimic natural cycles, the book uses the analogy of the cherry tree where there is a complex eco-system that is not only self-sustaining but through cleaning the air also enhances and improves the surrounding environment. This approach however does not fully take into consideration the wants of the consumer using the product, or the complex systems involved. Cradle to Cradle can be seen as a vision of the future to be aimed for.

A different approach to sustainable design, is to replace environmentally harmful materials, with ones that are less so. As long as the cost of production remains competitive, then take up of 'greener' products becomes a selling point, and consumers are content with using the products, however this may not 'close the loop', Braungart and McDonough (2009) describe this as being 'less bad'. In effect, lessening the environmental problem is not solving the problem. By taking a long-term view to developing replacement technologies enough progress will be made where by a Cradle to Cradle product is achievable.

There appears to be three distinct futures for environmental car design:

1. A future where current trends continue without change - commuters still travel to work in petrol powered cars indefinitely (an unlikelihood).
2. A future where producing and using petrol cars requires so much energy and resources they are uneconomical, leading to a decline in car use.
3. Developments in technology enable society to keep the current conveniences of car travel, but having to make allowances for lifestyle change.

Life Cycle Assessments (LCA)

LCA is a method used for categorising how materials, processes and products impact on the environment throughout the entire life of a product – from raw materials, production, transport and use through to end of life (EoL). These assessments have been standardised - ISO 14040:2006 provides guidance on LCA and inventory analysis. Many LCAs have been conducted on cars (Hawkins, 2012; Messagie et. al., 2010; European Commission, 2008 and Volkswagen AG, 2008) including bio-composites for cars (Zah et.al., 2007). The most detailed of these concern current materials and uses, solutions are offered in the form of replacement materials and processes.

This has led to incremental improvements in the 'greening' of cars, however no holistic vision of a closed loop system has been proposed by the automotive industry. A major reason for the lack of a closed loop system is the breadth of the scope required. Small areas are targeted for analysis such as improving the material used for a dashboard (Sapuan et al. 2011). Conducting targeted studies is more accurate, uses resources efficiently and allows for deeper analysis of the area marked for development. A modern production car is a complex machine, in order to rationalise an LCA study pre-LCA's have been developed to consider the broader picture, then narrow the scope of the investigation, this is achieved through setting boundary conditions. This is a logical approach, however the car as a single entity is problematic, and these methods avoid addressing this issue.

A more holistic approach could be adopted. Using the Cradle to Cradle methodology, a more sustainable, closed loop system could be decveloped - incorporating biological nutrients for both interior and exterior structures. In areas – such as the drivetrain - consideration can be given to materials which can be recycled without degradation – technical nutrients. An LCA would then be useful for giving direction to a project such as this, as a review of current practices and as a benchmark.

Creating products manufactured using 'biological nutrients' throws up challenges. Using materials from biological sources can have a detrimental impact on the natural environment because of sourcing and processing (Corbière-Nicollier, et al., 2001). This needs to be taken into consideration when selecting materials. The performance of the materials can be determined through testing samples and applying them to prototype products.

Embodied Energy

In addition to the biological and technical cycles, the energy used over a products lifecycle is a concern (Rahimifard, Seow, & Childs, 2010). The energy required to refine and process materials, manufacture products and for transport is ‘embodied’ in the product. “A product’s embodied energy can be improved by carefully selecting local suppliers and more-efficient transport methods to move raw materials.” (Kara, Manmek & Herrmann, 2010: p.32). This energy usage adds to the environmental impact of the product.

End of Life scenarios

A number of disposal options are available at the end of a products useful life:

- Extended life – extending the useful life of products reduces the demand for new products, decreasing the impact of a product on the environment. Reduced consumption rates reduce the amount of waste (Bakker et.al., 2014).

- Remanufacture – the remanufacture of products allows functions to be added and performance to be recovered (Du, 2013).
- Recycle – recovery of raw materials in products is important for the preservation of technical nutrients (Binnemans, et. al. 2013).
- Biodegradation – biodegradable products are decomposed by biological means – such as bacteria. Biodegradable products are a way of returning nutrients to the biosphere, “waste equals food” (Braungart & McDonough 2009).
- Energy recovery - energy may be reclaimed from the product through controlled combustion.
- Landfill – indiscriminate burial of unwanted material.

All materials 'bio-degrade', it is a matter of how long this takes, and whether concentrations of harmful substances are released into fragile ecosystems. Products decomposing before the end of their useful life is not desirable - especially where the product provides structural strength, outside, and in an environment where failure could be hazardous to the user. For industrial composting - European standard EN13432 describes under what conditions a material can be said to be biodegradable.

2.3.4 Design innovation

Designers are developing products to tackle the issue of sustainable vehicles. EV car manufacturer Tesla makes cars such as the Model S, which contains the latest in battery technology – improving the cost, range and charge times of EVs, Tesla has released patents on this technology to encourage a shift towards electric cars free of exhaust emission (Vance, 2014). More renewable energy and improved sustainable manufacturing methods are required before sustainability claims can be fulfilled (Winton, 2016 and Hawkins, 2012).

Riversimple have developed the Rasa, a hydrogen powered 2 seater vehicle, displayed in figure 2.10.

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Figure 2.10, Rasa hydrogen powered car developed by Riversimple (source: Riversimple.com)

"Every aspect of the Rasa has been created and interrogated for simplicity, efficiency, lightness, strength, affordability, safety and sustainability" (Riversimple, n.d.). In a case study on Riversimple, Wells (2016) states that the design of the Rasa follows "a 'mass de-compounding' approach… It has the following features:

- A lightweight carbon-fibre reinforced plastic structure that is stiff, safe and reduces energy demand during use;
- A hub motor in each wheel able to supply regenerative breaking; eliminating the need for a gearbox or driveshaft;
- A hybrid ultra-capacitor battery to store and deliver energy;
- A small fuel cell supplied with hydrogen." (p.4).

Building a vehicle that weighs 560Kg has several benefits compared to a typical road car. "Mass reduction in turn means power-assisted brakes and steering are not required, resulting in further mass and cost reductions. Pervasive minimalism is thus key to reducing material demands" (Wells, 2016). It is planned that the lifespan of the Rasa will be 15 years and that at end of life the car can be "recycled or remanufactured" (Fryer, 2016) as a technical nutrient. A focus on weight reduction may have led to a compromise in sustainability. "Material and energy flows are still present of course. Composite materials as used in the vehicle body are energy-intensive" (Wells, 2016).

Development of materials may improve sustainability. An example where biodegradable plastics (such as PLA and Starch based plastics) are replacing crude oil derived plastics (such as PP and polyethylene) is in the food packaging industry (Kumar, 2014). The use of bio-plastics in packaging applications improves the life cycle of the product being packaged. In this way, technology can drive improvements on a wider scale. Advances in materials could provide improvements to a variety of other applications – such as automotive. Using a new material with a focus on environmental sustainability can influence the design of a product, fundamentally changing how the product is manufactured, used and disposed of.

Figure 2.11: Renault Twizy EV, with central driving position. (source: Renault.co.uk)

The Renault Twizy, shown in figure 2.11, is manufactured using recycled plastic, as a small EV it is only suitable for short journeys in urban centres and recharging the battery forces consumers to adapt their lifestyle. These changes to cars have only come about recently, and so designs may not be fully developed. This situation offers an opportunity to improve the sustainability of urban vehicles in a way that further benefits to the user.

2.3.5 Further research

Investigation is needed regarding the sustainable design of cars. Current activity in the automotive industry centres around reducing CO_2 emissions and improving fuel efficiency. Further research should focus on more holistic approaches to car design – such as Riversimple, with consideration given to the wider transport network.

A case study and a forecast for the future of 'the motor car' would improve the foundation for suggesting materials in the design of a new breed of car.

2.3.6 Conclusion

Sustainability is a complex issue, and designing a sustainable product requires an in depth look into the impacts of a products lifecycle. More can be done in the design of cars to find solutions to environmental problems. The complexity of the industry and how reliant society is on the current technology may be holding back sustainable development. A holistic redesign may be required to produce a sustainable car. The 'Cradle to Cradle' approach needs to be carefully considered in order to achieve the most closed loop system.

2.4 Manufacture

2.4.1 Introduction

To achieve environmental targets governments have introduced legislation targeted at the automotive industry. Environmental commitments are such that to meet 2025 targets “the U.S., European Union, China and Japan are scheduled to require fuel economy of 45.9 mpg or more and CO_2 emissions of 122 grams per kilometer or less. Hitting the CO_2 target in the U.S. means a 53 percent reduction since 2000” (Lippert, 2016). These government pressures encourage manufacturers to increase the fuel efficiency of vehicles. Car manufacturers face other regulatory pressures - the EU regulates vehicle waste. (European commission, 2000) “Every year, end-of-life vehicles (ELV) generate between 7 and 8 million tonnes of waste in the European Union which should be managed correctly… Directive 2000/53/EC - the "ELV Directive"… aims at making dismantling and recycling of ELVs more environmentally friendly.” (European commission, n.d., b). The ELV Directive states that since 2015, 95% of materials should be recoverable.

Fuel efficient cars are desirable for UK consumers due to the price of petrol and the vehicle excise duty (VED) based on CO_2 emissions. Figure 2.12 shows that more polluting cars result in a higher rate of tax for motorists.

Figure 2.12, Vehicle excise duty tax bands based on CO_2 exhaust emissions. Chart reproduced from BBC (2015). Original data from HM Treasury (2015).

Pressures from both consumers and governments are driving development in car manufacture, as a result manufacturers are increasing the fuel efficiency of cars by improving drivetrains and reducing weight. The materials used to manufacture cars is changing, the car industry is moving away from steel bodied cars (Nikkei Asian Review, 2016)

Research into light-weighting vehicles focuses on replacing materials for mass production cars and reducing the costs of energy, materials processing and manufacture (Raugei et. al., 2015). The energy used to produce and process these materials adds to the embodied energy of the vehicles. Energy needs and materials flows are considered during LCA studies to assess the environmental impact of car manufacture (Kim & Wallington, 2013). Factors altering the way cars are built include vehicle architecture, EV's, components built for disassembly, consumer trends and further government legislation. These, and other pressures mean the effects of the motor car on the environment is becoming an increasingly significant factor for the automotive industry.

This manufacturing section aims to establish the need for further research into composite materials for use in cars. This will be achieved by studying the current thinking on the materials used for production cars, investigating what advances are being developed for future composite technology, exploring the future direction of the car industry and questioning how environmentally sustainable the new technologies coming through are. Recommendations for further research will then be made.

2.4.2 Current materials used to lightweight production cars

To increase fuel efficiency, car manufacturers have developed a number of strategies. These include developing engines that use less fuel, manufacturing cars that weigh less, and developing technologies that produce no exhaust emissions - for example EVs.

Selecting optimal materials for future vehicles is a challenge. To reduce vehicle weights, the automotive industry is using a variety of new materials and processes.

Aluminium and high strength steel

Automotive manufacture is moving away from mild steel to high-strength steels and aluminium (Wright, 2014). In 2015 Ford invested over $1 billion US dollars on developing aluminium processing capability for the manufacture of their best-selling US product - the F 150. The new F 150 has an “aluminum body, smaller turbocharged engines and a lighter and stronger steel frame.” (Lippert, 2016). Refitting the Ford production plant was needed because “unlike steel, aluminum bodies can’t be easily welded. They must be riveted and bonded with adhesives, requiring new equipment, processes and suppliers.” (Muller, 2014). The move to aluminium has drawbacks - it “is more expensive than steel, more complicated to assemble, and more difficult to repair” (Taylor III, 2014). By substituting steel for aluminium Ford have improved fuel efficiency, but are struggling to keep pace with the increasingly strict fuel efficiency regulations (Lippert, 2016).

Magnesium alloys

Magnesium alloys show better performance for the weight of the material than aluminium and have been used in the engine, chassis, interior and body of cars. (Hussein & Northwood, 2014). The use of magnesium in automotive manufacture is set to increase (Pollock, 2010). The barriers to adopting magnesium alloys include high costs and poor resistance to corrosion, while the high embodied energy of magnesium alloys is an environmental concern (Easton et. al., 2012).

Carbon fibre reinforced plastic (CFRP)

The use of CRFP in car production is predicted to double from 2015 to 2020 as manufacturers reduce the weight of vehicles (Milberg, 2016). CFRP has been developed to be more cost efficient to produce and process – this development is being led by BMW (Jacob, 2014) (discussed further in section 2.4.3). Cost is a barrier, CFRP is labour and energy intensive and therefore expensive to process (Bubna & Wiseman, 2016). Researchers are trying to bring down the cost of materials processing and manufacture (Turner, et. al., 2008), as well as the cost of the materials themselves (Baker & Rials, 2013). Recyclability of CFRP is being improved, carbon fibres can be recovered from the resin matrix while limiting the reduction in the strength of the fibres (Pimenta & Pinho, 2011), however, it remains "wasteful to produce and difficult to recycle" (Harris, 2017)

<u>Glass fibre reinforced polymers (GFRP)</u>
The weight savings of substituting steel for GFRP automotive components has been shown to impact less on the environment (Koffler, 2014). Two common forms of glass fibre are multidirectional chopped strand mat and woven fabric. Glass fibre has lower embodied energy than steel, CFRP and aluminium (Song et.al., 2009). Glass fibre is a much less expensive option than carbon fibre, there are also advantages to the manufacturing processes involved. Unlike woven carbon fibre, multi directional chopped strands of glass fibre can be applied to a complex mould more easily. However, glass fibre has lower mechanical performance (Ashby, 2011), this may limit its use in structural elements of vehicles. GRFP can be recycled although it is not currently commercially viable, as a result the majority goes to landfill (Job, 2013).

<u>Other materials</u>
Other materials are being researched to replace steel in cars. Plastics in vehicles is set to increase (Lyu & Choi, 2015). Hybrid woven glass and carbon fibre composites offer improved performance to GFRP for a small increase in cost (Kim, Kim & Kim, 2015), Natural fibres offer an alternative to carbon fibre and glass fibre and are discussed further in section 2.4.4.

2.4.3 Composites in automotive manufacture

The standard process for manufacturing carbon fibre components involves the labour intensive laying up and hand rolling woven carbon fibre cloth, pre-impregnated with epoxy resin before a lengthy heat curing process. The remaining barrier for use in mass produced vehicles is the expense, although this is being reduced by improved manufacturing technologies (Jacob, 2014).

BMW i3

In 2014 BMW launched their carbon fibre and aluminium EV the i3 – shown in figure 2.13. “The aim of developing the BMW i cars is not simply to build emission-free cars, but also to use the maximum possible amount of sustainably produced and recycled materials… LifeDrive vehicle architecture, with its carbon fibre passenger cell and aluminium drive module… reduce its weight enormously and extend the car's range.” (BMW, n.d.)

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Figure 2.13, BMW i3 carbon fibre EV. (Source: BMW.com)

BMW have developed a semi-automated process to manufacture CFRP panels - reducing the labour-intensive layering of composite manufacturing (Morey, 2011). To manufacture the i3, BMW use High-Pressure Resin Transfer Moulding (HP-RTM) to press layers of carbon fibre cloth into a mould and then inject a polymer resin. (Gardiner, 2015). A traditionally made carbon fibre component has a cycle time of 4 hours (Verrey, et al, 2006). The cabin (or ‘life module’) of the BMW i3 “is a notable example HP-RTM application. The key aspects of HP-RTM are the short injection times (i.e. less than 1min) and the fast curing of the thermoset resins (i.e. less than 10min).” (Cicala et. al., 2016). HP-RTM allows the production of “large, complex structural components” (Gardiner, 2015), these advances enable BMW to viably manufacture CFRP chassis components.

The manufacture of lightweight chassis is part of a wider drive towards sustainability. “the BMW i3 features door trim panels and a dashboard made from renewable natural fibres, naturally tanned leather, and open-pore eucalyptus wood sourced from 100 % FSC®-certified forestry. Overall, 25 % renewable raw materials and recycled plastics were used in the interior of the BMW i3. The textile upholsteries are made of up to 100 % recycled polyester, produced using 34 % PET. A further 25 % recycled plastics are used in the exterior." (BMW, n.d.) BMW claim to meet the ELV directive of 95% recoverable materials.

By using renewable energy sources, BMW have reduced their reliance on fossil fuels, this has been achieved through renewable energy being used in the manufacture of both the materials and the production plant (BMW, n.d.). Although the energy used is renewable, the manufacture of the i3 is heavily energy intensive (Bryant, 2013) and this adds to the embodied energy in the vehicle. Improvements to recycling can ensure this energy is recovered at EoL.

2.4.4 Bio-composites

An alternative to carbon fibre and glass fibre is to use natural fibres. Research is being carried out as to the viability of flax, coir and bamboo fibres (Van Vuure et.al., 2015), Jute and sisal fibres (Ramesh, et al, 2013), Curaua fibres (Zah, et al, 2007) as well as other abundant and affordable natural fibres. Alkbir, et. al., (2016) states that "due to their fairly good mechanical properties, low cost, high specific strength, environmentally-friendliness and bio-degradability, ease of fabrication, and good structural rigidity, these materials [natural fibres] can be used in an extensive range of applications, including aerospace and the automotive industry." Natural fibres "require lower energy consumption for their manufacture, compared to conventional composites." (Di Landro & Janszen, 2014) this helps keep the embodied energy of the natural fibre reinforced polymer (NFRP) product to a minimum. The EoL scenario for NFRP composites depends on the polymer matrix but includes energy recovery through controlled combustion, recycling and biodegradation. (Duflou et el, 2012)

Resins too can be bio-sourced, therefore a completely sustainable bio-composite can be achieved through using flax fibres and poly-lactic acid (PLA) plastic (Oksman, et al, 2003), The drawbacks of using natural fibres include that they: require low processing temperatures; are prone to absorbing moisture; can be poor at bonding with polymer matrices and have wide variation in mechanical properties. For these reasons they could be inappropriate for use in structural vehicle components (Koronis et. al., 2013). They are however being employed in the interior roof, door and boot linings of vehicles (Dunne et. al., 2016).

Lotus Eco Elise

An example of biocomposites being used in the automotive industry is the use of natural fibres in the 2008 Lotus Eco Elise, pictured in figure 2.15.

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Figure 2.14: Lotus Eco Elise featuring a number of natural fibre materials. (source: CarMagazine.co.uk)

Lotus took a holistic approach to improve the sustainability of the Eco Elise improving all stages of the vehicles lifecycle (Lotuscars, n.d.). Part of Lotus' approach was the use of natural fibres:

- The body panels of the Eco Elise are reinforced with locally sourced hemp fibres.
- The Hemp NFRP seats are manufactured using an RTM process.
- Locally sourced, dye-free wool is used in the interior upholstery
- The floor is carpeted with a sisal fibre material.

The chassis of the car is a standard Lotus Elise model (manufactured from aluminium). The resin matrix used is a non-renewable polyester resin used on the standard Elise model (Malnati, 2009). It is notable that where natural fibre materials have been used it is either in a non-loadbearing capacity, or in the interior of the car.

2.4.5 The future of automotive manufacture

Because conventional mass production of cars is changing, a new model of production may be required.

iStream manufacturing process

Car designer Gordon Murray has proposed a model for lightweight cars called iStream. This system questions the traditional model for manufacturing cars on large production lines for continental markets. iStream reduces the environmental impact of conventional factories by removing "the most polluting parts used in conventional factories - such as large stamping presses to make steel body parts, welding robots or paint shops.” (Madslien, 2010)

In an interview for BBC news, Gordon Murray describes the benefits of his production process, "The actual factory that builds an iStream car… is about 20% of the capital investment and 20% of the size of a conventional car manufacturing plant - and about half the energy." (Madslien, 2010)

The iStream system uses CNC machinery which laser cuts and bends steel tube. The tubes are then welded together to form a spaceframe. Composite panels are then bonded to the frame to fill the spaces - providing stiffness. This is combined with a small production base to produce lightweight electric vehicles for local markets. (iStream, n. d.)

Gordan Murray Design is “Working on 8 iStream® vehicles with five manufacturers and is very close to signing iStream® licences with some of them. A few other manufacturers have also shown an interest in working with it.” (Innovate UK, 2016)
The Yamaha Motiv is a city car EV concept has been developed using the iStream process. Figure 2.16 shows the Motiv concept and chassis.

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Figure 2.15: Left: Yamaha Motiv chassis, manufactured using iStream process. Right: Yamaha Motiv concept car at the 2013 Tokyo Motorshow (Source: Yamaha-global.com).

According to a report for the SMMT by Ian Henry (2015) titled ‘The future of UK automotive manufacturing in 2025 and beyond’ the vehicles being manufactured are going to change:

- There will be a shift towards in hybrid vehicles in the 2020s, with 25% of vehicles produced being hybrids by 2030 (Henry, 2015, p12)

- There will be an increase in EVs, increasing to 4% of vehicle production by 2030. For greater adoption "there needs to be a reduction in battery size and price, and an increase in energy storage capacity" (Henry, 2015, p12)
- A trend towards Increasingly connected vehicles and autonomous vehicles. "Autonomous vehicle technology could be worth over £50 billion a year to the UK economy by 2030" (Henry, 2015 p14)

These changes to vehicles could lead to changes to vehicle architecture and modes of use.

Automotive manufacturing is also going to develop. Henry (2015) predicts that future factories will include; sustainable manufacturing systems, reconfigurable production lines, the use of new materials and will be "highly automated" (Henry 2015). These new materials could be in the form of biocomposites: "The potential game changers have been identified primarily as advances in materials enabled by materials science. This includes graphene and nano materials, new surface coatings, new composite materials and resins including bio-composites, and biologically derived and natural, living materials." (Ridgeway et. al. 2013 p7)

2.4.6 Environmental concerns

A cars foremost impact on the environment is the emissions during the use of the vehicle. "The use phase accounts for 63−92% of the life cycle energy consumption, materials production 8−32%, manufacturing and assembly 1−4%, and the rest <4%." (Kim & Wallington, 2013). This issue is being addressed by advances in electric motors and batteries, hybrid technology, energy recovery and hydrogen fuel cells. In the UK this change is being driven by the UK governments 'Plug-in Car Grant' electric vehicle subsidy, congestion charges, developing the vehicle charging network, vehicle excise and fuel duty, and by environmentally conscious consumers.

Tackling the impact that emissions have on the environment (by light-weighting cars with materials such as CFRP) increases the significance of the manufacturing phase of the lifecycle (Duflou et al, 2012). Rather than solving the environmental problem created by cars, manufacturers are responding to legislation on emissions by moving the environmental impact to a different phase of the cars lifecycle. EVs are presented as a solution to the exhaust emissions issue, however: batteries contain rare metals and environmentally damaging chemicals; the impact of manufacture and the generation of electricity to power the vehicles can have a larger overall environmental impact compared to petrol (Hawkins, 2012). As EV technology is in relative infancy compared to petrol cars, there may be wider scope for improvement compared to steel bodied petrol cars which are a mature technology with limited capacity for improved sustainability.

Increasingly the use of LCA considers the more complex picture during the life of a product. In this way, a more holistic approach to the environmental sustainability of cars can be considered. Manufacturers will make environmentally sustainable vehicles when there is consumer demand for them.

2.4.7 Further research

When designing a more sustainable vehicle, not only will lightweight sustainable materials be required but also improved processes - transportation, manufacturing and disposal of vehicles. Research is also needed in the area of battery and fuel cell technology as there is potentially more sustainable developments to improve battery life, materials used, or the development of viable hydrogen fuel cells.

Ridgeway et. al. (2013) suggest that bio-composites could be a viable material in the future production of cars. The use of carbon fibre in weight reduction of vehicles could be a false avenue of development as this technology suffers from energy intensive processing and EoL problems. There may be a need for cars to be constructed using sustainable composite materials, as such, further research needs to be carried out into how these materials could be combined with other technologies in the manufacture of cars.

A holistic view of these factors could be used to develop the right materials technology for the construction of vehicles for the future. Materials need to be fit for purpose - sustainable, affordable and developed for mass production. There is scope for further application of sustainable composites to cars - this could be achieved by developing stronger structural composites, weather resistant bio-materials and manufacturing processes for their mass production.

2.4.8 Conclusion

Ultimately the petrol-powered steel motor car will need to be replaced because of political and environmental pressures. The demise of the petrol car will change how cars are manufactured, the current environmental focus on CO_2 emissions may be replaced by a focus on the impact of manufacture and disposal. In this way, sustainable composites could increasingly replace the use of CFRP as the optimal composite for the manufacture of lightweight vehicles. Vehicle architecture looks set to change, this could be an opportune time to develop a process whereby environmentally sustainable technology can be used in the manufacture of mass produced sustainable cars.

2.5 Environmental Car design philosophy

2.5.1 Introduction

Through analysis of the car industry and current theory on sustainable transport, it is clear that a new approach to 'the car' is needed. Analysis of the automotive industry (in section 2.2) demonstrates a need for a new decoupled approach to car manufacture. LCA offers a method to evaluate and compare the environmental impact of cars. This section will evaluate how - as a mass manufacturer of cars - VW is tackling environmental issues, and assess their approach.

2.5.2 Case study 2 - Volkswagen Environmental performance

2.5.2.1 Introduction

The following study will evaluate how VW's sustainability strategy evolved over time. This study will reveal trends in how a car's impact is assessed and VW's attitude towards the sustainability of their cars. This can then be used to develop a broader view of the automotive industry attitudes. This is achieved by considering the strategies set out in VW's 1995, 2000, 2008 and 2014 environmental reports.

2.5.2.2 Golf Sustainability

<u>1974 - 1992 (Golf Mk.1 and Mk.2)</u>

When VW first started production of the Golf in 1974, little action was being taken about the impact cars had on the environment - for example, in the 1970s all petrol was leaded, despite being a known poison and having a measured effect on human health and the environment (Landrigan, 2002). It has taken 40 years to eliminate lead from petrol globally

(Gardner, 2011). The first landmark United Nations Conference on Environment and Development (UNCED) dubbed the 'Earth Summit' was held in Rio de Janeiro, 3-14 June 1992 where governments first defined targets to reduce emissions and therefore introduce environmental legislation that affects manufacturing. As cars are a major contributor of CO_2 emissions, this was a major concern for the automotive industry.

<u>1992 - 1995 (Golf Mk.3)</u>

"Volkswagen initiated environmental inventories for whole vehicles in 1992. At the time, the Groups mass-volume model was the Golf A3 [Golf Mk. 3], which is why it was selected as the object of inventory analysis."(Schweimer & Levin, 2000: p.3) The reason for beginning environmental reports on the Mk3 Golf is interpreted as being a result of imminent global legislation following the Earth Summit in 1992. Up to this point there is little evidence of VWs concern for the environment.

In 1995 'The Volkswagen Environmental Report' was published, the automotive company sets out their vision for the future. "The challenge now is to deploy the vision of sustainable development in hard and fast goals for the ongoing development of products and production processes at Volkswagen" (Volkswagen AG, 1995: p.14) and introduced "7 basic principles" (Volkswagen AG, 1995: p.12-13). These principles consisted of some broad objectives: lessen the companies environmental impact; produce satisfying cars; develop ecologically efficient products and make sure the management, employees and customers are informed of the environmental policy. The main focus of the environmental strategy is to reduce vehicle emissions, however it is also stated that models of Golfs manufactured post 1992 can be returned to VW for recycling (Volkswagen AG, 1995: p.96). Other ecological initiatives include a limited use of natural fibre components in the boot lining, door lining and dash board supports. Every Golf Mk3 contains 5kg (a tiny proportion of the vehicle) of moulded wood fibre product Lignotock - "Long used in Europe for interior-trim substrates, the company's Lignotock family features 85 percent wood fiber with 15 percent phenol-formaldehyde binder resin."(Malnati, 2010). The many minor, disjointed and vague attributes of their environmental strategy demonstrate that in 1995 VW was only beginning to consider environmental issues in a serious manner.

<u>1995 - 2000 (Mk. 4 Golf)</u>

In 1999 VW released "Volkswagen's third Environmental Report"(Volkswagen AG, 1999: p.5) VW repeat the same 7 basic principles as they stated in their 1995 report. Since

1995, it appears they have developed their approach to lessen the environmental impact of their business.

"In 1995, when Volkswagen decided to take part in the EC's voluntary Environmental Management and Auditing Scheme. In September of the same year, the Emden plant became the first automobile plant in Europe to achieve certification under the scheme. By the end of 1998, the Mosel, Brunswick, Salzgitter, Wolfsburg and Kassel plants had followed suit. Now every one of Volkswagen's German production plants has an environmental management system" (Volkswagen AG, 1999: p.19)

Their sustainable approach focuses on: putting processes in place to collect data on waste management and CO_2 emissions; reducing fuel consumption in VW cars and improving their control over the EoL scenario of VW cars. In a drive for fuel efficiency, VW look for materials to reduce weight:

"Building environmentally acceptable, fuel-efficient cars calls for advanced lightweight design concepts. To this end, Volkswagen is researching and developing innovative technologies in the materials sector…One example from the research laboratories is a die-cast magnesium door with a carbon-fibre reinforced outer skin. This construction is more than 40 percent lighter than a conventional steel door." (Volkswagen AG, 1999)

Innovations such as this one - presented in a sustainability report - reveal that VW produce lighter cars to reduce emissions and fuel cost for their customers, while appearing sustainable at the same time. Producing a magnesium and carbon fibre door is not a sustainable technology, the manufacture has an impact on the environment and the materials are not easily recovered. During this period VW start to conduct "Cradle to grave" Life cycle assessments of their cars.

<u>2000 - 2008 (Mk.5 Golf)</u>

In 2007 the VW LCA model "was developed using Volkswagen's slim LCI [Life Cycle Inventory] methodology (Koffler et al. 2007). Vehicle parts lists were used as data sources for product data, and the weight and materials of each product were taken from the Volkswagen material information system (MISS). This information was then linked to the corresponding process data in the Life Cycle Assessment software GaBi." (Volkswagen AG, 2013).

The Sustainability Report 2007/2008 again repeats environmental goals of VW and starts to include social responsibility into the corporate philosophy. The general sentiments remain the same - continue with the sustainable management strategy, reduce the weight of the cars, reduce emissions and improve processes used to measure the sustainability.

2008 - 2014 (Mk.6 & Mk.7 Golf)

The VW "'Life Cycle Engineering' aims to improve the environmental footprint of a vehicle from cradle to grave. This process begins with a life cycle assessment (LCA), in which the environmental impacts of the vehicle under development are assessed across the full life cycle - from resource extraction through production and operation to eventual recycling. The LCA analysts make it possible to identify those areas where improvements will have the biggest effect." (Volkswagen AG 2014: p.94). Although knowing the full impact of their cars, VW concentrate their efforts on reducing vehicle emissions and weight reduction exercises.

Volkswagen corporate social responsibility

VW have been criticised for their products not aligning with their CSR reports (Lynn, 2015). It was discovered that a device hidden by VW in 11 million cars worldwide (including the Golf models) have been used to cheat emissions tests. (Hotten, R. 2015) “Volkswagen decided that it didn’t matter if its cars poisoned the planet by emitting 40 times the legal limit of nitrogen oxide, as long as doing so allowed it to become the world’s leading car maker.” (Dans, 2015), Dans (2015) concludes that to VW “CSR is a marketing exercise.”

Golf Mk.3, Mk.4, Mk.5 & Mk.7 materials usage comparison

From the environmental reports released by VW it is possible to compare the materials inventories of the Mk3, Mk4, Mk.5 and Mk.7 models of Golf. Figure 2.16 displays the components that make up a Mk.5 Golf.

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Figure 2.16, Disassembled Golf Mk.5 (Volkswagen AG, 2008, p.10).

Materials for the Golf Mk.3 are shown in the Volkswagen AG (1995) report, the Golf Mk.3 and Mk. 4 are described by Schweimer & Levin (2000), both the Golf Mk.4 and Mk.5 are listed in the Volkwagen (2008) report and the weights of materials for what is assumed to be the Golf Mk.7 is displayed in a further 2014 VW report (Volkswagen AG, 2014: p.101). Figure 2.17 displays the materials for each Golf model:

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Figure 2.17, Percentage of materials by weight for 4 models of VW Golf. (Data sourced from: Volkswagen AG, 1995; Schweimer & Levin, 2000; Volkwagen, 2008 & Volkswagen AG, 2014 p.101).

What can be drawn from the chart is limited as the data varies between reports. It can be observed that there is generally a trend of increasing aluminium content, reducing proportion of steel and an increasing amount of plastic. Generally it can be said that the materials used to construct the mass market VW Golf has remained broadly unchanged over the last 25 years.

2.5.2.3 Discussion

VW have introduced sustainability standards however this initiative is part of government legislation (Chaplier, 2014). VWs overall CO_2 emissions have increased (Volkswagen AG, 2014: p.126). The emissions reduction of their company and products is repeatedly described as a priority. Despite the sustainability strategies, the environmental impact of VW has not improved over the past 20 years. This could be evidence of VW using sustainability as a 'greenwashing' marketing exercise. VW and the wider automotive industry continue to build steel vehicles, that then burn oil for 12.5 years - a vehicles typical life span (European Commission, 2008: p19) before some of the materials are recovered. It is possible that VWs measurements vary from year to year - the reports differ in both the proportion of materials, how they are listed and grouped and also the weights of respective vehicle models.

2.5.3 IMPRO-car study

In 2008 the European Commission published a report by the Joint Research Centre (JRC) Institute for Prospective Technological Studies titled 'Environmental Improvement of Passenger Cars' (IMPRO-car). (European Commission, 2008)

"The objectives of the IMPRO-car project are to:

- Estimate and compare the environmental impacts of the passenger cars under a life-cycle perspective,
- Identify the main environmental improvement options that are technically feasible and available on the car market within the two coming decades, addressing all the different life cycle stages and estimate the size of the environmental improvement potentials,
- Assess the main improvement options regarding their feasibility, the main barriers for their adoption and the economic aspects." (European Commission, 2008: p.17).

The study defines the average petrol and diesel car used in Europe, an LCA study of these cars is carried out and the results analysed to project trends and suggest improvements which will create less environmental damage. The report identifies the following problems with a cars lifecycle (European Commission, 2008: p.80):

- The production of cars damages the environment - replacing steel with composites, aluminium and steel alloys increases the environmental impact of manufacture.
- Driving cars damages the environment - emissions during the use of cars is significant.
- Disposing of cars damages the environment - recovering composites and bonded materials is problematic.

The report's recommendations include overall weight reduction, air conditioning improvements, drive train and exhaust improvements, alternative fuels, better recovery of materials at end of life and improving driving styles.

These proposed changes fail to recognise that car production is inherently bad for the environment. The production of cars was conceived before it was realised their manufacture, use and disposal causes a global environmental problem. The proposed changes are minor and do not resolve the fundamental issues. A new philosophy is required regarding the whole lifecycle of cars.

2.5.4 Design and manufacture of an EcoCar

2.5.4.1 Introduction

The Aston EcoCar is a project run by Aston University where a team of students build a vehicle to enter the Shell Ecomarathon (SEM) (Shell Global, 2016). The SEM is an international competition to build fuel efficient vehicles. Each year Aston enters a vehicle into the 'urban concept' class and applies a holistic approach to design a sustainable vehicle. The 2012 vehicle was successful in winning the Eco-Design award at the competition.

2.5.4.2 EcoCar philosophy

A holistic sustainable design approach has been used for the 2012, 2013, 2014, 2015 and 2016 Aston EcoCars. Each vehicle was developed using the following sustainable principles:

1. Usability and fitness for the purpose as a vehicle for personal transportation.
2. Where possible, biodegradable materials (natural fibre) are used in the construction of the vehicle - 'wooden car' ethos.
3. Where natural fibres are not used, an effort is made to use components that can be reused, or the materials can be recycled (technical nutrient cycle).
4. Powered by Hydrogen fuel cell, a technology where water is the only emission, and has the potential to be renewable.
5. Innovative product architecture - considering the manufacture, use and disposal of the vehicle.
6. The vehicles are designed for ease of disassembly.

The Aston EcoCar provides a platform for the research of this project to be applied to a sustainable vehicle. The EcoCar is ideal for this purpose as the environmental design principles are similar to this research project.

The design of components on the EcoCar are not simply replacements for a conventional car, but meet the specific needs of the sustainable concept. For example, because of the low power output of the fuel cell - 1KW, the EcoCar has only one driven wheel. This requires an alternative vehicle architecture while following the framework of the SEM competition rules.

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Figure 2.18, 2012 EcoCar - winner of the EcoDesign award at SEM 2012

The project represents a practical outcome to environmental design. Understanding the practical challenges and the design compromises in the designing and building of an eco-vehicle provides useful feedback as to the success of the cars design philosophy. For example, the 2012 car displayed in figure 2.18 was constructed using CNC routed MDF board, while this represented a natural fibre material in keeping with the 'wooden car' ethos, the density of the material meant that the vehicle weighed in excess of 200Kg. Another feature of the design enabled the car to fold up, reducing the parking footprint to one smaller than a Smart car.

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Figure 2.19, 2013 EcoCar 'backbone chassis' flat-pack construction

Aston takes a holistic approach to design a sustainable urban concept car. The challenge is to use natural fibre materials (biological nutrients) where possible, but to also produce an attractive and functional design. The 2013 EcoCar (shown in figure 2.19) featured a completely flatpack structure - constructing the car using birch plywood panels. The vehicle featured entirely wooden suspension and wheel components. the wooden suspension components were much larger and heavier than conventional alternatives (steel springs).

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Figure 2.20, 2014 Aston EcoCar modular construction - balsa/pla sandwich monocoque. subject of pilot study.

The drive train, brake system, suspension, wheels, axles and wheel hubs prove challenging areas to implement natural fibre materials. A solution has been to use aluminium and steel which is widely recycled.

A number of natural fibre and composite materials could be used to manufacture an 'EcoCar'. The 2014 EcoCar displayed in figure 2.20 featured a sandwich panel construction - a balsa wood core skinned with plywood, this was used to construct a monocoque chassis. Experimenting with materials in this way is key to developing a lightweight vehicle. The 2014 EcoCar was chosen as a platform to develop a mouldable sustainable composite, this was made in collaboration with Dave Patel (Patel, 2014), an undergraduate student on the 2014 EcoCar team. This formed the pilot study of this research project (Chapter 4).

Figure 2.21, 2015 Aston EcoCar - subject of materials inventory.

Figure 2.21 shows the 2015 Aston EcoCar, the 2015 EcoCar was capable of transporting a driver and 2 passengers. Extensive use of balsa core and birch plywood was used in the construction. For a better understanding of the impacts the EcoCar has on the environment a lifecycle inventory was conducted by weighing the component parts of the 2015 EcoCar (detailed in section 2.5.4.4).

Figure 2.22, 2016 Aston EcoCar - flat pack construction, subject of main study.

The 2016 EcoCar shown in figure 2.22 returned to a flatpack plywood structure, however a lightweight marine ply (with a low-density wood) was used to construct a monocoque design. The 2016 car was the lightest car to date (170Kg), partly due to the plywood lattice structure.

The 2016 EcoCar was chosen as the platform to conduct the main study of this research project (Chapter 5).

2.5.4.3 Sustainable EcoCar challenges

Through using a sustainable philosophy to design and manufacture an entire vehicle, a number of recurring problems arise:

1. There are limitations in putting the philosophy into practice with an undergraduate student team and without the resources to manufacture a more sophisticated car.
2. There are limitations in applying the sustainable goals. Steel construction is best suited to components such as motors, axles and steering racks - limiting sustainable options
3. Sustainable alternatives for structural members are larger and heavier than steel.
4. Wooden panel products available can only be formed into 2-dimensional curves which limits their application. There is a need for a 'mouldable plywood' able to be formed into complex 3-dimensional shapes.

These sustainable challenges show the need for a lightweight material that meets the sustainable criteria but is not bulky. This has driven the development of a sustainable design process along with the formation of a new biocomposite material.

2.5.4.4 Life cycle Inventory

The traditional design of the car and the way it is manufactured has too many open ended systems where virgin materials are used during manufacture and the recovered materials are of significantly lower quality (Braungart & McDonough, 2009).

Advances in production methods such as VW's Modular Transverse Matrix (MQB) system have lowered costs and improved commonality between car models saving "weight, time and money" (English, 2013). However, although efficient through years of refinement, the current manufacturing model still consists of:

- a high usage of steel,
- an increasing use of fibre reinforced plastics and aluminium in order to lower the weight of vehicles,
- a large number of different materials that need separating at the end of life,
- a reliance on the large production line manufacturing model.

This shows that current manufacturing model lacks the radical innovation needed to improve sustainability.

The manufacturing and end of life phase of a vehicle is becoming increasingly important, it is recognised that "embodied CO_2e *[carbon dioxide equivelant*] emissions associated with vehicle production and disposal become a more significant part of the lifecycle as the use phase decarbonises." (Gbegbaje-Das & Smith, (2013): p1)

The automotive industry needs to move away from outdated steel bodied 'cradle-to-grave' (Schweimer & Levin, 2000) approach to car construction and towards a more holistic model, improvements need to be made in the materials and manufacture of vehicles.

With the Aston Eco-car a new approach to designing and manufacturing cars has been taken based on a Cradle to Cradle philosophy. The biodegradable wooden construction is coupled with fully recyclable or reusable components minimising waste products. A working prototype based on this philosophy, the 2015 Aston EcoCar, is a 3 seat 'Urban Concept' car. As a city car for personal transport able to take passengers the 2015 Aston EcoCar meets the same transport needs as conventional cars. The Aston EcoCar is therefore broadly comparable to a medium sized production car - in terms of designed function. It is recognised that as a prototype the EcoCar has limited performance (in terms of crash worthiness, speed and comfort) compared to production cars.

To validate the holistic and sustainable approach to building passenger cars the Aston Eco-car will be compared to the traditional car.

Objective

This study addresses the materials lifecycle of automobiles. This will compare the VW Golf and the average European petrol car to that of the sustainably designed Aston EcoCar.

2.5.4.4.1 Methodology

A simplified analysis is carried out comparing the materials used in the 2015 EcoCar, IMPRO-Car (European Commission, 2008) and the VW Golf Mk.5 (Volkswagen AG, 2008). The principle process for conducting the study into the sustainability of cars will use Life Cycle Inventory (LCI) to compare the materials used to manufacture the respective cars.

Due to a lack of a dataset, a full life cycle assessment of the 2015 Aston EcoCar is not possible. There is also insufficient evidence as to how long the useful life of an Aston EcoCar would be. Without this information, such a study would have low accuracy. However a full LCA would provide information as to whether the sustainable design philosophy is being developed in a successful way. A full LCA following the ISO14040/44: 2006 guidelines would follow these steps:

1. Set out the goal and scope of the study.
2. Establish a product system (and system boundary) for the Aston Eco-car.
3. Compile an inventory of the EcoCar components.
4. Conduct an impact analysis
5. Normalise the individual studies to the system boundary and functional unit.
6. compare the vehicles.

In this study, the first 3 steps of the LCA process will be conducted – compiling a Lifecycle Inventory of the materials used for each car. This inventory will then be assessed for their sustainable credentials.

2.5.4.4.2 Goal and scope definition

Goal - 'Carriage' of the car

This study will apply Life Cycle Assessment (LCA) techniques to compare the materials used in production of the 'carriage' of a car. The 'carriage' is defined in this study: as a car without the power unit, fuel or transmission. The following three vehicles will be compared during this study:

1. Primary study - Aston EcoCar,
2. Typical reference - The average EU car (JRC IMPRO-car report),
3. Case study - VW Golf.

The initial stages of a life cycle assessment (inventory analysis) will be conducted following ISO 14040/14044 guidelines. Comparable aspects (the manufacturing materials and end of life scenario) of the VW study and IMPRO-car study will be compared to the 2015 Aston EcoCar.

This study will indicate whether the 'Design Philosophy' of the Aston EcoCar is an improvement on current steel bodied cars. This study will provide guidance for the future development of sustainable vehicles such as Aston EcoCar.

The results of the study are to be used to put the Aston EcoCar philosophy into the context of automotive industry current practice.

Scope

As the Aston EcoCar is a prototype concept vehicle built for a competition, the full use phase as a method for personal transport replacing production cars, can not be fully validated. As such, a figure for the lifespan, spare parts required or distance travelled by such a vehicle can only be speculation. The scope of this study focuses on the raw materials, production, use and end of life phases of the car lifecycle.

The system

This study considers the system displayed in figure 2.18 for the inventory analysis of the vehicle carriage:

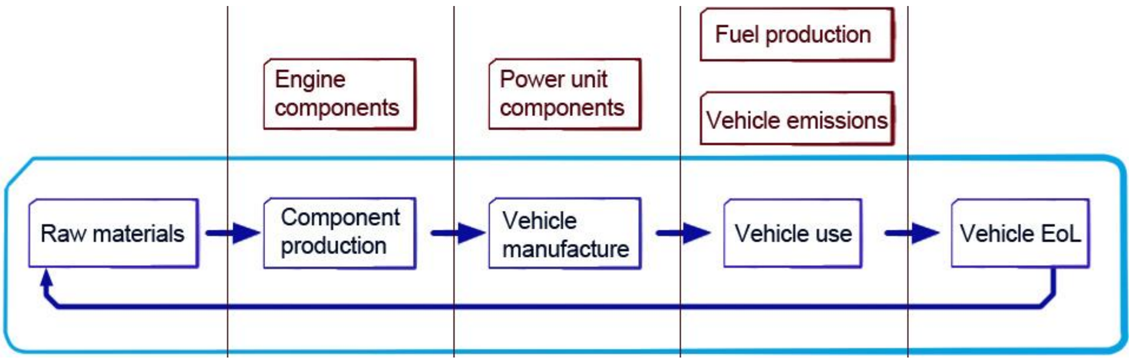


Figure 2.23, Product system, and system boundary (in blue)

The functional unit of the car carriage is:
'The transport of a driver plus passengers for 75,000km over 5 years.'

The average distance travelled per year is 15000km (European Commission, 2008: p.47). The deterioration incurred over this distance travelled will have an impact on the spares and repairs needed for the vehicle.

<u>Assumptions and limitations</u>

For comparisons with the 2015 Aston EcoCar, data is taken form the 2008 IMPRO-Car (European Commission, 2008) and the VW Golf Mk.5 (Volkswagen AG, 2008). This information will then be applied to the system boundary set out for this study and normalised to the functional unit stated above.

The spare parts and lifespan of the vehicle is not included in the product system as there is no data for the 'use' of the Aston EcoCar.

The type of vehicle suitable for this study is a M category vehicle as defined by the European Union. The comfort, space and performance of the vehicle is not considered. Since a broader range of vehicles is required when comparing a road car to an urban concept prototype, the function of 'a car' is considered to be the personal transport of people.

The sources for the production car comparisons are both from the same year of manufacture. The listed materials for the Golf are not as comprehensive as for the EcoCar and the IMPRO-Car because of the limited data set available.

Both the VW Golf and the IMPRO-Car car studies included the petrol engine and transmission in their studies. An engine and transmission is estimated to weigh 150Kg and is assumed to be constructed of steel. 150kg of steel has therefore been subtracted from the IMPRO-Car and VW Golf figures.

The size of the car (in terms of seating capacity) is considered to range from 2 to 6 seats - for general purpose transport of a driver plus passengers (EU category M). As the occupancy rate of vehicles is between 1 and 2 people per journey the model for this system can (broadly) compare 4 wheeled vehicles with more than 1 seat.

As the vehicles 'power unit' is not included in this study, it is assumed that any 'power unit/engine' technology is compatible with the cars studied.

2.5.4.4.3 Aston EcoCar Life Cycle Inventory

A full inventory of the 2015 Aston EcoCar was conducted. Each component was disassembled and weighed. The results of the Aston EcoCar LCI are displayed in a series of inforgraphics:

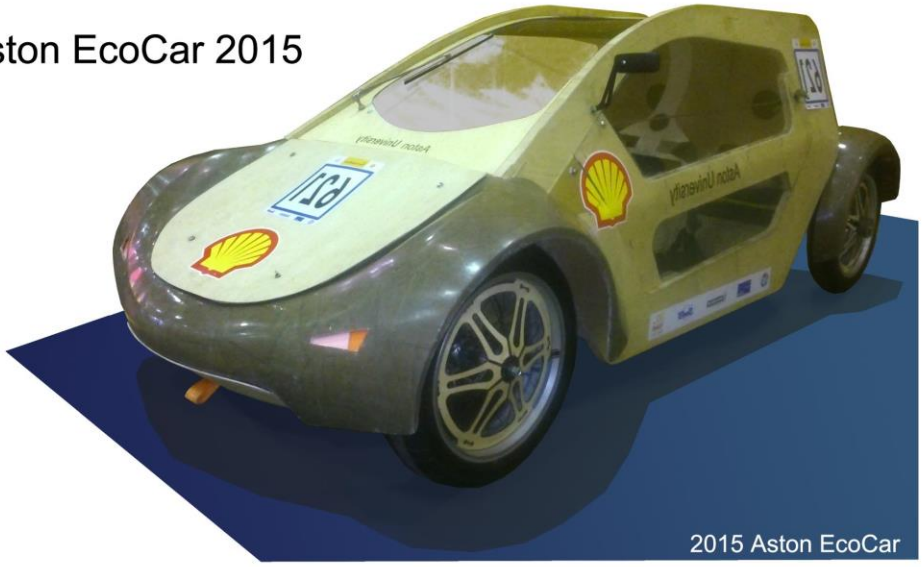
- Figure 2.24 displays the materials used in the 2015 Aston EcoCar composition by weight.
- Figure 2.25 categorises the 2015 Aston EcoCar by sub-assembly, displaying the weight for each sub-assembly.

Each subassembly for the 2015 Aston EcoCar is further categorised into materials and weights for each component:

- Figure 2.26a - 2015 Aston EcoCar chassis inventor
- Figure 2.26b - 2015 Aston EcoCar wheel inventory
- Figure 2.26c - 2015 Aston EcoCar body inventory
- Figure 2.26d - 2015 Aston EcoCar power unit housing inventory
- Figure 2.26e - 2015 Aston EcoCar interior inventory
- Figure 2.26f - 2015 Aston EcoCar rear subframe inventory
- Figure 2.26g - 2015 Aston EcoCar front upright inventory
- Figure 2.26h - 2015 Aston EcoCar brake system inventory
- Figure 2.26i - 2015 Aston EcoCar steering inventory

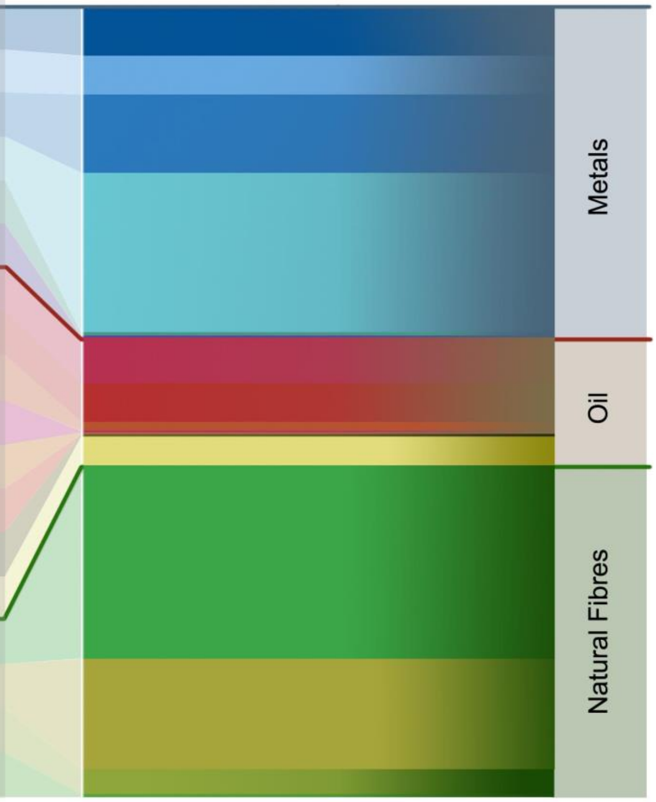
In figure 2.27 the materials used in the VW Golf, IMPROcar and 2015 EcoCar are displayed in a materials comparison infographic.

Inventory - Aston EcoCar 2015



Car Carriage - composition by weight

Material	Weight	%
Mild Steel	9,478g	6%
Stainless Steel	7,326g	5%
Steel - unspecified	14,930g	10%
Aluminium	30,002g	20%
Copper	500g	0%
Bronze	64g	0%
Polycarbonate	8,840g	6%
Epoxy	7,200g	5%
PVC	1,395g	1%
Nylon	850g	0%
Polystyrene	140g	0%
PP	20g	0%
Brake Fluid	300g	0%
Rubber	5,630g	3%
Birch Ply	35,740g	24%
Balsa	20,820g	14%
Hessian	4,800g	3%
Pine	590g	0%



Total Weight 150kg

Figure 2.24, Aston EcoCar composition by weight

Figure 2.24 shows the amount of natural fibres in the Aston EcoCar to be 41%. Data of embodied energy from Ashby (2011) states that wood has a low embodied energy of 7-8MJ/kg, metals are higher with steel at 29-35MJ/kg, stainless steel at 77-85MJ/Kg and 200-220MJ/Kg for aluminium. The energy used to make the EcoCar is minimised by using wood as a material.

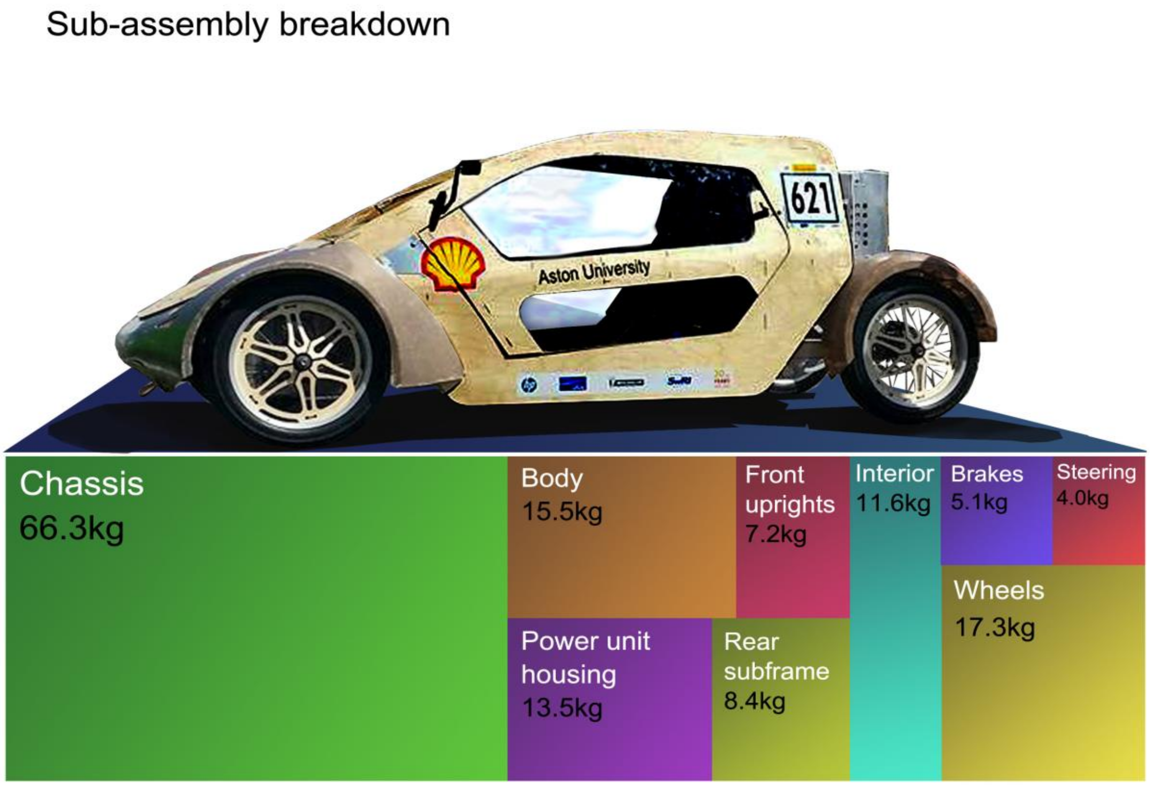


Figure 2.25, 2015 Aston EcoCar Sub-assembly breakdown

As displayed in Figure 2.25, the chassis comprises over 44% of the weight of the car.

2015 AstonEcoCar Inventory - Chassis

Assembly	Component	Material	Weight	Sub tot	Assembly	Component	Material	Weight	Sub tot
Monocoque	Sandwich panel Core sides	Balsa core	5300g		Door	2x Central frame - core	Balsa core	2000g	
	Sandwich panel Core floor	Balsa core	11000g			2x Central frame - skin	Birch Ply	3200g	
	Sandwich panel Skin	Birch ply	26500g			2x Upper & Lower windows	Polycarb	4340g	
	Sandwich panel Extra skin	Aluminium	9000g			4x Hinges	S/S	160g	9700g
	Windscreen	Polycarb	4500g	56300g		6x Typ bolt, washer & nut	S/S	276g	

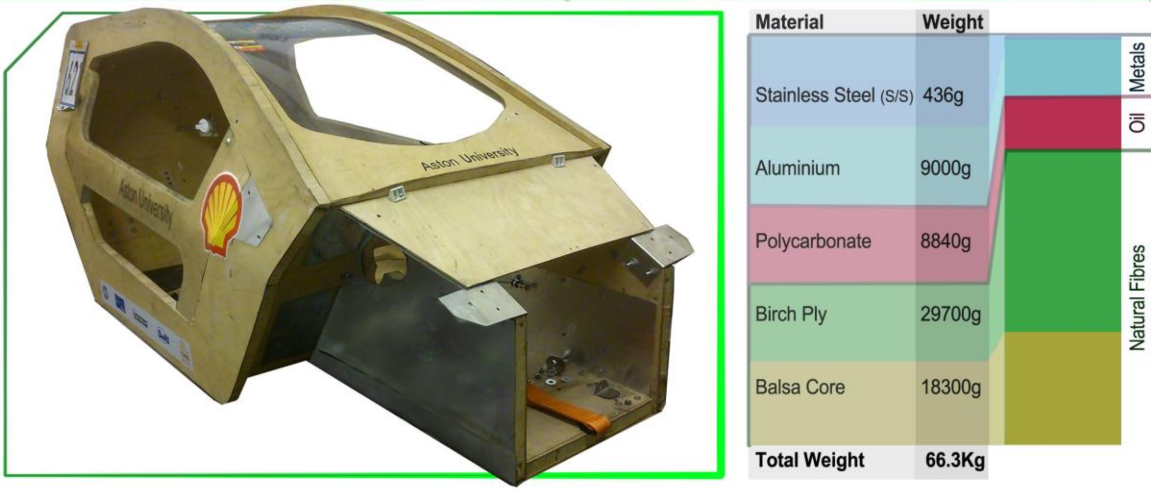


Figure 2.26a, 2015 Aston EcoCar chassis inventory

The majority of the chassis is shown by figure 2.26a to be constructed using birch and balsa wood. Usage of some materials such as polycarbonate for the windscreen is dictated by the SEM rules.

2015 AstonEcoCar Inventory - Wheels

Assembly	Component	Material	Weight	Sub tot	Assembly	Component	Material	Weight	Sub tot
Wheels	Spokes	Steel	2440g		Axles	4x Axle shaft	Mild steel	1320g	
	4x Rim	Auminium	3880g			12x M12 Large washer	S/S	180g	
	4x Hub	Steel	4000g			8x M12 Nut	S/S	160g	
	4x Inner tube	Rubber	1440g			4x spacing block	Mild steel	120g	1780g
	4x Tyre	Rubber	3280g						
	4x Cosmetic panel	Birch ply	520g	15560g					

Figure 2.26b, 2015 Aston EcoCar wheel inventory

The wheel components listed in figure 2.26b make up 12% of the EcoCar vehicle. As the wheels are made of steel and aluminium they contribute a significant amount of these materials to the vehicle.

2015 AstonEcoCar Inventory - Body

Assembly	Component	Material	Weight	Sub tot	Assembly	Component	Material	Weight	Sub tot
Wheel Arches	Moulded cast - resin	Epoxy	7200g			Brackets	Aluminium	2240g	
	Moulded cast - fibres	Hessian	4800g	12000g		Bonnet	Birch ply	600g	
						14x Typ bolt, washer & nut	S/S	644g	

Figure 2.26c, 2015 Aston EcoCar body inventory

As Figure 2.26c shows, epoxy resin as the main component of the body work. Epoxies have a high embodied energy of 105-130Mj/Kg (Ashby, 2011) compared to wood.

2015 AstonEcoCar Inventory - Power Unit Housing

Assembly	Component	Material	Weight	Sub tot	Assembly	Component	Material	Weight	Sub tot
Case	Folded case	Aluminium	10280g			12x Typ bolt, washer & nut	S/S	552g	
	Floor inner	Balsa core	1320g						
	Cover	Aluminium	1300g	12900g					

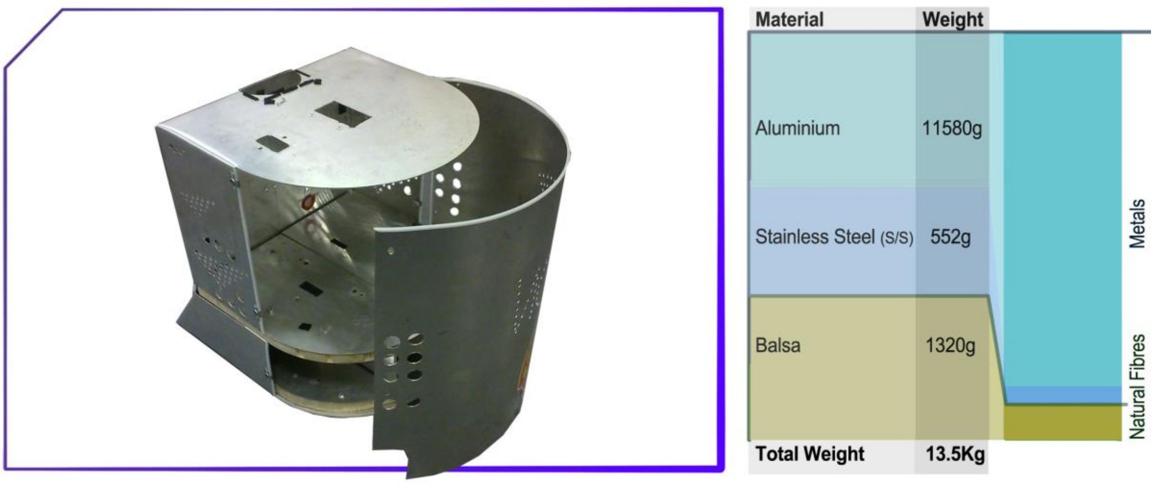


Figure 2.26d, 2015 Aston EcoCar power unit housing inventory

The high aluminium content of the power unit displayed in figure 2.26d is a fire safety feature, efficient use of materials such as aluminium reduces embodied energy.

2015 AstonEcoCar Inventory - Interior

Assembly	Component	Material	Weight	Sub tot
1. Seat	Bracket	PVC	45g	
	Back support & frame	Birch ply	2200g	
	Foam mat	Polystyrene	140g	
	Bracket blocks	Pine	350g	
	Screws	Steel	44g	
	10x M6 bolt (10mm) & nut	S/S	100g	2879g
2. Harness	Webbing	Nylon	830g	
	Catches & buckles	S/S	1190g	
	5x Mounting points	S/S	850g	
	10x Typ bolt, washer & nut	S/S	460g	3330g
3. Wiper	Motor and case	Steel	670g	
	Blade	Rubber	30g	
	Arm	Aluminium	80g	780g
4. Pedals	Bracket	Aluminium	330g	
	2x pedal	Birch ply	200g	
	Pivot	Steel	70g	
	8x Typ bolt, washer & nut	S/S	368g	968g
5. Mirrors	2x arm & case	Steel	320g	
	Mirror	PP	20g	340g
6. Dash	Top and face	Birch ply	750g	
	Bracket blocks	Pine	240g	
	Mounting brackets	S/S	120g	
	4x Typ bolt, washer & nut	S/S	184g	1294g
7. Electrics	Wires	Copper	500g	
	Insulation	PVC	1350g	
	Horn	Steel	150g	2000g

Material	Weight
Stainless Steel (S/S)	3272g
Steel	3150g
Copper	500g
Aluminium	410g
PVC	1395g
Nylon	830g
Polystyrene	140g
Rubber	30g
PP	20g
Birch Ply	3150g
Pine	590g
Total Weight	**11.6Kg**

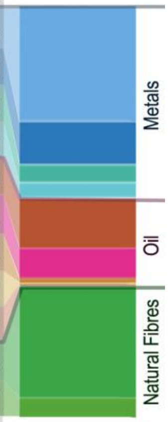
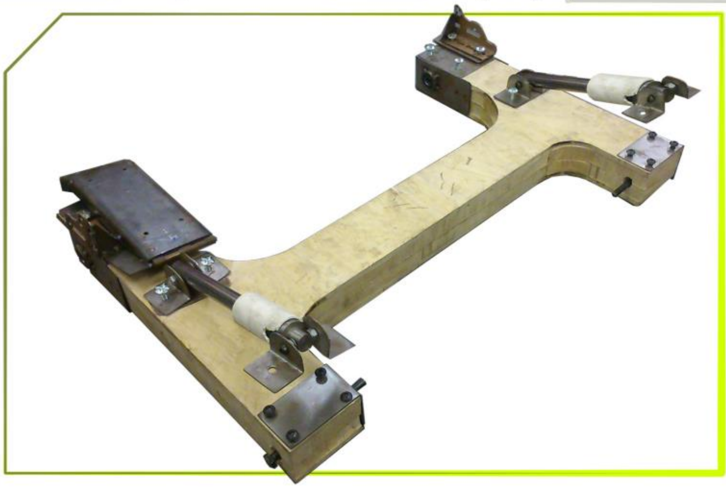


Figure 2.26e, 2015 Aston EcoCar interior inventory

Materials for components such as the harness, wiper motor and wiring displayed in figure 2.26e are difficult to replace using alternative ‘greener’ materials.

2015 AstonEcoCar Inventory - Rear Subframe

Assembly	Component	Material	Weight	Sub tot
H Beam	Sandwich panel core	Balsa core	1200g	
	Sandwich panel skin	Birch ply	1450g	2650g
Axle Mounts	2x Bracket	Mild steel	480g	
	2x Bearing housing	Mild steel	300g	
	4x Bearing	Steel	220g	
	2x Caliper mount	Mild steel	300g	1300g
Chassis Mount	2x Bracket	Mild steel	720g	
	2x Pivot pin	S/S	220g	940g
Suspension	2x Strut case	Mild steel	620g	
	2x Strut shaft	Mild steel	680g	
	8x spacing washer	Mild steel	120g	
	8x Elastomer block	Rubber	240g	
	4x Pivot mount	Mild steel	640g	
	20x M8 Coach bolts	S/S	800g	
	8x Typ bolt, washer & nut	S/S	368g	1300g



Material	Weight
Mild Steel	3860g
Stainless Steel (S/S)	1388g
Steel	220g
Rubber	240g
Birch Ply	1450g
Balsa	1200g
Total Weight	**8.4Kg**

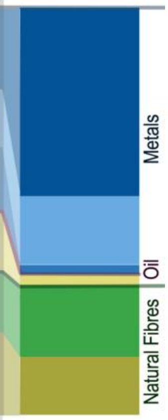
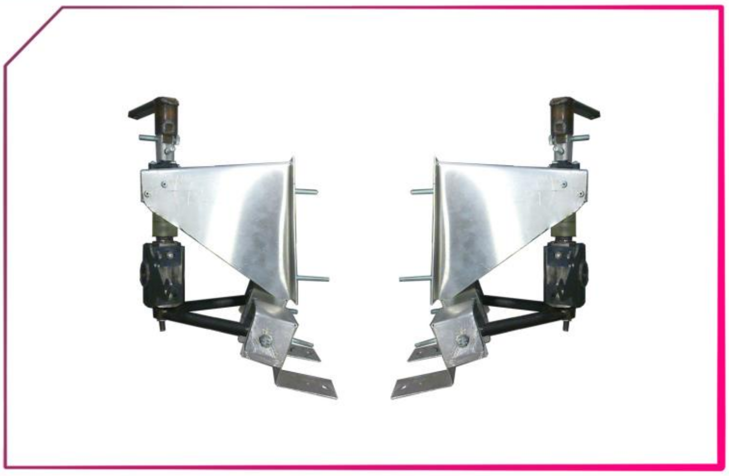


Figure 2.26f, 2015 Aston EcoCar rear subframe inventory

Figure 2.26f shows that larger structural components can be built using natural fibres, however smaller structural components requiring joints and moving components appear more compatible with steel construction.

2015 AstonEcoCar Inventory - Front Uprights

Assembly	Component	Material	Weight	Sub tot	Assembly	Component	Material	Weight	Sub tot
Bearing Blocks	2x Bearing Housing block	Mild steel	2120g		Wishbones	2x Bearing housing	Mild steel	100g	
	4x Bearing	Steel	440g			2x Spherical bearing	steel	16g	
	2x Caliper mounts	Mild steel	260g	2820g		8x Bush	Bronze	64g	
Suspension	2x Shaft	Mild steel	320g			4x arm tubes	Mild steel	430g	
	6x Elastomer block	Rubber	90g			8x M8 Large washer	Mild steel	52g	662g
	6x Spacing washer	Mild steel	160g		Chassis mounts	2x Main bracket	Aluminium	1000g	
	2x Thrust bearings	Steel	20g			4x Wishbone brackets	Aluminium	492g	
	2x Spherical bearings	Nylon	20g			4x Back plate	Mild steel	116g	1608g
	2x Steering arms	Mild steel	620g	1230g		20x Typ bolt, washer & nut	S/S	920g	



Material	Weight
Mild Steel	4178g
Stainless Steel (S/S)	920g
Steel	476g
Aluminium	1492g
Bronze	64g
Rubber	90g
Nylon	20g
Total Weight	**7.2Kg**

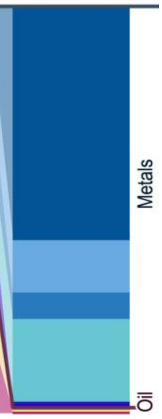
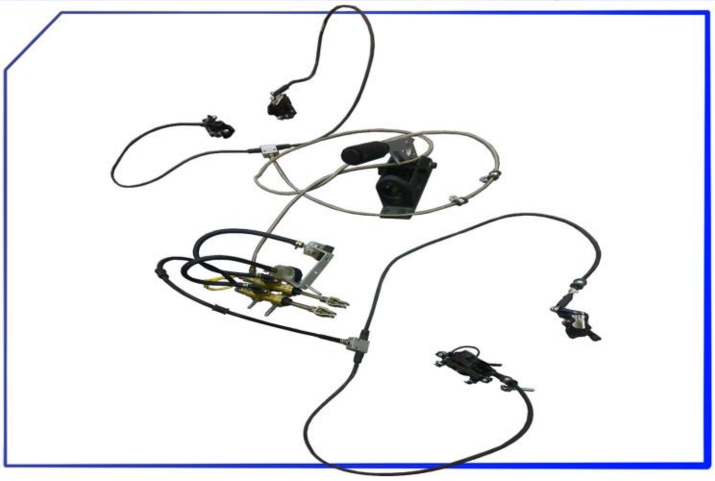


Figure 2.26g, 2015 Aston EcoCar front upright inventory

2015 AstonEcoCar Inventory - Brakes

Assembly	Component	Material	Weight	Sub tot	Assembly	Component	Material	Weight	Sub tot
Brake System	3x Brake cylinders	Steel	650g			Hand brake	Steel	980g	
	Brake fluid	Brake fluid	300g			4x Brake disc	Steel	520g	
	Lines	Rubber	850g			4x Brake disc wheel mount	Steel	440g	4530g
	2x Union joints	Aluminium	70g			13x Typ bolt, washer & nut	S/S	598g	
	4x Brake caliper	Steel	720g						



Material	Weight
Steel	3310g
Stainless Steel (S/S)	598g
Aluminium	70g
Rubber	850g
Brake Fluid	300g
Total Weight	**5.1Kg**

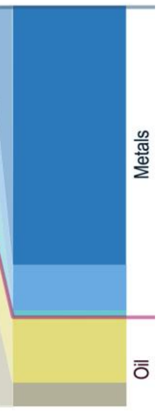


Figure 2.26h, 2015 Aston EcoCar brake system inventory

The brake components displayed in figure 2.26h contain materials with high embodied energy compared to wood.

2015 AstonEcoCar Inventory - Steering

Assembly	Component	Material	Weight	Sub tot	Assembly	Component	Material	Weight	Sub tot
Wheel & Shaft	Steering wheel outer face	Birch ply	320g		Rack	Rack & pinion mechanism	Steel	2050g	
	Steering wheel mid layer	Aluminium	200g			Steering rack arms	Aluminium	155g	
	Steering wheel bracket	Aluminium	220g			2x Mounting brackets	Aluminium	220g	
	Steering column	Aluminium	300g			2x M8 Rod ends	S/S	210g	2635g
	Steering column guide	Aluminium	115g	1155g		6x Typ bolt, washer & nut	S/S	276g	

Figure 2.26i, 2015 Aston EcoCar steering inventory

For the safe operation of the vehicle, systems such as the brakes (shown in figure 2.26h) and steering (shown in 2.26i) contain standardised components. These parts (steering rack, brake cylinders and calipers) are made from steel and aluminium.

Figure 2.27, Materials comparison Graphic displaying the proportion of materials by weight for the 2015 Aston EcoCar, the VW golf Mk.5 (Volkswagen, (2008): p.22,) and the Average European Car (European Commission, 2008: p.53,).

It is recognised that the comparisons made in this study are basic (due to the additional capabilities of the Golf). The Golf study lists the materials used in vague groups.

From figure 2.27 the Aston EcoCar weighs only 14% of the European average. it is also noticeable that the VW Golf Mk.5 is very similar to average European IMPRO-Car - with a high steel and plastic content.

2.5.4.4.4 Life Cycle Inventory Analysis

The full environmental impact results can be seen in the IMPRO-car (European Commission, 2008) and VW Golf Mk.5 (Volkswagen AG, 2008) studies.

	Golf Mk. 5	IMPRO-car	2015 Aston Ecocar
Raw materials	Finite resources - Iron ore, bauxite and Oil comprise the majority of the raw materials.	Finite resources - Iron ore, bauxite and Oil comprise the majority of the raw materials.	41% of the materials are natural fibres - from renewable resources. 59% finite resources. (from figure 2.24)
Manufacture	improvements to the VW production processes (MQB) have reduced the environmental impact of manufacture.	Car manufacturing has become more efficient.	Production of the EcoCar could utilise Modern CNC manufacturing and construction for disassembly.
Use	Spares and repairs include oil and brake fluid. lifespan – 12.5 years (European Commission, 2008).	Spares and repairs include oil and brake fluid. lifespan - 12.5 years (European Commission, 2008).	The lifespan of a wooden car would be reliant on maintenance. A well maintained vehicle such as a wooden boat could have a 30 year lifespan. [1]
End of Life	EU directives that around 95% of materials are recovered. Much material may be recycled to a lower grade	EU directives that around 95% of materials are recovered. Much material may be recycled to a lower grade.	Much of the materials used on the car are biodegradable. The car can be disassembled with materials recovered, and parts reused.

Table 2.2, Generic car, VW Golf and EcoCar lifecycle comparison.

[1] A LCA study conducted by Pommier et al. (2016) suggested a well maintained wooden boat could have a lifespan of over 30 years. A wooden vehicle such as the EcoCar may be exposed to similar weathering and environmental conditions as a wooden boat.

Table 2.2 displays approximate lifecycle information of the IMPROcar, Golf and Aston EcoCar. A change to the materials and manufacture of vehicles could have implications for each stage of the vehicles life cycle – designing vehicles for sustainability may reduce the environmental impact.

<u>Aston EcoCar discussion</u>

Much lighter and more sustainable cars could be manufactured. The Aston EcoCar demonstrates that a vehicle can be built with a significant proportion of biodegradable materials (41% from figure 2.24). The main downside to a wooden car is the short lifespan.

The 41% of biodegradable materials is a success in terms of the sustainable goals of the EcoCar. The high aluminium content keeps the weight of the vehicle down. The high plastic content is a concern, it is proposed that a new design of bodywork using natural fibres is used. In some areas where steel and plastic are used - the axles and brake systems - it is difficult to see where alternatives could be applied. An area for improvement is in the steering and uprights where there is no biodegradable content at all. For future developments, these areas require more natural fibre content.

2.5.4.4.5 Further work - Lifecycle Assessment

A full LCA would compare the VW Golf and average EU car with the EcoCar to ascertain whether the EcoCar design was successful in lowering the environmental impact in categories where a typical car is harmful to the environment. A full lifecycle assessment would reveal the challenges - lifespan, sourcing materials and viability of such an EcoCar. Considering the lifecycle in this manner would provide better understanding of the feasibility of the Aston EcoCar and indicate the direction of development for future Aston EcoCars.

2.6 Materials

2.6.1 Introduction

At present automotive design is “based on metal-intensive uni-body structures” (Mayyas et al., 2012). The materials used in vehicles is set to become more sustainable (Koronis, Silva & Fontul, 2013). A change to how cars are designed by using a holistic approach and through better use of sustainable materials could improve vehicle sustainability.

This section will explore the current research in the field of sustainable materials. The ambiguous nature of 'sustainable materials' is explored and the scope and limitations of these materials is discussed. With a focus on biocomposites, the merits of the sustainable materials which are currently used are considered and the possible range of materials, the applications and where improvements can be made are discussed. This evaluation of the extensive range of natural fibres and polymers will aid in the selection of materials for use in a car.

2.6.2 Sustainable materials

'Sustainable materials' (or ‘ecomaterials’) is a broad term used to describe a material “that has a minimal impact on the environment but offers maximum performance for the required design task. Ecomaterials from the biosphere are easily recycled by decomposing agents in nature, while ecomaterials from the technosphere are those recycled by man-made processes” (Fuad-Luke, 2009: p278).

Due to recyclability, PET (polyethylene terephthalate) can be described as a nutrient in the technical cycle - a sustainable material (Coelho et al., 2011). PET is used in products such as water bottles. “PET has mainly substituted glass as packaging material, but also metal cans” (Welle, 2011). Recycling saves virgin, non-renewable crude oil from being used during manufacture. Recovered PET bottles are processed into flakes and pellets, this “reprocessing is costly and a major concern is to remove all contaminants” (Coelho et al., 2011). Contaminants and additives in recovered PET introduce impurities into the manufacturing process, Braungart & McDonough (2009) suggest that recycled plastics are of lower quality and due to ‘downcycling’ (where the performance of the material is lost during reprocessing) do not remain in a closed loop system this results in plastics eventually being landfilled. (p.56-59). There is also an issue with low recycling rates - In Brazil 58% of PET bottles are recycled with the rest being landfilled (Coelho et al., 2011). This demonstrates some of the challenges associated with developing closed loop systems.

Through LCA it is possible to identify and design out the factors where a product most negatively impacts on the environment (La Rosa et al, 2013). As discussed in section 2.3.3, these factors are important when considering materials in a Cradle to Cradle design process. Materials which do not biodegrade or cannot be recycled multiple times (in closed loop systems) should be avoided. When selecting materials the ‘material and energy consuming systems’ need to be taken into consideration (Ashby, 2011, p.240-242). Where compromises to a closed loop system occur then materials can be selected by matching “the material to the system requirements” (Ashby, 2011, p.240).

In energy consuming systems, the energy represents CO_2, NO_x and SO_x emissions (Ashby, 2011, p.246). It is therefore more sustainable to select materials with low embodied energy over the lifetime of the product (extraction, processing, manufacture, use and disposal).

2.6.3 Composite sustainability

2.6.3.1 Traditional composites

Traditional composites (such as CFRP and GFRP) are increasingly used in the automotive industry – for example carbon fibre is extensively used in the manufacture of the BMW i3 (as discussed in section 2.4). It has been recognised that these materials are not sustainable (La Mantia & Morreale, 2011). Efforts to improve the recyclability of CFRP (Pimenta & Pinho, 2011) and recover energy from CFRP and GFRP through incineration (Witik et al., 2013) have reduced the burden of traditional composites on the environment. These developments lessen the environmental impact of traditional composites, however Braungart and McDonough (2009) describe these ‘less bad’ materials as still being ‘no good’. Composite materials that are sustainable are required (Dicker et al., 2014).

2.6.3.2 Biocomposites

Ho et. al, (2012) have identified biocomposites as “key materials in all industries in coming centuries.” Biocomposites are categorised as composites where “at least one of the constituents is derived from natural resources” (Vilaplana, Strömberg & Karlsson, 2010) and can be categorised into two types:

1. Engineered wood and panel products

Described as a “composite of wood and adhesive” (Thompson, 2013) wood composite panels, such as oriented strand board and plywood are “strong, dimensionally stable and are very efficient uses of wood for structural and engineering applications” (Thompson, 2013). The use of wood composite panels is limited as they are most suitable for large structures and they are challenging to mould into complex 3-dimensional forms.

2. Natural Fibre Reinforced Plastics (NFRP)

“A fiber reinforced polymer (FRP) is a composite material consisting of a polymer matrix imbedded with high-strength fibers” (Ku et al., 2011). Increasingly, natural fibres and bioplastics are being used in applications where traditionally synthetic fibres and crude oil derived plastics (such as GFRP and CFRP) are used (Pickering, Efendy & Le, 2016).

Research into biocomposites is a broad field. Until recently researchers have focused efforts on natural fibres and non-sustainable epoxy resin (Bos, 2004). An LCA study by La Rosa et al (2013) proposes that non-sustainable glass fibres can be replaced with fibres derived from natural resources as a method of decreasing the environmental impact of traditional GFRP composites. A common example of this material substitution is where natural fibres are used to reinforce epoxy resin (Di Landro & Janszen, 2014; Muralidhar, 2013). Focusing on the 'greening' of the material in this way, ignores the application and disposal of the composite. The use of epoxy resin means the composites cannot be recycled (La Rosa et al, 2013) posing a problem with using natural fibre/thermoset composites in a closed loop ‘Cradle to Cradle’ system.

2.6.3.3 Green composites

The amount of natural material content in NFRP varies. An Epoxy/glass and flax composite with less than 30% natural material content (Muralidhar, 2013) and a PLA/bamboo composite with 100% natural material content (Porras & Maranon, 2012) can both be described as biocomposites. The sustainability of different biocomposites varies depending on the constituents used. ’Green composites’ refer to “wholly bio-based composites, that is, both fibers and matrix from renewable resources.” (Zini & Scandola, 2011). Vilaplana, Strömberg & Karlsson (2010) suggests that the environmental impact over the full life cycle should be considered when assessing the sustainability of biocomposite materials.

2.6.3.4 Glass fibre benchmark

“Fiberglass is a lightweight, extremely strong, and robust material. Although strength properties are somewhat lower than carbon fiber” (Ramesh, Palanikumar & Reddy, 2013). In an LCA study conducted by La Rosa et al, (2013) glass fibre is used as a benchmark to compare the environmental impact of hemp as an alternative reinforcement material to glass fibre in a pipe product. Researchers generally use glass fibres and epoxy resin composite as a benchmark for comparison during evaluation of NFRP materials (Di Landro & Janszen, 2014; Scarponi & Massano, 2015; Koronis, Silva & Fontul, 2013), this is because glass fibres are commonly used, non-sustainable, applied in a similar way and are of comparable strength.

2.6.4 Natural fibres

Traditionally natural fibres are farmed for the production of rope, cloth and cord. Natural fibres offer a sustainable alternative to synthetic fibres (glass and carbon) due to “renewability, biodegradability, lower energy requirements for processing, low cost and relatively less wear and tear in processing” (Muralidhar, 2013). Artificially engineered synthetic fibres are more predictable and offer better mechanical properties than natural fibres (Ramesh, Palanikumar & Reddy, 2013).

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Illustration removed for copyright restrictions

Figure 2.28, the classification of different natural fibres - reproduced from Ho et. al. (2012)

Figure 2.28 displays many types and sources of natural fibres. Plant fibres are identified by Pickering, Efendy & Le (2016) as having higher strength and stiffness compared to animal hair fibres. A study by Shah et al. (2014) found that silk fibres are strong but also have a high embodied energy and are expensive to produce. Compared to animal fibres "plant based fibres [are] the most suitable for use in composites with structural requirements" (Pickering, Efendy & Le, 2016). Plant based fibres are produced from several sources, many are farmed commercially or are agricultural by-products (Vaisenen, Das & Tomppo, 2017). Plant based fibres are comprised of a cellulose polymer chain bound together in bundles by the phenolic polymer known as lignin (Maya & Sabu, 2008).

2.6.4.1 Natural fibre properties

Table 2.3, Properties of a range of natural fibres - reproduced from Koronis, Silva & Fontul, (2013).

Table 2.3 displays a range of natural fibre (and glass fibre) properties. Advantages offered by natural fibres include:

- Lower density – as shown in table 2.3, natural fibres are lower in density than glass fibre.
- Lower price – The cost of different natural fibres varies, but is generally lower than glass fibre, as can be seen in table 2.3. Dittenber & GangaRao, (2012) suggest "jute, sisal, kenaf, bamboo, and lower-cost flax or hemp" are best able to compete with glass fibre (based on cost, weight and strength).
- Comparable stiffness – The stiffness of natural fibres can be comparable to glass fibres but is generally lower (Pickering, Efendy & Le, 2016).
- Lower embodied energy - Dicker et al. (2014) reports that the production of natural fibres uses 20% - 55% of the energy used by glass fibres.
- Lower production costs – Lower energy costs and reduced wear on machinery allow manufacturing costs to be reduced by 30% compared to glass fibre (Ahmad et al., 2015)
- Improved sustainability – Natural fibres are biodegradable and carbon neutral. (Xie et al, 2010).
- Low toxicity – Natural fibres present low health risks being "generally non-toxic" (Dicker et al., 2014).
- Insulation – Natural fibres offer good "acoustic and thermal insulation" (Dittenber & GangaRao, 2012).

However, some drawbacks of using natural fibres can be:

- Tensile strength – As shown in table 2.3, flax fibres offer good tensile properties for a natural fibre, however the strength of natural fibres is “generally lower than glass fibre” (Pickering, Efendy & Le, 2016).
- Variable properties – Compared to synthetic fibres “natural fibres have significantly greater variability in their mechanical properties” (Yan, Chouw & Jayarama, 2014), this can be attributed to growing conditions, time of harvest and damage during fibre processing (Pickering, Efendy & Le, 2016).
- Temperature sensitivity - Temperatures over 200°C can destroy the structure of plant fibres (Summerscales, et al., 2010). This limits the use of thermoplastics with high melt temperatures and common processes such as post curing.
- Durability - Natural fibres suffer from low durability (Yan, Chouw & Jayarama, 2014) the structures are susceptible to degradation and water absorption (Ahmad et al., 2015).
- Raw material processing - Natural fibres require “relatively excessive processing requirements” (Yan, Chouw & Jayarama, 2014) compared to synthetic fibres.
- Limited supply – Dicker et al., (2014) suggest that predicted growth in natural fibre demand could affect availability.

2.6.4.2 Environmental impact of natural fibres

The use of natural fibres is not without environmental impact, growing crops puts pressure on land and resources (Broeren et al., 2017). Crops need to be watered - a resource which has become scarce (Pearce, 2006). An LCA study conducted by Deng & Tian (2015) suggests that the different methods used in China and France to farm flax effects the environmental impact of flax crops. Farming of fibre crops like flax is also in direct competition with food crops in terms of ‘agricultural land occupation’ (Deng & Tian 2015). An advantage of sisal is that it is grown in arid conditions and so does not require irrigation and does not compete with food crops (Terrapon-Pfaff, Fischedick & Monheim, 2012).

To produce a sisal FRP composite in the UK, the sisal would need to be transported from places such as Brazil, East Africa or China (Broeren et al., 2017). Vilaplana Strömberg & Karlsson (2010) suggest that biocomposites should be manufactured using local materials and resources - promoting sustainable development and removing the environmental impacts (and costs) of transportation. Local sourcing of materials is also important for biosecurity and biodiversity (Braungart & McDonough, 2009, p.125). These different environmental factors need to be taken into consideration when selecting natural fibres.

2.6.4.3 Wood Fibres

A common use of wood fibres in NFRP is the use of wood flours – fibrous particles of various sizes produced from processing timber (Hietala et al., 2011). Compared to other natural fibres “wood is cheaper and simpler to handle during processing.” (Muller et al.,2014). In a study on the effect of aspect ratio (length of fibre/width of fibre) and surface treatments on wood polymer composites Hietala et al. (2011) found that longer fibres (less than 1mm in length) increase flexural strength and impact properties and surface treatments increase tensile strength.

The use of longer wood fibres in FRP is limited to issues associated with cost and also processing longer, bulky fibres. (Hietala et al., 2011).

2.6.5 Bioplastics

Bioplastics can be defined as polymer materials “consisting of units that are entirely or in part derived from biomass” (Vilaplana, Strömberg & Karlsson, 2010). Many bio-resins sold commercially are a combination of bio-based and crude oil material. The non-sustainable proportion is used to improve processing and mechanical properties. (Soroudi & Jakubowicz, 2013), these 'blends' can be as high as 50%. Figure 2.29 displays a range of bioplastics and their sources.

Figure 2.29, Classification of bioplastics based on their production routes – reproduced from Reddy et al. (2013).

Bioplastics displayed in figure 2.29 have been used as matrix material in sustainable composite studies, for example thermoplastics like PLA (polylactictide) (Yu et al., 2010), PBS (polybutylene succinate) (Lee et al., 2005) and PHBV (polyhydroxybutyrate-co-valerate) (singh, mohanty & misra, 2010) as well as thermosets such as bio-epoxy resin (Di Landro & Janszen 2014)

The choice of matrix material in FRP is critical “in determining the overall properties of a composite” (Thakur et al., 2014). Table 2.4 displays the properties of a range of polymers used in NFRP composites including polyesteramide (PEA) and soy protein isolate (SPI) (Yan, Chouw & Jayarama, 2014).

Table 2.4, Properties of a range of polymers - reproduced from Yan, Chouw & Jayarama (2014).

From table 2.4 it can be observed that biodegradable polymers have lower tensile strength, greater elongation and are temperature sensitive when compared to ‘typical thermoset polymers’.

2.6.5.1 Bio-epoxy thermosets

Epoxy resin is a thermoset plastic with excellent properties as a matrix material for composites - good adhesion, mechanical properties, low moisture content, little shrinkage, and processing ease (Faruk et al., 2012). Epoxy resin systems described as ‘Bio-epoxy’ are a blend of bio-sourced and crude oil based material. An increase in bio-based content of epoxy resins have improved the sustainability credentials of epoxy (Di Landro & Janszen, 2014), the biological content reduces the embodied energy compared to epoxy (La Rosa et al., 2014). A study into biocomposites using bio-epoxy by Barari et al. (2016) used a commercially available bio-epoxy resin - Super Sap, that has 50% bio-derived content.

Composite materials using a Bio-epoxy matrix still contain a significant percentage of non-renewable crude oil material. Corona et al., (2015) describe the “environmental impact profiles” of Bio-epoxy as of the “same magnitude” as synthetic epoxy. A Bio-epoxy FRP composite is not biodegradable and poses the same EoL issues as traditional composites (as discussed in section 2.6.4.1). Bio-epoxy cannot be reintroduced into closed loop systems, this limits their selection as a ‘sustainable material’ for a vehicle.

2.6.5.2 Thermoplastic biopolymers

Biodegradable, bio-based and renewable thermoplastics are alternative candidates for the resin matrix in a sustainable composite. There is a variety of existing bio-based thremoplastics, many of these may be unsuitable for use as matrix materials in structural composites: Some are not widely available, others like bio-based polyethylene do not biodegrade, and biopolymers such as soy protein isolate (SPI) have low mechanical strength (Fernandez-Espada et al., 2016). Another barrier to adoption of bio-polymers is cost, “most biodegradable resins currently cost three to five times” (Yan et al. 2014) commonly used crude oil based polymers (such as PP).

To select a sustainable polymer matrix for a NFRP composite the following commonly available, bio-based polymers are under consideration for use in the construction of a sustainable car component:

1. Starch (TPS)

Thermoplastic starch (TPS) is a biopolymer sourced from various plants including cereal crops, corn, potato, tapioca, and pea. TPS is biodegradable and is generally comprised of 20–25% amylose and 75–80% amylopectin (Zhang, Rempel & Liu, 2014). TPS is hydrophilic and has low mechanical properties – having a tensile strength of less than 20 MPa (Zhang, Rempel & Liu, 2014). De Campos et al., (2013) have explored blending other biopolymers such as polycaprolactone (PCL) to improve the mechanical properties of TPS in a sisal composite.

2. Cellulose

All plants contain structures composed of cellulose crystals forming stiff rod like structures in cell walls, these microfibrils are made up of chains of anhydrosglucose polymers (Pandey, et al, 2011). Cellulose is a renewable, biodegradable and abundant bioplastic (Huber et al., 2011), with 1.5×10^{12} tonnes produced annually it is the most common organic polymer (Khalil, Bhat, & Yusra, 2012). The use of these natural thermoplastics goes back to celluloid films in the early 20th century. Appendix A contains the technical information for a cellulose bioplastic with a tensile strength of 70MPa.

3. Polylactide (PLA)

Polylactide (PLA) is a naturally sourced thermoplastic polymer produced from lactic acid by fermentation of raw materials like corn, sugar cane and potato (Frone et al., 2013). Bajpai, Sing & Madaan, (2014) describe PLA as a “fully sustainable polymer” as it is renewable and biodegradable. PLA is produced in large quantities with over 140,000 tonnes of PLA produced annually (Mukherjee & Kao, 2011) and can be processed using traditional manufacturing technologies at temperatures below 200°C (Porras & mananon 2012). PLA has similar strength and stiffness properties to those of PE, PP and PET (Hamad et al, 2014) and possesses the highest tensile strength (60MPa) of the bio-polymers listed in table 2.4. Drawbacks to the use of PLA in biocomposites include high cost and brittleness (Mukherjee & Kao, 2011).

2.6.5.3 Selection of a polymer matrix for NFRP

Significant differences between bio-epoxy and bio-based thermoplastics matrices are set out in the table 2.5.

	Thermoplastic biopolymers	**Bio-epoxy resin**
Type	Thermoplastic	Thermoset
Processing	Hot press, injection moulding at temperatures of 150°C to 200°C	Vacuum infusion, RTM
Sustainability	Can be completely bio-based and biodegradable	Crude oil source, not currently recycled or biodegradable
Absorption	Susceptible to degradation	Resistant to water absorption
Mechanical properties	PLA possesses similar characteristics to PP. Comparatively less rigid and lower tensile strength	High tensile strength, very rigid
Process	More than one heat cycle can be made.	1 stage process of adding catalyst

Table 2.5, plastics comparison.

Table 2.5 provides a general comparison as different plastics, blends, and manufacturing methods change the resulting material characteristics. Thermoplastic biopolymers offer sustainability advantages over epoxy resins, however of bio-epoxy offers better mechanical performance and low processing temperature. “Matrix selection is limited by the temperature at which natural fibres degrade” (Pickering, Efendy & Le, 2016), materials required for the construction of car components will need selecting based on mechanical properties and performance characteristics as well as sustainability.

2.6.6 Development of new biocomposites

A broad range research has been carried out to critically consider the relevant methods and techniques used to develop new composites. Many different bioplastics and various natural fibres have been paired together to create novel materials, presenting a challenge when selecting the most appropriate fibre/polymer pairing. Reviewing this will aid in establishing an approach for further research. Along with the selection of fibre and matrix other factors affecting the mechanical performance of NFRP composites include interfacial strength, fibre dispersion, fibre orientation, manufacturing process, aspect ratio and porosity. (Pickering, Efendy & Le, 2016)

Fibre and matrix interface

The interface between the fibre and polymer matrix is critical to the performance of FRP composites (Yu et al., 2010). Hydrophilic plant fibres and hydrophobic polymers can display "limited interaction… leading to poor interfacial bonding limiting mechanical performance as well as low moisture resistance" (Pickering, Efendy & Le, 2016). Methods to improve fibre and matrix interface include:

- Coupling agents - "A coupling agent is a chemical that functions at the interface to create a chemical bridge between the reinforcement and matrix" (Xie et al., 2010).
- Surface treatments - Poor adhesion of the polymer matrix to the fibres can be solved by surface treatments such as bleaching or alkaline treatments (Yu et al., 2010) "Alkaline treatments increase the surface roughness that results in a better mechanical interlocking" (Tran Bénézet & Bergeret, 2014), using NaOH can increase the strength of flax/epoxy composites by 30% (Van de Weyenberg et al. 2006).

These chemical treatments also increase the complexity and cost of processing (La Mantia & Morreale, 2011).

Fibre dispersion

Fibre dispersion has been identified by Pickering, Efendy & Le (2016) as important for short fibre NFRP composites. An even distribution of fibres within the composite is desirable as there will be fewer weak points and voids, thus providing a more predictable material.

Fibre orientation

Orientation and alignment of fibres parallel to the direction of loading is known to improve tensile properties of NFRP composites (Pickering, Efendy & Le, 2016). Many natural fibres are woven into fabrics as this aligns fibres and allows for an efficient process (Muralidhar, 2013). The twisted strands in woven fabrics can weaken the composite structure as the twisted fibres are always pulled 'off axis' (Liu & Hughes, 2008).

Processing

Biocomposites are manufactured using a range of standard processing methods including "resin transfer moulding (RTM), vacuum infusion, compression moulding, direct extrusion, compounding and injection moulding" (Ho et al., 2012). Extrusion followed by injection or compression moulding are typical techniques for manufacturing green composites (La Mantia & Morreale, 2011). Injection moulding is only suitable for short fibres, whereas longer fibres can be used in compression moulding (Ho et al., 2012).

Processing parameters such as "viscosity, pressure, holding time and temperature" (Pickering, Efendy & Le, 2016) have a critical effect on the mechanical properties of composites during compression moulding. Hot processing techniques expose natural fibres to temperatures where thermal degradation may occur (200°C) (Xie et al., 2010). Pickering, Efendy & Le (2016) report that processing biocomposites by film stacking "limits natural fibre degradation due to involvement of only one temperature cycle" during compression moulding.

Aspect ratio

An additional factor influencing the mechanical property of a composite is the aspect ratio - length/diameter – of the fibres (Pickering, Efendy & Le, 2016). Muller et al. (2014) have studied the aspect ratio of short wood fibres (less than 1mm in length) in injection moulded STP, finding that longer fibres improve the strength and stiffness of the composite. A study of composites with longer non-aligned sisal and banana fibres (5-20mm) by Venkateshwaran et al. (2011) found that there is an optimal fibre size. Most green composite research concern short natural fibres. (Porras & maranon, 2012)

Longer fibres such as woven and continuous have been shown to improve flexural strength and load bearing properties of composites (Jawaida, Khalil & Bakar, 2011). Biocomposites containing long fibres could be exploited to "manufacture composites for structural applications." (Porras & maranon, 2012)

Porosity

Cavities can form within a composite during processing caused by pockets of air, hollow features within fibres and poor wettability (Pickering, Efendy & Le, 2016). Faruk et al. (2012) reports that alkaline surface treatments reduce porosity by improving fibre wettability. Porosity can increase with fibre content and reduces the mechanical performance of the composite (Kabir et al., 2012).

2.6.6.1 Durability

Absorption of moisture by natural fibres weakens matrix/fibre adhesion (Xie et al., 2010), this drastically reduces the mechanical properties of the composite over time (Assarar et al. 2010). Water absorption over time is a barrier for bio-composites use in structural applications. Another concern is fungus and bacterial growth reducing the mechanical properties of the composite (Dicker et al., 2014). “Accurately predicting the lifetime of green composites is a major challenge to their widespread implementation” (Dicker et al., 2014). Protective coatings (such as paint or varnish) could be applied to the finished product (Azwa, et al,2013).

2.6.7 Biocomposite end of life scenario

Careful management on biocomposite waste is important (Piemonte, 2011). To achieve conservation of materials and energy in within a closed loop system the EoL scenario for biocomposites consist of recycling, composting and incineration (Vilaplana, Strömberg & Karlsson, 2010).

Recycling

Recycling the material at the end of the biocomposite product’s life “is the optimum way to minimize the environmental impacts.” (La Mantia & Morreale, 2011). Recycling prolongs the lifetime of the material - preserving the embodied energy and the demand for virgin materials (Piemonte, 2011).

Composting

“Biodegradation is a desired quality since it prevents accumulation of solid waste, which is a major consideration for composite materials in general” (Dicker et al., 2014) Most biodegradable bio-polymers “degrade through enzymatic reactions in suitable environments (typically, humid)” (La Mantia & Morreale, 2011). The various EU and US standards for biodegradability have been summarised by Summerscales et al. (2010) to describe biodegradation as: degradation of over 90% in 180 days, disintegration of over 90% in 3 months and an absence of hazardous chemicals causing ecotoxicity.

The rate of biodegradation is dependent on factors such as the exposed area, temperature, moisture levels and the chemical composition of the material (Aranguren, González & Mosiewicki, 2012). Biocomposites using surface treatments to improve the fibre/matrix interface have been shown to inhibit biodegradation (Mukherjee & Kao, 2011).

Incineration

“Incineration should be considered as a final approach to partially recover the energetic value of the biocomposites” (Vilaplana, Strömberg & Karlsson, 2010).

2.6.8 Further research

Faruk et al. (2012) describes the research effort to develop biocomposites for load bearing applications as ‘significant’. The use and lifetime of biocomposites in structural applications has also been recognised as an area for further development by Vilaplana, Strömberg & Karlsson (2010).

2.6.9 Conclusion

La Mantia & Morreale (2011) identify that “the role of automotive industry in this [sustainable composites] field is of primary importance”.

Individual types of natural fibres offer different strengths and weaknesses regarding their application in FRP. Generalisations can be made about the characteristics of natural fibres compared to glass fibre; they are not quite as strong and they absorb water but they are also less dense and cost less.

For the right combination of fibre and polymer a balance therefore must be found between the sourcing, processing, sustainability and manufacture of the composite material. Raw materials for use in NFRP “should be obtained from renewable sources and the processing of the composites should be based on sustainable practices. The concept ‘Think global, act local’ should be adapted as an essential mindset” (Vaisenen, Das & Tomppo, 2017).

Currently, studies such as (Scarponi & Messano, 2015) suggest sustainable materials can be substituted for GFRP. Rather than considering biocomposites as suitable for a straight swap of synthetic materials, the design of the product could be aligned with the properties of the material. Biocomposite materials could be formulated for specific purposes and applied in such a manner that the product will perform.

A green composite consisting of a biodegradable bio-plastic and a natural fibre could be used to make a composite for structural component in a vehicle. The production of such a material may require:

a) Completely bio-derived from sources that do not compete with food crops.
b) Require as little energy usage during processing from a raw material.

2.7 Literature review conclusions

The automotive industry is a global political, socio-economic entity. Although environmental challenges have been recognised, there is no evidence that the main car manufacturers have a desire to change the way they make cars. Further research is needed to determine the sustainability of the car industry in the next 15-20 years.

Environmental design is a complex issue. To design an ecological car, the lifecycle needs careful attention. A holistic strategy has been identified as a method to improve the sustainability of cars (Nunes & Bennet, 2010). The Cradle to Cradle approach can be used to achieve the most closed loop system.

To improve fuel efficiency, car manufacturers produce lighter diesel cars. Weight reductions are achieved by introducing materials to replace steel such as aluminium and CFRP. Current manufacturing innovations to improve sustainability include EVs and hybrid vehicles. These technologies reduce exhaust emissions but fail to consider the impact of the car as a whole.

The VW Golf is a typical example of a car. Analysis of the VW environmental strategy reveals that the fundamental product has not changed. Over 40 years the Golf remains a vehicle constructed of steel, powered by petrol. The Aston EcoCar presents an alternative 'wooden car' philosophy. This uses sustainable design principles to build an environmentally focused vehicle. Comparisons between the Golf and the EcoCar expose the amount of unsustainable resources used in manufacturing the Golf.

Researchers can aid the development of a more sustainable model for car manufacture by formulating materials to perform in a specific role. A viable bio-composite for structural use in cars has not yet been found. From the literature, this is a case of car companies wanting to replace materials as like-for-like. A Cradle to Cradle approach will allow the 'the car' to be redesigned and sustainable materials used in a manner that compliments the material properties.

A new sustainable, yet also structural material is needed for manufacturing cars. In developing a bio-plastic/natural fibre composite there is a large amount of work to be done in creating a composite with the desired strength, stiffness and durability. A new methodology is required to combine the materials selection with the design and manufacture of a product.

Chapter 3: Methodology

3.1 Project review

This research project aims to address how the motor car can be developed to be more environmentally sustainable.

Sustainability is a key issue for manufacturing globally. Through analysis of the mechanisms which drive the automotive industry, it can be observed that the automotive industry could improve sustainability. There are several examples where traditional 'steel bodied motor cars' have been replaced with a less damaging alternatives. It is believed however that these like-for-like efforts are unsuccessful, and that personal transport in cars needs to be 'decoupled'. The Aston EcoCar demonstrates a different model for urban vehicle design. Through a holistic approach, this sustainable model can be developed further with the ultimate goal being the creation of a vehicle with minimal impact on the environment.

3.2 Scope of the research project

The design philosophy of the Aston EcoCar has been successful in introducing sustainable design and biodegradable materials into a vehicle. There are however limitations to both the materials used and the areas they have been applied to. There is a need for a sustainable, structural material that can be moulded into complex 3-dimentional curves.

The scope of the research project will be to investigate the application of sustainable composites to a structural part of a sustainable vehicle.

3.3 Approach

The primary focus of this research employs a holistic strategy to investigate how sustainable materials can be applied to vehicles. The test bed for implementing the research is the Aston EcoCar. The EcoCar is a project where the challenges of designing sustainable components can be applied to a sustainable test vehicle that will undergo rigorous evaluation at an international race event for environmental car concepts - the Shell Ecomarathon competition. This provides a suitable end product for the research.

3.3.1 Design goal

The broad goal of the project is to achieve sustainability for the design of a structural vehicle component. This project uses Cradle to Cradle (Braungart & McDonough, 2009) as the chosen approach.

Cradle to cradle is a concept where the manufacture and consumption of products is reconsidered. The traditional, industrial cradle to grave attitude, was conceived at a time when natural resources were considered inexhaustible, this is now known to be incorrect, yet industry continues as though supplies are not running out. Current environmental practise focusing on improving products to be "less bad is no good" (Braungart & McDonough, 2009: p.45-67). Reducing the damage, still does not improve the situation. In order to improve the situation, Braungart and McDonough (2009) introduce the concept of "waste equals food" (p.92), an idea that manufactured products consumed by people create the "two kinds of material flows on the planet… biological and technical nutrients" (Braungart & McDonough, 2009: p93). Harmful substances are cut out of manufacture, the quality of recycled materials is maintained (technical nutrients) and materials returned to the environment do not damage it (biological nutrients). This holistic, 'closed loop' Cradle to Cradle approach will be used to rethink how car components are made. The materials used in this research project should be either technical nutrients or biological nutrients and these materials need to be recoverable to reintroduce into closed loop systems at the end of the products lifespan.

One of the principles used by the Cradle to Cradle Innovation Institute (2016) is “Eliminate the concept of waste” – waste equals food. The other principles “use renewable energy” and “celebrate diversity” may also be reflected in the design of products. Additionally, reducing the quantity of materials and the embodied energy over the product lifecycle lessens the environmental impact of the product.

3.3.2 Holistic strategy

The overall aim of the project is to develop a strategy for sustainable product design focusing on sustainable materials, the design process and the manufactured product. This is achieved by using a holistic approach to the research project. Within this strategy, various materials development, design techniques and manufacturing experiments comprise the data collection for the research.

To achieve the sustainable goal, a combination of established methods are used to achieve a final product that considers the material, design and manufacture.

The holistic structure used is based on the Roozenburg and Eekels 'model of reasoning' set out in figure 3.1.

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Figure 3.1, Model of reasoning by designers. (Roozenburg & Eekels, 1995)

The ‘model of reasoning’ methodology illustrated in figure 3.1 consists of a holistic strategy where by "developing a product proceeds from right to left" (Van Boeijen & Daalhuizen, 2010: p.10). This method can be used for the holistic strategy in this research as it includes material, design, manufacture, and use. This structure fits elements that are to be experimented with during this project. For this research project the Roozenburg and Eekels' model is modified so that the materials, form and conditions of use are informed by each other. In this way, the intensive properties can be used to formulate a material to suit the function and conditions of use. Figure 3.2 displays a modified model of reasoning:

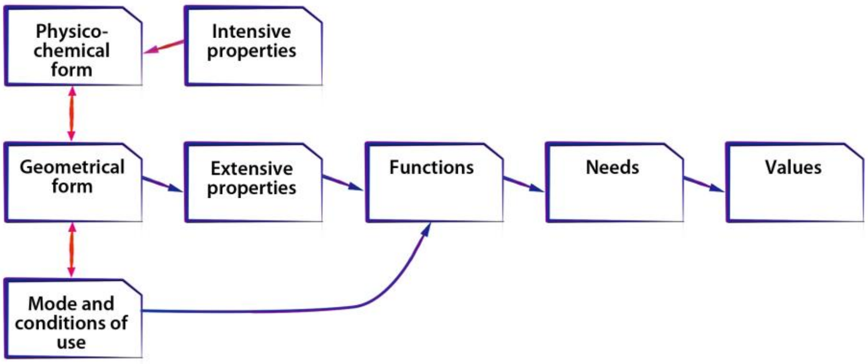

Figure 3.2, Modified model of reasoning

The difference between the 'model of reasoning' method in figure 3.1 and the modified version in figure 3.2 is that the desirable material properties are not simply matched to an existing material. Where no suitable material is available, one needs to be created. In order to achieve sustainability (Cradle to Cradle) in this new method, the desired properties inform the design of a material. Formulating a new material with the desired sustainable properties that suits the design goal.

To develop a holistic strategy based on the model of reasoning by designers, two studies are conducted:

1. Pilot study: A trial of the general strategy, applied to the chassis of the 2014 Aston EcoCar - described in section 4. This first 'proof of concept' study is used to assess viability and inform improvements to the overall approach (methods listed in section 3.4).
2. Main study - Detailed examination of the holistic approach to sustainable design - described in section 5. The main study consists of the design and manufacture of a wishbone for the 2016 Aston EcoCar (methods listed in section 3.5).

3.4 Pilot study methods

The structure of the pilot study is set out in figure 3.3. Materials investigation involves selecting and testing of materials and material processes. A design and manufacture process then applies the materials to a structural vehicle component on the Aston EcoCar. The component is then evaluated on the vehicle at the SEM competition.

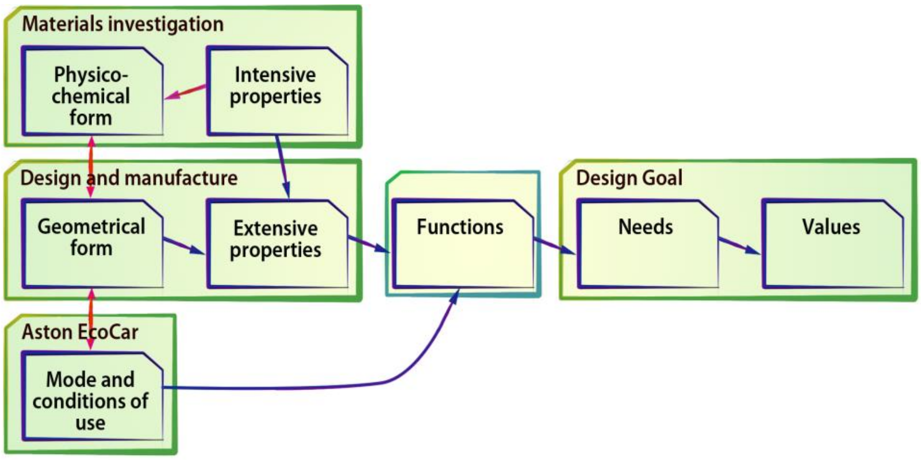

Figure 3.3, Pilot study structure

3.4.1 Materials investigation

<u>Materials selection</u>

To begin the Pilot study a suitable sustainable material is needed. The review of literature suggests a number of sustainable material options. As this is the start point of the pilot study, the design and manufacturing process of the final product is yet to be defined. The material properties are therefore intangible and subjective. A materials specification is drawn up to select materials based on their intensive properties. The prospective natural fibre and resin matrix material is selected based on the sustainability, performance and properties desired in the final product.

<u>Materials investigation</u>

A natural fibre (birch wood veneer) and bioplastic (Biome HT90 cellulose bioplastic) were selected as promising candidates to develop. An initial assessment of the usefulness of such a material is then required. The general material properties need to be found and possible manufacturing processes investigated in order to inform the design of a product.

The materials investigation consists of the following methods of enquiry:

- Basic hot press processing of the materials - as used to process materials to compare GFRP to natural fibres (Wambua, et al. 2003).
- Tensile testing - tensile strength is a key materials characteristic and easily comparable to materials in other studies (Wambua, et al. 2003) and (Kamath, et al. 2005)

- Film pressing - parameter variation similar to methods used by Bahnu Kiran, et. al. (2011).

Basic hot press processing. - Alternate layers of birch veneer and Biome HT90 sheet are stacked into a cavity and then heat and pressure are applied using a water cooled 25 Tonne hot press (essentially creating a plywood). The results of which are inspected visually for layer cohesion and cavities.

Tensile testing. - Biome and veneer layers are stacked into a cavity (in a similar method to the previous step) for a tensile sample specified by ISO 527. A single veneer/Biome sample was produced and compared to a plywood sample of the same thickness. An increased number of samples would provide consistent results, however this test generates a broad outcome useful in context of the pilot study.

Film pressing. - As a limited investigation into processing parameters two samples were prepared using layers of films and veneers and pressed into 'films'. Films consist of pressing a material between the press beds - without the constraints of a mould.

3.4.3 Design and manufacture application.

The design and manufacture of the 2014 Aston EcoCar applies the knowledge gained from the materials investigation. This is conducted in the following manner:

- Design a veneer/Biome part for the 2014 Aston EcoCar.
- Manufacture a component using the veneer/Biome

Design for the 2014 EcoCar. - The chassis design for the 2014 EcoCar is of a plywood and balsa construction. The veneer/Biome is used in a supporting structural element. Designing this part is achieved using a combination of prototyping and CAD modelling. The properties of the material and how it may be formed during moulding is considered during the design process.

Application of material onto 2014 EcoCar. - A 'proof of concept' sample section of the design is manufactured and applied to the vehicle. The stress and loading of the material are not considered during this initial pilot study.

3.4.4 Evaluating the pilot study

The assessment of the pilot study is conducted at the 2014 SEM. The manufactured part is fitted to the Aston EcoCar to prove principle. SEM perform a technical inspection assessing the vehicles roadworthiness. The performance of the EcoCar (and thus the material and design process) is then tested on the SEM track.

3.4.5 Holistic methodology review

The pilot study provides a precursor to a much larger study. This first 'proof of concept' study is used to assess the viability of the holistic method. An evaluation of the pilot study (detailed in section 4.5) revealed the way the pilot study has been structured generated a flawed product:

- The scale of the application was over ambitious,
- The intricacies of designing with the veneer/Biome was not fully appreciated.
- The limitations of the processing equipment were not fully understood,
- The capabilities of the material did not allow parts of the design to be manufactured.

Conducting this rehearsal of the holistic design method allows the method to evolve. The pilot study:

- Proves that the application of veneer/Biome to the EcoCar is feasible.
- Demonstrates the potential of the material,
- Provides technical knowledge of the material and manufacture.

The materials, design and manufacture of the product need to be better considered in order to develop the holistic sustainable design method. The pilot study has provided a wealth of information regarding the application of the holistic strategy.

3.5 Main study methods

The results of the pilot study provide the trial run of the holistic methodology needed in order to make a critical assessment of the process. From the results of the pilot study, a full study is performed. The 'model of reasoning' used in the pilot study provides a useful foundation, however, for developing a material together with designing a product, an approach that better connects the material with the design and manufacture is required.

M/D/M holistic methodology

A holistic methodology incorporating materials, design and manufacture is applied as follows:

Design goals – The needs and values of the project are established (as stated for this project in section 3.3.1). These can then be applied to develop a functional product.

Materials – Materials are selected and investigated with a view to design and manufacture a product in line with the design goals.

Design – Using product design methods, the material is used to develop a design concept

Manufacture – The materials and design investigations are used to manufacture a functional product.

Functional product – A prototype manufactured product is tested to check the design goals have been achieved.

This approach is illustrated in figure 3.4:

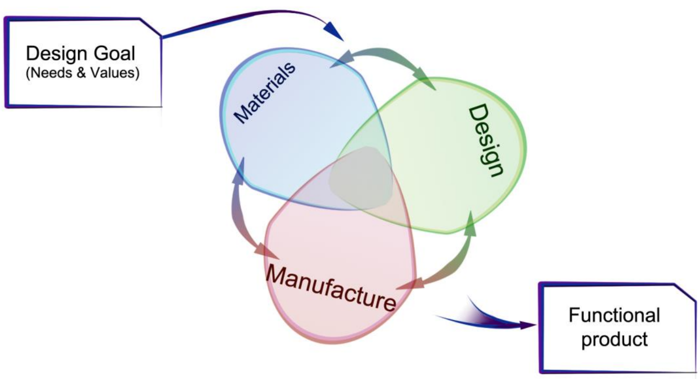

Figure 3.4, Materials/design/manufacture (M/D/M) strategy

This approach, although less defined than the 'model of reasoning' better describes the process created during this project. In order to conduct an in depth examination, the material, design and manufacture of a component for the 2016 EcoCar is completed using this holistic M/D/M approach.

The success of the design and material (and the holistic M/D/M process) created for this research is assessed using the final product tested on the 2016 EcoCar. Various materials and design techniques are performed throughout the process in an effort to produce a functional product meeting the needs and values of the design goal - the most sustainable design.

3.5.1 Materials Development

The pilot study revealed that further investigation of the veneer/Biome composite is required in order to successfully mould a component. These additional experiments are performed in sufficient detail to inform where and how the material is applied and also the parameters for the manufacturing process. This research is concerned with the holistic approach to sustainable design. The traditional materials science approach such as the one used by Van de Weyenberg (2005) are limited in scope and may not sufficiently consider the application of the material to a product. The material is to be investigated to a point where a product can be designed and manufactured using the material under development.

3.5.1.1 Benchmarking

The result of the final material used will be a product of this materials development stage. The material properties of the final Veneer/Biome composite used will be measured against properties of comparable materials. The benchmarks chosen are: the non-reinforced bioplastic - Biome HT90; a wood fibre composite – birch plywood; a standard synthetic composite - GFRP and a commercial Flax/PLA biocomposite - Biotex.

3.5.1.2 Characterisation experiments

Following on from the materials investigation conducted in chapter 4, further experimentation of using hot press processing on wood veneer and bioplastic is carried out in the main study (chapter 5). A series of experiments are conducted to better understand the relationship between the process and the resulting material. Experimentation using film pressing is conducted to examine the effect of heat and pressure on the separation of fibres. The scalability and mouldability of the material is then investigated to establish design and manufacturing parameters - directed by published literature (discussed in section 2.6 of the literature review). Each investigation is built on the previous results, developing an understanding of the materials character, thus informing the optimised manufacture of a veneer and Biome composite. The experiments are targeted towards understanding the manufacturing capabilities, and the design constraints.

The characterisation studies consist of pressing small films (allowing a range of pressures to be used) to identify processing characteristics in three experiments:

1. layering of the birch veneer and Biome plastic.
2. processing variables (temperature and pressure).
3. Investigating sample size and shape (small scale).

3.5.1.3 Manufacturing experiments

It is important to then relate the samples in the characterisation experiments to a design and production method. Conducting further experiments demonstrates how the material might be pressed into a component for the Aston EcoCar. Using the knowledge gained from characterisation experiments and the pilot study, two experiments are performed to identify:

1. The scalability of the films.
2. The minimum radius moulded without breaking the fibres.

3.5.2 Design strategy

Using the gathered materials knowledge, it can now be applied to the EcoCar. It is important that a feasible area of study is chosen to demonstrate the materials/design/manufacture process. The area of application is carefully chosen based on:

- The processing constraints - ensuring the part can be manufactured.
- Suitability of application - ensuring the material is applied where needed.
- The impact of the study - maximising research results.

To create the car component a product design process was followed. A modified version (using suitable design tools) of a standard process displayed in figure 3.5 was used.

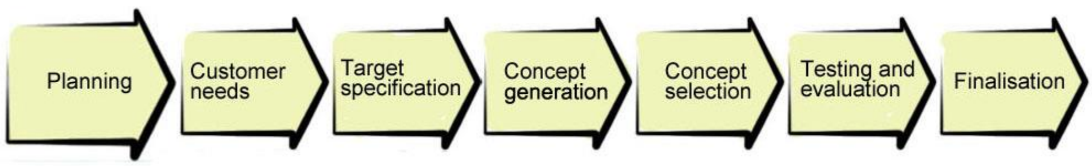

Figure 3.5, Generic product design process (Ulrich & Eppinger, 2008:p.9)

The scope of the project is outlined by stating a project brief with clear aims and objectives.

Benchmarking

Evaluating the design is key to understanding whether the material development and manufacturing process succeeds. The design of the new product is therefore benchmarked against:

- Previous EcoCar components
- Commercial automotive components

The benchmarks are measured in terms of materials, components and performance. These benchmark comparisons also provide guidance on how much progress is being made with regard to the design goal - sustainability (Cradle to Cradle).

Forces modelling

The forces acting on the part are modelled based on the loading of the car at the speeds travelled. Along with the materials development, this provides useful data for testing the veneer/Biome component.

Needs and specification

A needs analysis (Ulrich & Eppinger, 2008: p.65) and a target specification (Ulrich & Eppinger, 2008: p.71) provide the basis for the design of the component. The benchmarks and forces modelling provide the technical details for defining the needs and specification. Going forward, they provide a direction for the product in development.

Concept generation and selection

A number of concepts are drawn up. It is important to fully explore the possibilities in answering the brief, and meeting the needs. This process can be iterative (Lidwell, Holden & Butler, 2010: p.142) and involve prototyping (Lidwell, Holden & Butler, 2010: p.194). The concepts are then scored against the needs, using the benchmarks as a comparison.

A smaller range of concepts is evaluated further, and through a process of elimination, a final concept is decided upon, which (using the concepts generated) best meets the criteria for the product.

3.5.3 Manufacture

The final design concept now needs to be developed for manufacture. This is achieved by:

- Sourcing fixtures and fittings
- Developing a CAD model based on the final design, the material development and the target specification.

Tooling is required to manufacture the component, the CAD model enables technical drawings to be sent for machining. The manufacturing process is dictated by the development of the material - in this case hot press forming. The design needs to be properly married to both the material and the manufacturing process.

The 5 stage process illustrated in figure 3.6 is developed based on the pilot study and the materials development. Experimentation of the manufacturing compared 2 processing methods.

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Figure 3.6 Pressing process

To evaluate the success of the strategies, the final product is tested in each of the materials development, product design and manufacturing stages. The manufactured part is fitted to the Aston EcoCar and tested at the SEM to prove principle. The SEM performs a technical inspection assessing the vehicles roadworthiness.

The success of the M/D/M methodology can be measured by the performance of the component at SEM. Analysis of the material developed, the design of the product and the manufacturing process indicate the success of the individual elements. The key to the process is in how each piece of the process informs the others. The design goal is used to guide the project towards the end product. The methods used during the main study can be described by the M/D/M strategy diagram in figure 3.7.

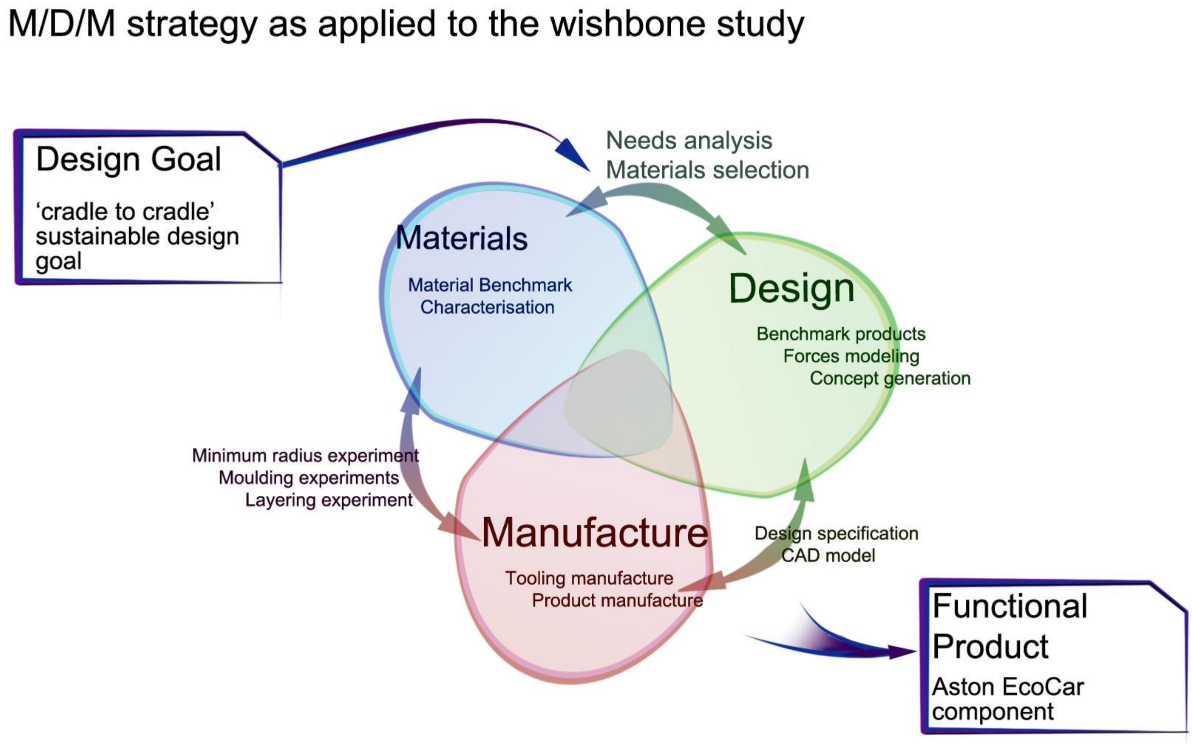

Figure 3.7, Holistic M/D/M design methodology as applied to the main research study.

Conventional methods (such as a design specification and benchmarking) are used, but are structured so that the material development and design process inform the manufacture. Researching a material in this manner produces a focused investigation with practical outcomes.

3.6 Alternative Methods

The methods used were chosen for their familiarity, suitability to the task and best use of the time and resources available. At each stage of the process a number of alternative methodologies could be used.

The chosen M/D/M methodology was suited to the task of producing a prototype part, manufactured using the formulated material (the stated goals). Had the goal of the study been different, other approaches would have been used. The research may have been the focus of a narrower study - for instance a materials development study to improve the veneer/Biome properties. A wider approach to the research could have been adopted encompassing the production of an entire EcoCar.

3.6.1 Sustainable design goal

<u>Ecological design (Van der Ryn & Cowan 2007)</u>

Van der Ryn and Cowan introduce five principles to ecological design:

1. Solutions grow from place,
2. Ecological accounting informs design,
3. Design with nature,
4. Everyone is a designer,
5. Make nature visible.

Van der Ryn and Cowan’s philosophy resembles Cradle to Cradle, principle 3 - designing with nature - discusses the benefits of "waste equals food" (Van der Ryn &Cowan 2007 p.127). Principle 2 - Ecological accounting - discusses the use of LCA. The first principle is about localism and diversity, adapting to local surroundings and enriching the local ecosystem.

Whilst raising valid points, the ardent environmentalist direction of the strategy is a draw back. Some of Ecological Design's broad aims are unrealistic, the book advocates an entire change in culture. "Making nature visible is a way of reacquainting us with wider communities of life, but it also informs us about the ecological consequences of our activities" (Van der Ryn &Cowan 2007 p.189). Van der Ryn and Cowan suggest society is reminded of environmental issues in the products they use. If the sustainable goals are inherent in the product, the user may not need to be aware of them.

Cradle to Cradle offers a more positive and practical approach by linking environmental thinking with a more pragmatic methodology.

Cradle to grave

An alternative 'cradle to grave' strategy, producing an incrementally 'less bad' end result would produce a more feasible product that the automotive industry might be ready to accept. The point remains that being 'less bad' does not improve the situation. The development of the M/D/M process seeks to provide a real alternative route to sustainability.

3.6.2 Materials development

Range of materials and processing methods

Experimentation involving a broader range of natural fibres and bioplastics would have produced a greater range of potential materials. Other manufacturing processes are also available. These were not explored in detail as this research is clearly focused on product design and applying materials.

Materials Investigation

The favoured approach to materials development focuses on the production of small sample films to understand the separating of fibres. The drawback of this method is that the broader properties and potential of the material is not explored.

A full robust experiment using Taguchi experimental design (Phadke, 1989) would produce a fuller understanding of the materials capabilities, and optimise the processing parameters to be used. Unfortunately, the lab press used is not capable of producing samples at accurate temperatures and pressures. These inaccuracies increase the noise in such experiments, reducing the value of this approach. To investigate the veneer/Biome material further, a larger study of this nature - using Taguchi experimental design - would be recommended. Inaccurate equipment and limited resources put it beyond the scope for this project.

3.6.3 Holistic Strategy

Product design methodology

The whole project could have employed a linear product design strategy as advocated by Ulrich and Eppinger (2008) (figure 3.5). The generic product design process described does not have the same relationship to materials and manufacturing as the M/D/M and ‘model of reasoning’ (described in figure 3.1) processes use. It is unlikely that this process would have identified the need for a new material to be developed.

Materials science

The general materials science research approach would result in a lab test of a material, but with no end product or clear direction of development. Materials are produced and presented as being complete with no suggestions of potential use (Sutharson, 2012). A full materials science approach would require accurate equipment and a supply of materials that were not available for this project. Such an approach does not apply the material to a practical problem.

3.7 Conclusion

It is recognised that there are development methods concerning engineering and materials science that are not explored as the scope of this research is concerned with the design approach. In this regard a holistic method has been developed and tested through the use of 2 'proof of principle' studies. The results of these studies prove the Cradle to Cradle sustainable design goal can be realised in a car component.

Chapter 4 M/D/M - Pilot study

4.1 Introduction

The VW Golf and the Aston EcoCar were compared in chapter 2. It was demonstrated that traditional steel bodied cars are not sustainable, in order to improve the situation there is a need for a holistic solution and for green materials. This Pilot study will trial a holistic methodology to develop a green material for use on a sustainable vehicle (the 2014 Aston EcoCar).

Following the Cradle to Cradle philosophy (Braungart & McDonough 2009) the whole life cycle is considered when designing a product. Sustainability can be achieved through developing within two closed loop systems:

1. Biological cycle.
2. Technical cycle.

In the development of the Aston EcoCar, biological nutrients are favoured where possible, this is because:

- A car is a 'product of consumption' (Braungart & McDonough, 2009: p.105) - a car has a limited life span and as such disposal needs to be simple.
- Disposal (composting) at the end of a biological products life is straightforward.
- No finite resources - oil or ore - is required.
- Avoids the use of harmful chemicals.

This pilot study applies the cradle to cradle philosophy to the Aston EcoCar in a basic way.

Considering the 2012 and 2013 Aston EcoCars, there are areas where natural fibre materials have successfully been applied: plywood monocoque chassis, fabric and plywood interiors and plywood body panelling. Much of this has involved bending plywood into 2-dimensional curves and forming large structures. The use of plywood on the Aston EcoCar has been less successful in other areas.

Creating compact, lightweight and load bearing wooden components is difficult. The 2013 Aston EcoCar suspension, for example, was constructed of plywood. Construction using wood joints and the space needed to secure linkages resulted in bulky resolutions.

Suspension components would ideally be packaged into a small space. This presents a design issue that needs solving.

To create lightweight, compact and load bearing structures that are sustainable, a material is needed that can be moulded into complex 3-dimensional curves. A mouldable composite will allow stiff, compact structures to be made while keeping the wall thickness thin and the component light.

Both the design of the component and the material used needs to be considered together. This pilot study attempts to use a holistic strategy to consider the material, design and manufacture of a sustainable, structural component.

4.1.1 Pilot study method

As described in chapter 3, a modified version of Roozenburg and Eeekels' (1995) 'model of reasoning' shown in figure 3.3 is used to develop a material for the design and manufacture of an Aston EcoCar component.

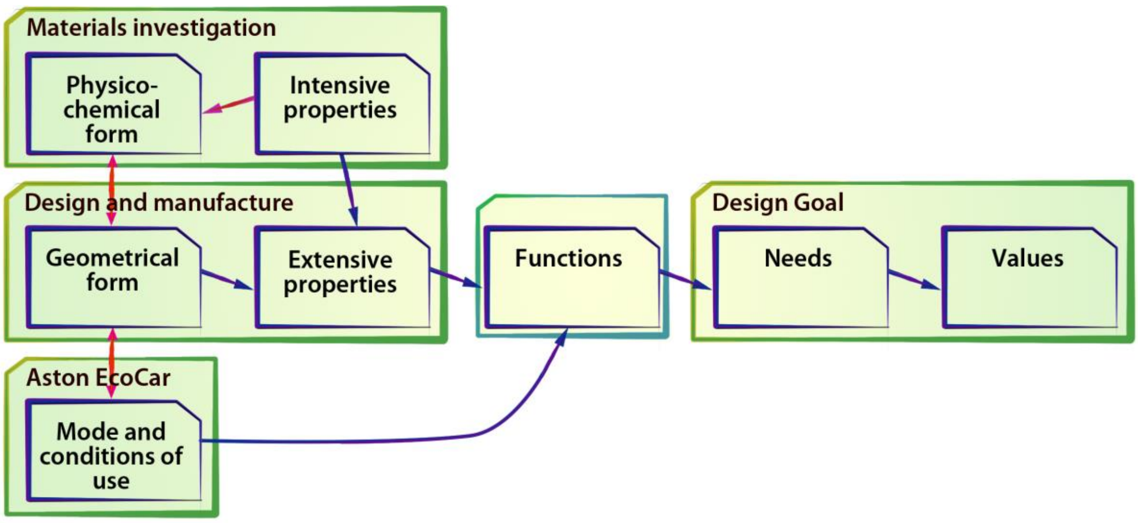

Figure 3.3, Pilot study structure

This is structured in the following way:

- Design goal - Cradle to Cradle philosophy to create a sustainable vehicle.
- Materials selection - specified qualities are matched to materials.
- Materials investigation - viability of a chosen material is explored.

- Design and manufacture - the developed material is applied to the EcoCar.

This is set out as 3 experiments:

- Experiment 1 - Veneer/Biome materials investigation and tensile tests.
- Experiment 2 - Investigating veneer/Biome pressing parameters.
- Experiment 3 - Aston EcoCar application.

This series of experiments will be carried out in order to develop a feasible composite for use in a car. The first stage will be to decide on which materials will potentially offer the best solution. The second stage will be to experiment with these materials by creating and testing samples. A promising material, developed through analysis of the samples will be applied to the 2014 Aston EcoCar. The results of this 'Pilot' study will then inform the direction and method of conducting a larger study.

4.2 Materials selection

A variety of materials have been identified, these materials require varied methods of processing (heating, pressing, vacuum bagging, curing). Different combinations of polymer and fibre would produce composites with an array of performance characteristics due to the strength of the fibre, and also the strength of the bonds in the resin matrix. Examples of such materials have been discussed in chapter 2. A range of options for formulating a composite for use on the Aston EcoCar are considered. The materials in table 4.1 are examples of combinations of commercially available products that could be tested.

Material	Description	Process
Woven flax/PLA	Composites Evolution - commercial bio-degradable composite product.	Hot press
Wood veneer	Thin layers of wood can be heated to make pliable, before gluing and moulding.	Glue and press
Woven (coarse) hemp/bio-epoxy	Natural fibre fabric, layered in a mould and sealed in a bag. liquid resin is then infused into the fabric (not biodegradable)	Vacuum infusion
Cotton/Supersap bio-epoxy	Supersap is a blend of vegetable and mineral oil. This epoxy-blend can be combined with cotton. (not biodegradable)	Wet laying
Wool/PLA	A thermoplastic proposed for use as a resin matrix, could be combined with animal hair forming pellets.	Injection moulding

Table 4.1, Possible materials.

Table 4.1 displays a sample of the variety of materials and processes available. There are many combinations of fibre, polymer matrix and processes available.
It is therefore important to:

a) Select the desirable properties of a material,
b) Pair suitable polymers with fibres,
c) Choose a suitable process.

The list of possible candidates is extensive, for example various fibres offer different characteristics:

- Root fibres - these fibres do not contain lignin so could provide a better bond with the resin matrix.
- Animal hair (carded sheep wool, or horse hair) - These will require stretching to straighten and align fibres.
- Cotton - extremely high cellulose content, could provide a good bond with a cellulose bioplastic matrix.
- Wood fibres - not produced using GM sources or competing with food crops.

- End grain bamboo - can be glued into a sandwich as the material is stiff and strong under compression, however it is not possible to mould this material into complex curves.

To decide on a direction, some possible materials need to be compared, with factors regarding the processing, environmental credentials and feasibility taken into account.

The material is to be utilised as a structural member of a car. The material therefore, can be specified based on desired characteristics - performance requirements, cost and environmental targets. As displayed in Table 4.1, there are many options as to: which natural fibre to use; which material is chosen for the resin matrix; and the processing method. As the test samples are being developed for a prototype car there are numerous considerations. To get a representation of the requirements, a materials specification is drawn up. This is used as a guide in the selection of a suitable material to develop.

The performance requirements are general as they depend on the design of the vehicle and manufacturing processes developed. The quality of materials can vary depending on the source. The properties vary depending on the manufacturing processes used.

Key areas where the new composite material will need to perform are:

- <u>Sustainability</u> - ideally materials will be from renewable sources, the aim is to make the chassis of the car biodegradable, with materials which are 'biological nutrients' (Cradle to Cradle) mechanically fixed to the chassis for disassembly, before being composted.
- <u>Mechanical performance</u> - It is anticipated that the vehicle will undergo loads of the vehicle plus two persons (approx 150kg for the vehicle and 90kg per passenger). This load will be spread at 4 points on the car, where there may be impact loads. The composite will need to be stiff, light weight and have reasonable strength. It is therefore desirable for the material to contain long aligned fibres.
- <u>Longevity</u> - The material will need to maintain structural integrity through the lifespan of the car - predicted to be 5-10 years - just short of current levels (Mildenberger & Khare 2000).
- <u>Mouldable</u> - It is proposed that these materials will take the form of a supporting component on the chassis, overcoming some of the limitations presented by panel

products (plywood is flat). It is therefore important that the materials can be moulded into complex curves.

4.2.1 Material specification

The following specification is a general list of considerations.

1) Environmental performance - source, processing, use, manufacture and disposal:

a) Sourced from environmentally sustainable stock,
b) Sources not in competition with food crops,
c) Locally sourced (local to the UK),
d) Not deplete fresh water resources,
e) Low energy use from acquiring raw material,
f) Minimal waste materials during processing and manufacture,
g) Low energy usage during processing and manufacture,
h) Suitable for disassembly,
i) Biodegradable,

2) Performance characteristics:

a) Light weight,
b) Low water absorption,
c) Needs to be mouldable into complex curves,
d) A useful lifespan comparable to that of a car - 8 to 12 years,
e) Maintained performance up to temperatures of 60°C+,
f) Good tensile strength - comparable to GFRP and steel,
g) High stiffness - comparable to GFRP and steel.

3) cost compared to the material normally used (GFRP):

a) Lower cost of raw materials,
b) Readily available,
c) Lower processing cost,
d) Lower disposal cost.

4.2.2 Selection matrix

A number of readily available natural fibres and 'sustainable' plastics have been identified. The following table scores these potential materials against the specification criteria. Glass/Epoxy (GFRP) is scored as a benchmark. Although rudimentary, this method narrows down potential candidates for development by estimating the relative potential. Judgements are made about certain materials, for example a PLA bio-plastic will need processing by heat and pressure, so assumptions will be made about the relative energy required for processing in comparison with wet lay-up of glass fibre and epoxy.

A score of 10 represents good characteristics, where as 0 show flaws in certain criteria.

	Flax/ PLA	Wood chip/PLA	veneer/ cellulose	Sisal/ cellulose	Coir/ starch	Hemp/ BioEpoxy	Flax/ Epoxy	Glass / Epoxy
1a	6	10	9	7	9	5	2	0
1b	2	8	8	8	10	9	4	10
1c	8	8	8	5	3	4	8	10
1d	3	9	8	6	10	7	4	10
1e	4	7	6	4	4	3	2	0
1f	9	10	6	6	10	8	5	5
1g	4	5	5	5	10	2	1	1
1h	5	5	5	5	5	5	5	5
1i	10	10	10	10	10	0	0	0
1 s/t	51	72	65	56	71	43	31	41
2a	6	4	4	4	2	10	10	9
2b	4	4	4	4	0	6	6	10
2c	6	5	3	6	6	8	8	10
2d	3	1	3	3	0	10	10	10
2e	4	4	4	4	0	10	10	10
2f	6	3	6	5	2	8	8	10
2g	6	6	8	6	3	9	9	10
2 s/t	35	27	32	32	13	61	61	69
3a	4	5	2	4	10	6	8	10

3b	5	5	5	5	7	5	7	10
3c	5	8	7	5	5	6	6	10
3d	10	10	10	10	10	0	0	0
3 s/t	24	28	24	24	32	17	21	30
Tot	110	127	121	112	116	121	113	140

Table 4.2, Materials selection matrix.

The scoring system used in table 4.2 is simplistic. For example, the monetary cost of materials is difficult to score. Examination of future supply chains and the availability of raw materials are not within the scope of this study. The production of raw materials used in GFRP is well established. Historical investment in infrastructure and the high volume used in industry dictates that costs will be low with little scope for reduction. For a new natural fibre/bio-plastic composite, there is little historic investment in the raw materials needed, the supply is limited and the costs high. In this regard the selection method is flawed, however the comparisons made are for consideration on a basic level.

The criteria that are considered to be critical have been marked in red. A judgement must be made on how materials will perform as part of a composite. The properties and attributes of similar materials discussed in the literature review provide an indication as to which materials show the most promise.

4.2.3 Selection

The use of a casting resin (such as an Epoxy) has been rejected. Although they offer the best mechanical performance, damaging chemicals are used in the manufacture and no materials can be recovered on disposal. Continuing with casting resins do not offer a step forward in the development of a closed loop system.

The mechanical performance of a Coir/starch bioplastic material is considered limited. Based on the scoring system it will not be considered further.

After consideration of various types of natural fibres and plastics, three candidates have been short listed for development:

FLax/PLA - Flax fibres possess excellent mechanical properties, the material is widely available across Europe. A flax/PLA composite will provide a fully sustainable biodegradable material.
Drawbacks to the use of flax include: the cultivation of the crop competes with food crops; flax fibres require a lengthy and drawn out process to harvest, dry, extract, align fibres to ultimately produce a fabric. There is scope to improve the processing, however a large amount of research has already been conducted using these materials.

Wood chip/PLA - Advantages of using PLA bioplastic and wood chips are that both materials are readily available and inexpensive. Wood chips can be considered as a waste by-product of woodland management. The production of woodchips has little impact on the environment. The drawbacks of using woodchips is that the fibres are short compared to others available and the fibres would be randomly orientated in large bundles. The size of wood chip limits the processing possibilities. Large chips (20-30mm) offer longer, stiffer fibres but need to be pre-inserted into a mould before heat and pressure is applied. Smaller chips (such as wood flours discussed in chapter 2) allow the PLA/wood blend to be processed using injection moulding. Similar materials to this have been developed before and because of the downsides in processing and short fibre length, woodchips will not be considered further.

Wood veneers/cellulose bio-plastic - Using wood fibres to reinforce bio-plastics is an area previously studied, however using veneers presents a new challenge. The reasoning for using veneers is that they are already in full production for use in making ply wood panels, the process to obtain the veneers - to shave them off of a log - impacts relatively little on the environment, no untoward chemicals are used in processing. The resulting product is a sheet of aligned natural fibres. Using a cellulose plastic - derived from wood - means that a bio-degradable composite could be made using wood products, providing the forests are managed effectively this does not interfere with food crops or use damaging amounts of fresh water.
These materials present challenges in terms of processing and creating a composite that can be moulded into complex shapes. The resulting composite material will take a substantial amount of development to create a useful fibre/resin matrix, refine the material for optimal characteristics, and to optimise a processing method. This represents a challenge with the opportunity to produce a novel material and processing method.

4.2.4 Selection summary

It is recognised the list of materials considered is not comprehensive and other natural fibres and bioplastics may be suitable for use on the Aston EcoCar. However, the samples have been chosen from the general spectrum of materials available. After experimenting with sisal and hemp fibres in casting resins it has been decided that a thermoplastic combined with wood or flax fibres offers a combination that provides the correct balance of raw material availability, effective manufacturing process, useful properties and biodegradable disposal that compliments the Cradle to Cradle goal.

4.3 Materials investigation - veneer/Biome composite

4.3.1 Introduction

These first two experiments will take a broad approach to processing structural birch veneers and Biome HT90 bioplastic (for data sheet, see appendix A), performing some broad comparisons before manufacturing a component. The results of these general investigations will open paths of enquiry for more detailed studies to occur. This is also an efficient way to assess the promise of a veneer/Biome composite.

Two materials have been selected for formulating a potential composite:

- Birch veneer - panels of wood sliced off of a birch log,
- Biome HT90 - a cellulose based bioplastic, extruded into sheet.

Biome bioplastic is a thermoplastic, and as such will require an amount of heat, and pressure to mould. The datasheet for Biome HT90 [appendix A] states the optimum temperature for moulding Biome HT90 is between 200°C and 230°C. Other parameters such as pre-heat times, and pressure will need investigating to provide a starting point from which to perform experiments on this material.

The effect of heat and pressure on the wood veneer will have consequences for the strength of the resulting composite. A study into the properties of natural fibres (Saheb & Jog, 1999) suggests that natural fibres will lose their integrity at temperatures higher than 200°C - this needs investigating. Finding out the general parameters such as these will enable more detailed experiments.

Aim

Investigate the parameters of creating a veneer/Biome HT90 composite material.

Objectives

- Conduct a broad assessment of veneer/Biome, including a comparison with another composite.
- Discern the best method for creating samples.
- Determine a realistic temperature and pressure range for future experimentation.
- Evaluate the different ways to stack the layers of Biome sheet and veneers.

4.3.2 Processing method

Two common plastic moulding methods were considered - hot press and injection moulding. Injection moulding was ruled out because a desired property of the material is to have long, aligned fibres. It was felt this would be better achieved by using compression moulding using a hot press, where different layers of fibrous material and polymer can be stacked allowing the alignment of fibres to be maintained.

The press used was a 25 tonne, water cooled hot press. The process involved:

1. Laying sheets of material in a stack between sheets of Teflon,
2. Bringing the hot plates of the press in contact with the stacked sample,
3. Heating the sample through - pre-heating,
4. Applying pressure to the sample in the hot press,
5. Cooling the sample down under pressure,
6. Releasing the pressure and removing the sample.

The hot press process used is described in figure 4.1.

Figure 4.1, Diagram showing the hot press process.

4.3.3 Experiment 1 - Veneer/Biome fabrication

An experiment is conducted to investigate whether a birch veneer/Biome HT90 composite could be successfully fabricated using a hot press. The sample is prepared by stacking alternate layers of veneer and bioplastic into a cavity - the shape of cavity being a tensile test sample specified by ISO 527. The material is then pressed using the processing method described in figure 4.1. The strength of the sample can then be tested.

A key performance characteristic of a material is the tensile strength. The results of experiment 1 will provide an indication as to the usefulness of a veneer/Biome composite. Comparisons with equivalent materials show the potential of the material. For this experiment an approximate tensile strength comparison between birch plywood and birch veneer/Biome composite is conducted. Two 5mm thick test samples, specified by ISO 527 are prepared (1a and 1b).

Sample 1a

A single Veneer/Biome sample is fabricated by stacking alternate layers of birch veneer strips (0.6mm thickness) and extruded sheets of Biome HT90 (0.6mm thickness) into a cavity. The direction of the veneer grain is also alternated to run the length of the sample and then the width. 5 layers of veneer were used, and 6 layers of Biome HT90. These layers are stacked into the test sample shaped cavity 'mould', demonstrated in figure 4.2. The cavity is overfilled by 1.6mm to ensure the volume of the cavity is filled and reduce voids within the sample.

Figure 4.2, Layers of Biome and veneer stacked into a cavity

This stack of sheets is placed in the press, preheated for 5 minutes, hot-pressed at 20 tonnes and 170°C for 5 minutes. The press and mould are then water cooled over a period of 20 minutes.

Sample 1b

A similarly shaped test piece was cut from 5mm thickness birch ply (BB grade quality). Care was taken to ensure the grain of the outer layers run longitudinally.

Results

The tensile test results of samples 1a and 1b are displayed in figure 4.3

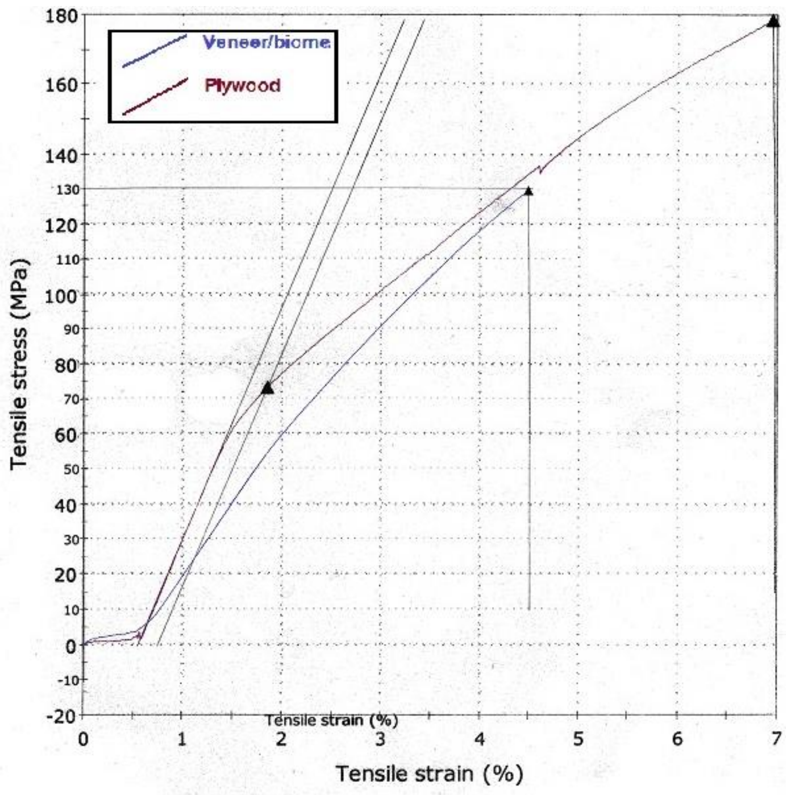

Figure 4.3, Tensile test results of sample 1a (veneer/Biome) and 1b (birch ply).

The test results in figure 4.3 show that the ultimate tensile strength of the veneer/Biome sample is 70% the strength of birch ply. The yield point for the veneer/Biome sample is not clear. The straight section of the veneer Biome graph stops at approximately 50MPa.

What can be learned from this test is limited. Natural fibres have inherently variable mechanical properties, for more accurate results and to determine the consistency of results the test would need to be repeated many times. The results of experiment 1 are useful as a general indication. As the material needs further development, these results are helpful in supplying a rough indication of the potential of the veneer/Biome composite.

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Figure 4.4, Sample 1a (left) and sample 1b (right).

Figure 4.4 shows the failed samples 1a and 1b. The failure of sample 1a was caused by sudden brittle fracture. In sample 1b the wood fibres were pulled through. Neither samples show any delamination between the wood and polymer which is encouraging for future development. With sample 1a it can be seen in the cross section of the sample that the veneer sheets have been distorted during pressing, it was expected that the distribution of the Biome and veneer layers would be in uniform layers (as stacked in the mould).
It is unclear how this distortion will have affected the strength of the material, however it shows that there was sufficient heat and pressure during the processing to press the veneer and Biome together. It is also encouraging that no voids can be seen within the sample.

The tests demonstrate birch veneers and Biome bioplastic can be combined using compression moulding to form a composite. Processing the materials using a hot press provides a controllable way to mould the composite.

This experiment has created a 'plywood' using the bioplastic as a bonding agent, although, this has less strength than the regular plywood sample. This is clearly a failing of the material. There is scope for development in moulding and improving the fibre distribution within the veneer/Biome for moulding complex 3-dimensional shapes. Standard plywood is limited in this regard as when pressed in large sheets the wood fibres in veneer would break during gluing and pressing.

Further investigation is needed to determine the optimum way of processing the layers, stacking the layers in the mould and the design of products using the veneer/Biome material. The material could be improved by increasing the number of long fibres (extra layers), evenly distributing the fibres within the polymer matrix and by optimising the processing conditions (excessive heat and pressure damage the fibres).

4.3.4 Experiment 2 - Basic parameter variation

In order to ascertain basic parameters for a more detailed investigation, samples are created in the hot press under varying conditions. Small test samples of material are created. The 'films' are made by compressing layers using the hot press without a mould. The results of the test are observed by the behaviour of the fibres in the sample.

An initial test of two samples is conducted. Samples of 0.6mm thick veneer 50mm (along the grain) by 35mm (across the grain) were prepared. These veneers were sandwiched between two layers of 0.3mm Biome HT90 bioplastic sheet. Table 4.3 contains the pressing parameters used for experiment 2, the preheat and press times were kept the same as the pressure and temperature were considered to be of greater interest.

Sample	Pressure (MPa)	Temperature °C	pre-heat time	press time
2A	56	150	5 mins	2 mins
2B	123	200	5 mins	2 mins

Table 4.3, Experiment 2 pressing parameters.

Results

Figure 4.5, Hot press film sample 2a and 2b.

The samples in figure 4.5 display an interesting occurrence during the pressing of samples 2a and 2b. Under heat and pressure the plastic forced apart the wood fibres in the veneer, while keeping the full length of the fibres intact and aligned.

In sample 2B, the plastic flows well at temperatures of 200°C, this is expected as the data sheet specifies melt processing temperatures in the range of 200°C - 230°C. This poses a problem in that the integrity of the wood fibres is destroyed at this temperature. The fibres have become discoloured and distorted. As can be observed in the figure 4.5, sample 2B is very brittle and has disintegrated to a degree.

In sample 2A, the 150°C temperature does not destroy the fibres, however the plastic is not fully molten. This could mean the bonds between the plastic and the fibre are weak. The spreading of the fibres during pressing could form the basis of a promising composite where long fibres are distributed evenly in the polymer matrix.

Further work needs to be carried out in order to determine how the fibres split apart and the processing conditions that would produce the most promising layers in a composite. To do this, the manner in which the fibres separate will need to be characterised.

4.4 Experiment 3 - Veneer/Biome applied to 2014 Aston Eco-car

Experiment 3 in this initial broad investigation, applies the veneer/Biome material to a practical application. A section of veneer/Biome is to be applied to the 2014 Aston

EcoCar. A better understanding of the limitations is gained by using veneer/Biome as a structural component on a biodegradable car. This experiment will provide feedback as to whether the material is useful. This will allow targets for future development to be identified. Applying the veneer/Biome to the chassis will inform how it can be used in combination with other materials on the car - balsa and plywood.

The ideal use for the material will be for a structural part of the car where the use of a plastic would not be stiff or strong enough, and where 3-dimensional complexity reduces the suitability of using a flat panel products such as plywood. Ideally the component for the car is a moulded complex shape. These features would express the qualities desired from the material.

The veneer/Biome material used will be processed using the knowledge of previous investigations. Experiment 1 shows that layers of Biome and birch veneer can be stacked to form composite panels and experiment 2 gives a good indication of the processing temperatures and pressures. Although it is an early stage of the veneer/Biome composite development, a moulded piece of material similar in composition to that formed in experiment 1 will be used on the vehicle.

There is a finite period for the design and manufacture of the Aston EcoCar for SEM 2014. What is learned about processing the veneer and Biome is put into practice without further developing the material.

4.4.1 Area of application

There are a number of considerations for the area of the car on which to apply the veneer/Biome. To obtain full value from the experiment, the veneer/Biome component is required to be:

- Applied as a structural member of the car - in a load bearing capacity testing both rigidity and strength.
- Integrated with other components of different materials.
- In an exterior area of the car (to be most useful in future applications)
- Able to be made with the equipment for processing available (the hot press at the university has a bed size of 300mm x 300mm).

A number of components are considered for the application of the veneer/Biome material. Options for areas to apply material on the EcoCar include:

- A structural element of the seat.
- A load bearing section of the dash supporting the steering.
- A supporting structure for the chassis.
- The rear uprights and bearing housing.

The dash and seat options were part of the interior of the car, and while load bearing, were not on the exterior of the car. These options were also rejected as it was clear the design would be finalised too late in the production of the car for the designs to be put into practice. The current development of the veneer/Biome composite does not offer sufficiently substantial or reliable properties to be used for the construction of the rear uprights for the car.

The chosen area of application is a supporting structure on the vehicle chassis. As an external, structural component a chassis support also combines the material with plywood and balsa structures. This provides a challenging application to assess the feasibility of the veneer/Biome material.

4.4.2 Component design

The 2014 Aston EcoCar was built with the aid of final year undergraduate engineering students, who were briefed on the design and sustainable philosophy of the car. The members of the team focused on various areas of the car suspension, interior, drive train or fuel cell. One member of the team - Dave Patel conducted the chassis build and assisted in applying the new material to the vehicle (Patel, 2014).

The chassis design consists of end grain 'balsa core' skinned with ply to form a stiff and lightweight sustainable sandwich panel composite. This sandwich structure forms the floor and bulkhead sections of the chassis. Balsa/ply panels provide excellent stiffness across the width of the car, however additional support is required due to flex along the corners. For this reason, a supporting frame on the sides is needed to improve the stiffness of the monocoque chassis when supporting the 200 Kg car and two 80 Kg passengers.

Designs for two full sides displayed in figure 4.6 are constructed using veneer/Biome.

Figure 4.6, 2014 Aston EcoCar chassis design.

Figure 4.6 shows a render of the chassis design with the veneer/Biome supporting frame in white. The size of the parts to be moulded was limited to the size of the press (300mm x 300mm). The frame was therefore designed in small sections to be made using 8 different moulds. Each moulding has been designed to overlap, with the overlapping sections bonded together with a two part epoxy resin. This overlapping provides sufficient surface area to bond the whole frame together.

Figure 4.7, Support frame construction sketch.

Figure 4.7 displays the basic design of the frame's straight sections. These sections are designed to be used along the base and bulkhead edges of the chassis. Upper and lower 'L' brackets bonded to the ply skin of the chassis are fixed to a rigid face panel. Machining the moulds and pressing the parts for these sections is straightforward.

Figure 4.8, CAD model of corner section geometry.

The design for the corner section shown in figure 4.8 contains geometry which is difficult to hot press in a two part mould, especially with the desired orientation of fibres providing strength and rigidity in the correct areas of the component. A part could be injection moulded - without any fibres. The part could also be manufactured in sections and bonded together. To be produced using the available equipment, the design may require simplification. The challenges posed by the design have meant that the component could not be fabricated using the veneer/Biome material.

The design of components such as this corner section (figure 4.8) demonstrate the limitations of the pressing process and the veneer/Biome material. Attempting to design parts such as this show the challenges of designing and manufacturing using veneer/Biome. The increasing complexity of the frame increases the number of moulds needed for construction, the number of pressings needed and the number of parts to be glued and clamped. The time and resources required to achieve this are not available within the constraints of the EcoCar project. Another issue includes the quantity of veneer/Biome layers required for pressing into components. The time constraints on designing the part are compounded by the machining of moulds and pressing of parts.

At this point during the study it is clear that due to equipment, resources and time available it is not feasible to construct two entire veneer/Biome side frames for the car chassis. In order to complete the car in time, the experiment is scaled down to a section of the frame being constructed using the veneer/Biome material.

Figure 4.9 shows a moulded straight section of the supporting frame – consisting of a flat section and two L shape mouldings. Integrating the veneer/Biome component to the car is achieved by bonding the overlapping sections with a two-part epoxy adhesive.

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Figure 4.9, Veneer Biome section of the 2014 EcoCar chassis frame.

The area chosen for application is along the floor section of the chassis, where the structure would experience a high degree of strain due to the load of the passengers. It is however, recognised that this component does not take full advantage of the material.

The remainder of the frame was constructed using 9mm thickness birch plywood. The completed car is displayed in figure 4.10.

Figure 4.10, 2014 Aston Eco car.

4.4.3 Evaluation

Clear differences between the plywood construction to the veneer/Biome section have been observed, table 4.4 compares the two methods of construction. A subjective score out of 10 has been awarded as to how successful each part performed.

Performance criteria	**Veneer/biome composite frame**	**score**	**Birch plywood frame**	**score**
Integration with chassis	Bonding flat surfaces allowed tight tolerances and little movement	8	Joints worked loose after repeated loading and unloading	4
Repeatable manufacture	Moulds would allow many identical parts to be manufactured	9	Most sections are able to be CNC machined, some forming in moulds and difficult joints to be cut	6
Construction time	Long lead time to production	1	Relatively easy to machine parts and fit to car	8
Fitness for purpose	Part performed, however, producing a corner section would have proved more conclusive	4	Wooden frame performed well, improvements could be made in the design of windscreen pillars and door mounts.	5

Table 4.4,Veneer/Biome and plywood performance comparison.

There are several issues with the way the veneer/Biome component was added to the vehicle:

- The epoxy adhesive used is clearly not contributing to the biodegradable aim.
- It is difficult to measure the strain on the component due to the dynamic nature of the forces acting on the chassis and the number of components within the chassis.
- The size of the veneer/Biome sample was smaller than anticipated.
- More consideration needs to be given to the attachment of the side structure to the balsa/ply chassis.
- Pressing of large components has been unachievable.

A second iteration of the chassis frame using more time and resources, would provide a more informed design for components. A larger study would supply further information for the future use of the material.

Although there was a compromise to the scale of this experiment, the results were promising and the general capabilities of the material were found. The design passed the technical inspection at the Shell EcoMarathon 2014 competition, and the veneer/Biome component did not fail. Much was learned from this experiment.

4.5 Pilot study results

From this pilot study a greater understanding has been developed regarding the processing and use of the Biome bioplastic and birch veneer in a composite material. This provides a basis on which to design a usable biocomposite and develop a product for manufacture. In this regard the general approach to the pilot study has been successful.

The strength of veneer/Biome is comparable to birch ply (it has 72% the tensile strength of birch ply). An advantage of veneer/Biome over plywood is that it is mouldable in 3-dimentions and may be used in structural capacity in designing sustainable vehicles. From experiment 2, stacking materials to produce films in the hot press offer a controlled way to vary parameters in future tests. The application of the veneer/Biome to the Aston EcoCar was limited. The production of a chassis component was flawed - largely due to underestimating the tooling required and overestimating the lab equipment.

This pilot study has provided a wealth of information to take forward the further development of both the holistic approach used and the application of the veneer/Biome composite. This pilot study has made clear the following challenges:

- Ensuring a consistent product.
- Manipulating grain orientation of the veneer layers.
- Minimum radii the fibres can be moulded needs defining.
- Maximum size of the component and the machinery needed for processing needs defining.
- Thought needs to be given to the required complexity of the moulding tool.
- Cost of mould tooling needs to be realistic considering budget.
- A supply of raw materials is required to produce components.
- More accuracy is needed in manufacturing components.
- The methodology needs improving.
- Progress through the study needs to be measurable.

It is important these issues are recognised for the next study using veneer/Biome. Limitations can be accounted for during the further development.

Through conducting the pilot study, it has been recognised that there was a disconnect between the materials investigation and the manufacture of a part for the car:

- benefits of using the veneer/Biome material were not exploited,
- The scope of application was overly ambitious,
- The viability of the supporting frame design was not fully tested,

Further consideration needs to be given to the methodology. Improvements are required so that the material developed is influenced by the design process and the manufacturing capability. By linking all 3 elements - materials, design and manufacture - a sustainable Cradle to Cradle component may be produced.

It has been proven through these experiments that a successful composite can be processed using Biome bioplastic and birch ply veneers. This composite has then been successfully applied to the sustainable Aston EcoCar. Pressing the veneer and Biome into films suggests a route forward to increase the mechanical properties of the veneer/Biome composite.

4.5.1 Further work

<u>Material development</u>

It is anticipated that two major factors will improve the performance of the veneer/Biome composite:

1. Improving the processing of the layers to produce a composite with evenly distributed fibres,
2. Defining the optimal temperatures, pressing times and pressures to press the samples.

To further develop the Veneer/Biome composite, a greater understanding of how the material behaves needs to be attained. This includes:

- How the fibres in the veneer separate when pressed.
- The affect various parameters (temperature, pressure and time) have on the material.
- Develop a process to manufacture a part using Biome plastic and veneer.
- Explore how the veneer/Biome can be moulded.
- Repeat the comparison of the material after development.
- Applying the developed material to a structural car component.

Taking these steps will allow a recommendation to be made for manufacturing parts using this material, and the sort of components that can be made.

Component Design and manufacture

Further materials investigation is needed for future application of the veneer/Biome. A suitable area of application needs to be chosen with care, along with a feasible scope for the study. This will be followed by a product design process.

Further work will take into account the limitations of the processing equipment available. The main manufacturing focus will be to fully exploit the lab equipment and release the potential of the material.

Holistic methodology

The basic 'holistic method' needs to be developed further to make the most of the material during the design and manufacturing stages.

To properly evaluate the holistic method, it is proposed that the material is tested, the design is tested and the manufacturing is tested. The success of each element can then be measured. The proof of the overall method should be demonstrated by the final component - answering the following questions:

- Does the component function?
- Have the design goals been met?

This pilot study paves the way for a much larger study, applied again to the Aston EcoCar project and tested at the SEM.

Chapter 5 M/D/M - main study

5.1 Introduction

In the pilot study (chapter 4) a sustainable composite was applied to the Aston EcoCar, this demonstrated that a sustainable material can be moulded and applied to a vehicle. The results show that the structure of the approach needs improvement, and a more in depth study may develop the methodology further. This will provide a more in depth understanding of the strengths and flaws of the material, design and manufacturing processes. This main study provides a full examination of the M/D/M methodology.

The results of the pilot study suggested that the scale of the application - a frame supporting the EcoCar chassis - was too ambitious. The scope of this main study needs to remain realistic so that a functional product can be manufactured. The resources available for this study will allow for the manufacture of a single tool for moulding. The manufacturing capability at the university is a lab press with a bed size of 300mm x 300mm. A suitable component needs to be designed to match these manufacturing capabilities. This main study will apply the knowledge gained from the pilot study to a new component for the 2016 Aston EcoCar.

<u>Main study aim</u>

A 'proof of principle' study to design a sustainable - Cradle to Cradle, structural component for a sustainable vehicle (2016 Aston EcoCar).

<u>Main study objectives</u>

- Trial the improved M/D/M holistic methodology,
- Examine the pressing of the veneer and Biome in more depth,
- Investigate the material for the manufacture of a moulded component,
- Choose an application that best exploits the veneer/Biome material,
- Define the requirements of the chosen application,
- Design a sustainable car component - meeting the mechanical requirements.
- Manufacture the sustainable component,
- Install the component on the 2016 Aston EcoCar,
- Test the component at the 2016 SEM.

5.1.1 Main study methodology

As explained in the methodology section 3.5. this main study employs a structure based on materials, design and manufacture (M/D/M) - displayed in Figure 3.4.

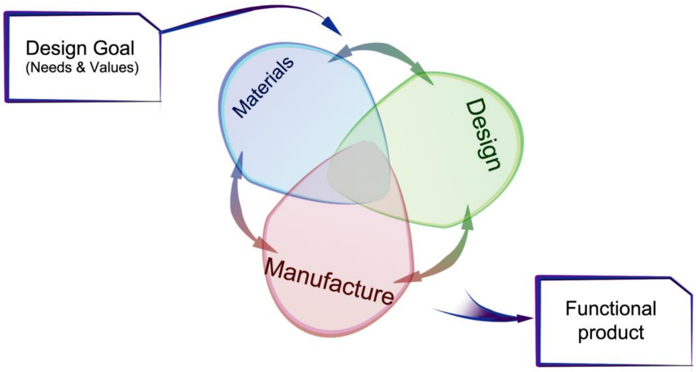

Figure 3.4, Materials/design/manufacture (M/D/M) strategy

The M/D/M strategy is developed from the experience of the pilot study. It was learned from the pilot study that more attention is needed in applying the veneer/Biome material to the proposed manufacturing process. This main study develops the holistic methodology further by incorporating feedback from the manufacturing into the development of the veneer/Biome. The sustainable goal of this main study - to produce a sustainable Cradle to Cradle vehicle - remains the same as in the pilot study.

The chosen veneer/Biome material, formulated during the pilot study is also carried forward. The option exists to choose a new pairing of biodegradable plastic and natural fibre (or to use a commercial material), however the Veneer/Biome displayed promising stiffness and strength characteristics that are worth pursuing. The reasons for choosing wood based cellulose and veneer remain valid.

This main study will attempt to respond to the shortcomings of the pilot study and provide a more rigorous examination of both the material and the methodology. This main study will be deemed a success if a functional product is produced that meets the design goals. The main study is presented in the following structure:

Materials development - A series of materials investigations informing the design and manufacture using the veneer/Biome.

Design Report - A component to be manufactured using veneer/Biome is designed for the 2016 Aston EcoCar.

Manufacture - A moulding tool is made based on the materials investigation. The designed component is then manufactured.

The functional product is then tested on the Aston EcoCar at the 2016 SEM. The results of each section (materials, design and manufacture) are then analysed. This provides an assessment of the product, the material and also the methodology.

5.2 Materials Development

5.2.1 Introduction

The materials testing in this section will focus on further developing a biodegradable thermoplastic (Biome HT90) and structural birch wood veneer composite.

A series of experiments are conducted to investigate the pressing parameters for producing veneer/Biome films. Understanding the effect of various pressing conditions is critical to producing a functional product. Increasing the scale of samples and experimenting with a basic mould will provide the parameters for design and manufacture of an EcoCar component.

<u>Aim</u>

To increase understanding of veneer/Biome in order to exploit it's properties in the design and manufacture of a component on the 2016 Aston EcoCar.

<u>Objectives</u>

- Experiment with the stacking of veneer and Biome layers,
- Investigate the behaviour of the fibres and polymer during processing,
- Characterise the properties through varying the processing parameters.
- Investigate the effect veneer size, shape and grain direction has on the material,
- Increase the scale of film size to be useful for creating a component.
- Evaluate the moulding capabilities.

5.2.1.1 Methodology

The materials investigation during the pilot study (Experiments 1, 2 and 3) is continued with an iterative investigation of the veneer/Biome material. This is performed in a series of further experiments designed to provide better understanding of the material for use in the manufacture of a component:

Characterisation of fibre separation in veneer/Biome

Experiment 4 - Stacking of Biome and veneer,
Experiment 5 - Processing variables,
Experiment 6 - Pressure and scale variation.
Experiment 7 – Aspect ratio

Manufacturing investigation

Experiment 8 - Increasing scale of film size,
Experiment 9 - moulding capabilities.

5.2.1.2 Benchmarking

This materials development will inform the design and manufacture a veneer/Biome component for the Aston EcoCar. The veneer/Biome used to manufacture the component can then be evaluated. While the final component will test the veneer/Biome material, benchmarking will put the properties of the veneer/Biome into context. A range of materials have been selected for comparison:

1. Biome HT90 - Providing a comparator to the reinforced plastic.
2. Birch Ply - For comparisons with a veneer product.
3. GFRP - Allows comparison with a standard, non-sustainable mass manufactured composite.
4. Flax/PLA Biotex - For comparisons with a fully sustainable commercial product.

The properties of these materials are detailed in table 5.1.

Material	Tensile strength (MPa)	Tensile Modulus (MPa)	Flexural strength (MPa)	Flexural modulus (MPa)	Density (g/cm^3)
Biome HT90 (Appendix A)	70.4	1564	Not available	4260	1.3
6.5mm thickness birch plywood [1]	42.2	9844	50.9	12737	0.63
E-Glass/Epoxy (GFRP) [2]	241	Not available	455	18000	1.82
Flax/pla Biotex [3]	110	14000	123	7100	1.33

Table 5.1, benchmark materials

[1] For birch ply along the grain of the face veneers. Data produced by Finnish Forest Industries Federation (data sheet available from www.upm.com/cn/products/plywood/Documents/Handbook_EN.pdf).
[2] Lytex 9063 63% Glass Fiber Epoxy SMC, manufactured by Quantum composites. (datasheet available from www.matweb.com).
[3] Biotex Flax/PLA 400g/m2 2x2 Twill, manufactured by Composites Evolution Ltd. (data sheet available from www.compositesevolution.co.uk).

Tensile tests

A key property for assessing the material is tensile strength. This measure will also allow for comparisons with similar materials.

Flexural tests

It is expected that an advantage to the use of wood fibres is that this will provide enhanced stiffness of the composite developed in comparison with benchmark materials.

5.2.2 Characterisation of veneer fibre separation

The preliminary testing conducted in the pilot study (chapter 4) investigated the general feasibility of a birch veneer/Biome composite. It was discovered, that the fibres separate laterally during the pressing process, whilst the fibres remained aligned. It is theorised that this could form the basis for a novel processing method.

Fibre separation is desirable because when stacked up in a mould, they are more evenly distributed within the polymer matrix rather than being in distinct layers. This should improve the desired strength and stiffness properties of the composite when compared to the veneer/Biome sample produced in experiment 1. The freedom of the fibres during processing should also allow veneer/Biome to be moulded into complex shapes.

Aim

Investigate whether the separation of birch veneer fibres using the hot press process could form the basis of a mouldable composite.

Objectives

- study the different ways to stack the Biome and veneer layers.
- Investigate the mechanisms by which fibres in wood veneer split apart.
- Determine the optimum conditions for splitting the fibres.
- Evaluate the potential of the material.

A series of experiments - similar to those of experiment 2 - were conducted using a hot press to create small test films. The size of the sample as well as the temperature, pressure and time are the variables that are able to be controlled. The resulting samples can then be measured in terms of the size of the resulting film and the manner in which the wood has separated within the sample.

5.2.2.1 Experiment 4 - stacking of Biome and veneer

Experiment 4 explores different methods of layering the Biome and veneer. Varying how the materials are stacked will increase understanding of the fibre separation during processing. Films are produced to examine whether using Biome plastic pellets in place of the extruded sheets of Biome creates the same effect of separating the wood fibres in the pressed films.

Within this set of tests the influence of preheat times was also explored.

If the use of pellets creates the same separating effect as with the sheet, this would remove the need for extruding Biome plastic pellets into sheets - reducing the number of processes. The benefits of which not only cut down the time and processing costs of making the material, it should also create a better composite as the plastic will be processed fewer times.

Layer preparation

In the experiment the effect of varying the birch veneer and Biome layers were examined. Sample films 4A, 4B and 4C were created by stacking veneer and Biome pellets in the following fashion:

Top layer	20g Biome HT90 pellets.
Middle layer	50mm x 35mm birch veneer.
Bottom layer	20g Biome HT90 pellets.

Sample film 4D - A single 20g top layer of Biome pellets was placed on the veneer layer.

Sample film 4E - The veneer is sandwiched between layers of Biome sheet (in the same configuration as experiment 2).

Test conditions

The following test conditions were kept consistent across experiment 4:

- A sample size of 50mm x 35mm birch veneer.
- The press temperature and Pressing time.

The processing conditions for making the films in this experiment are shown in table 5.2.

Sample	Pressure (MPa)	Temperature (°C)	Pre-heat time (minutes)	Press time (minutes)
4A	112.9	170	3	5
4B	56.9	170	6	5
4C	56.9	170	10	5
4D	56.9	170	10	5
4E	56.9	170	10	5

Table 5.2, Experiment 4 parameters.

Results

The resulting films from experiment 4 are shown in figure 5.1.

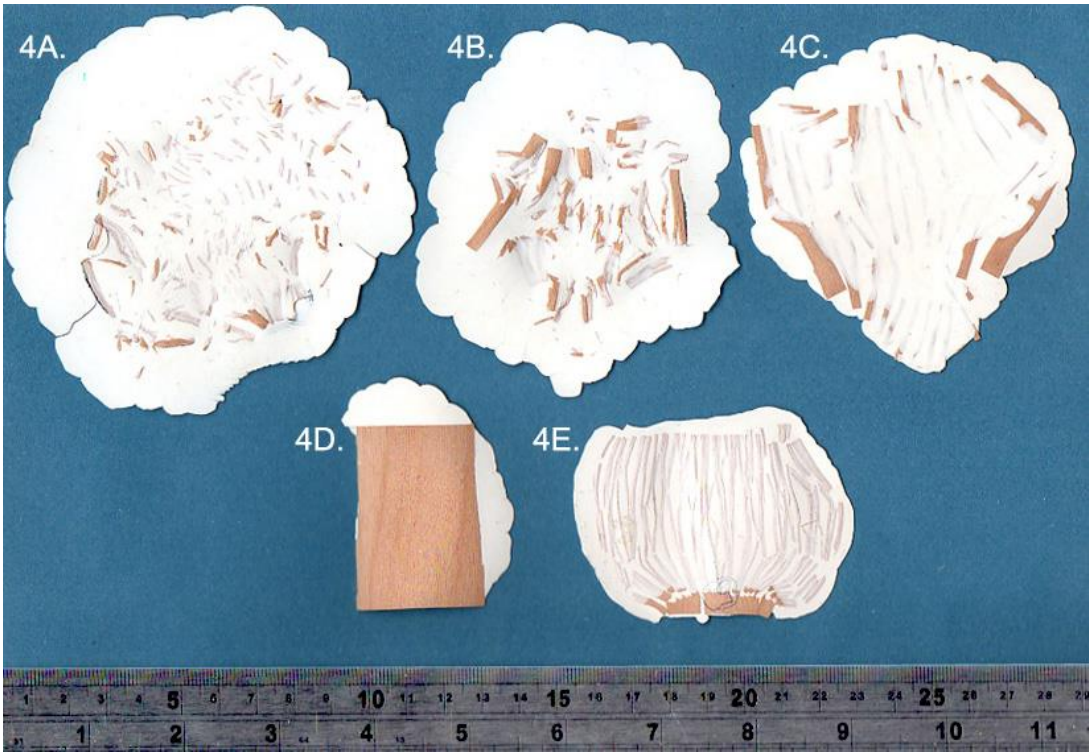

Figure 5.1, Images of the films created during experiment 4.

<u>Discussion</u>

Where the pellets have been used to produce films 4A, 4B and 4C, it is clearly shown in the figure 5.1 that the pellets have forced their way through the birch veneer layer and in doing so, this has broken the fibres. This has lead to short randomly distributed bundles of fibres in the resulting film. Using pellet layers in producing these films does not show the promising results of experiment 2 (which are replicated in sample 4E), where long aligned fibres are evenly distributed in the Biome film.

In processing samples 4B and 4C the preheat time was varied. it is noticeable that the fibres are longer in sample 4C - where under similar pressure the pre-heat time allowed the pellets to become more pliable while also allowing the heat to penetrate through the wood. Longer pre-heat times have preserved the fibres better, it is presumed this is due to the pellets being softer and flattening before pressing into the veneer.

This experiment demonstrates the importance of longer preheat times for creating these films more generally as the heat enables the lignin holding the fibres together to soften, making the fibres more conducive to separating.

The use of pellets is probably not as promising as using extruded sheet for creating a veneer/Biome composite. Even with the 10 minute preheat time, there is still an appreciable amount of misalignment and unevenness of split fibres in sample 4C compared to when sheet Biome is used in sample 4E.

In regions of samples 4A, 4B and 4C it is evident that there are areas of the wood veneer that do not have a covering layer of Biome. These regions have occurred where the pellet layers are too sparse, creating a gap in the coverage of Biome. Were these films to be stacked to form a composite, the large cavities in the resulting polymer matrix would be unacceptable.

In the regions where there are gaps in the polymer layer (when pellets are used), the wood veneer has remained intact. Sample 4D (where only a top layer of Biome is used) shows that two layers of the thermoplastic are required to sandwich the veneer as there is no separation of the fibres at all when a single layer of Biome is used. That the fibres do not separate when covered on one side or when stacked in a mould gives an indication as to the mechanism by which the fibres separate during the pressing process. What happens to the layers when creating the films is shown in the diagram in figure 5.2.

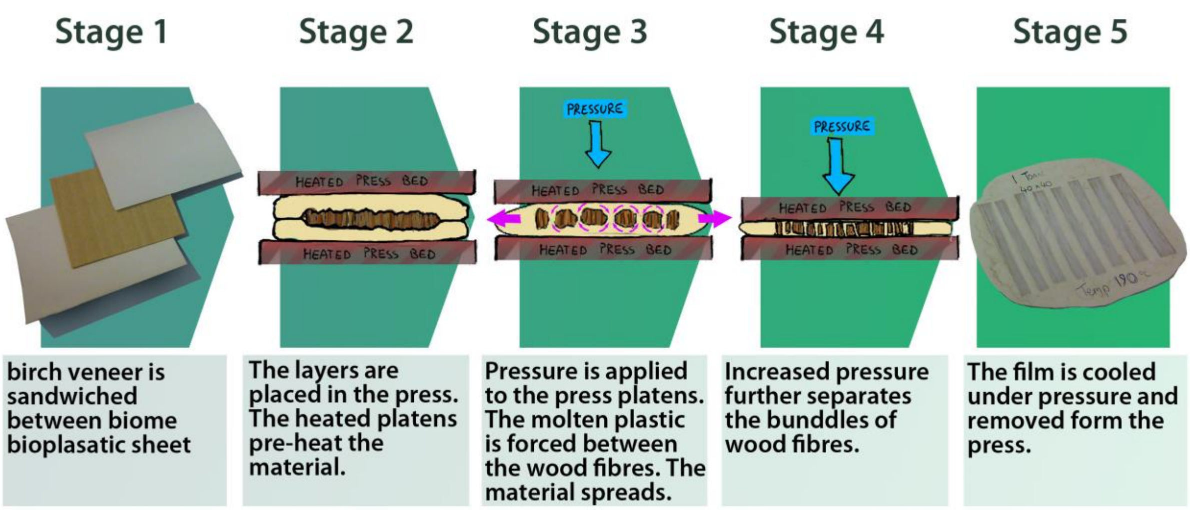

Figure 5.2, Diagram demonstrating the wood fibre separation during pressing.

It is clear from this experiment that certain pressing conditions are needed in order to successfully separate the wood fibres in a veneer/Biome film. The process for creating a veneer/Biome film with separated fibres requires the following:

- Stacked layers - The veneer needs to be sandwiched between Biome bioplastic when stacked in the press.
- Preheat - The top bed of the press is brought down to a point where the bed is in contact with the stack of Biome and veneer layers. This is then left for a period of time for the heat to permeate through the stack of material.
- Pressing - The pressure is increased to the point (to be investigated in future experimentation) where the plastic gets forced between the fibres of the veneer.
- Flow - The sample then spreads towards the edges of the press bed. Because the separated fibres are suspended within the Biome, the fibres flow with the Biome and spread out.
- Cooling - The heating element is turned off and the press is cooled whilst still maintaining the pressure.
- Release - The pressure is then released and the sample film removed.

Conclusion

During the pressing, the Biome bioplastic is forced through weaknesses between the wood fibres, the molten Biome creates a medium for the fibres to flow through. As the sample is compressed the fibres suspended in the Biome can then only travel sideways. This can only happen when:

1. The veneer is completely sandwiched between layers of Biome.
2. There is no mould restricting the movement of the Biome and veneer (such as in experiment 1) allowing the fibres to spread out with the Biome as the film is made.

Further work in pressing veneer/Biome films will focus on pressing films using extruded sheets of Biome. In this experiment there is a clear trend (although the number of samples is small) that the use of pellets breaks apart the veneer and offers poor coverage. Using layers of sheet Biome provides a consistent even coverage for the veneer, producing a film with more aligned and intact fibres.

Ideally, further samples would have been made to characterise the effect of preheating the samples before pressing, however the use of pellets is not a direction for further research. For pressing films using sheet Biome, the heat will transfer through the Biome more efficiently because there is improved contact between layers - meaning a reduced preheat time can be used. As far as preheating is concerned it is important for both the simplification. The challenges posed by the design have meant that the component could not be fabricated using the veneer/Biome material.

The design of components such as this corner section (figure 4.8) demonstrate the limitations of the pressing process and the veneer/Biome material. Attempting to design parts such as this show the challenges of designing and manufacturing using veneer/Biome. The increasing complexity of the frame increases the number of moulds needed for construction, the number of pressings needed and the number of parts to be glued and clamped. The time and resources required to achieve this are not available within the constraints of the EcoCar project. Another issue includes the quantity of veneer/Biome layers required for pressing into components. The time constraints on designing the part are compounded by the machining of moulds and pressing of parts.

At this point during the study it is clear that due to equipment, resources and time available it is not feasible to construct two entire veneer/Biome side frames for the car chassis. In order to complete the car in time, the experiment is scaled down to a section of the frame being constructed using the veneer/Biome material.

Figure 4.9 shows a moulded straight section of the supporting frame – consisting of a flat section and two L shape mouldings. Integrating the veneer/Biome component to the car is achieved by bonding the overlapping sections with a two-part epoxy adhesive.

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Figure 4.9, Veneer Biome section of the 2014 EcoCar chassis frame.

	Conditions		Results		
Sample	Pressure (MPa)	Temperature (°C)	Film size after press L x W (mm)	No. of splits	Thickness (mm)
5a	0.4	190	30 x 30	0	1
5b	7.6	190	30 x 42	6	0.7
5c	11.5	190	30 x 44	7	0.6
5d	44.7	190	30 x 50	>12	0.4
5e	44.7	180	30 x 46	>11	0.6
5f	44.7	160	30 x 42	7	0.8
5g	44.7	140	30 x 41	6	0.9

Table 5.3, Experiment 5 parameters

Results

The resulting films are shown in

Figure 5.3, Films pressed during experiment 5

Analysis

At low pressures there is not enough force for the Biome to penetrate the gaps between the wood fibres. At the pressure where the fibres start to separate, the fibres in the film spread out dramatically, increasing 40% - 50% the width of the original wood veneer. At between 11MPa and 44MPa the wood in the film ceases to spread, and the wood fibres are compressed further.

The resulting thickness of sample 5D demonstrates that the wood fibres are being excessively compressed to a point where they are certainly being damaged. Damaging the fibres in this way will weaken a material that is made of a stack of these films.

The graph in figure 5.4 displays how far the fibres travel in the film for samples 5A, 5B, 5C and 5D.

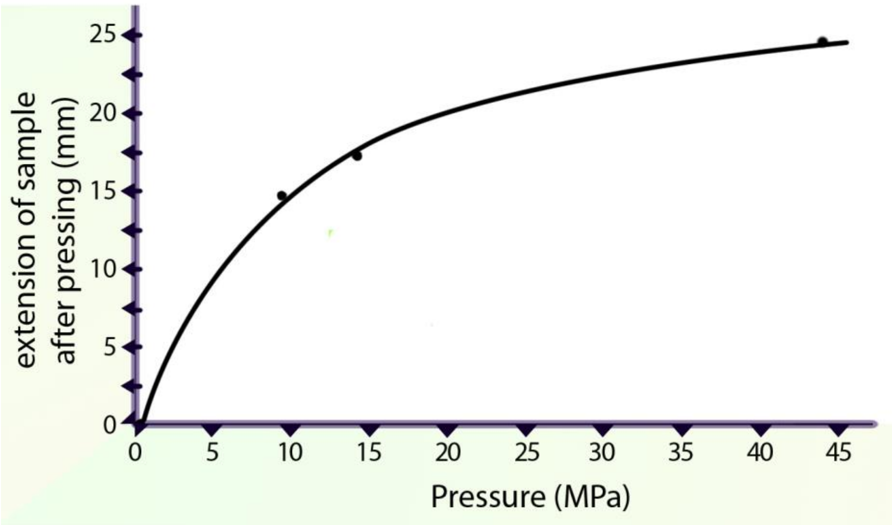

Figure 5.4, Sample extension due to pressure graph.

What the results of this test do not show is the exact pressure at which the samples start to split apart. There may be factors that affect the pressure at which this happens due to the shape of the veneer in the sample. Increasing the width across the grain would increase the number of splits and means the fibres have more resistance when spreading. Longer fibres mean a larger split is needed. These variables need further examination.

When the temperature is varied, at the lower temperatures (140°C) the two layers of Biome sheets can still be distinguished, demonstrating that the temperature was not high enough for the Biome to flow properly. This is expected as the temperature range for this experiment is below the 200°C - 230°C processing range as stated in the Biome data sheet (Appendix A). It is worth noting however, that the combination of temperature and pressure is still sufficient to split the veneer.

As the temperature was increased to approach the melt processing range, the Biome layers could not be distinguished. As the plastic has become more molten, the wood fibres can be seen more clearly indicating the Biome has penetrated further through the veneer in the sample.

The graph in figure 5.5 shows how the temperature has affected the processing of samples 5D,5E, 5F and 5G.

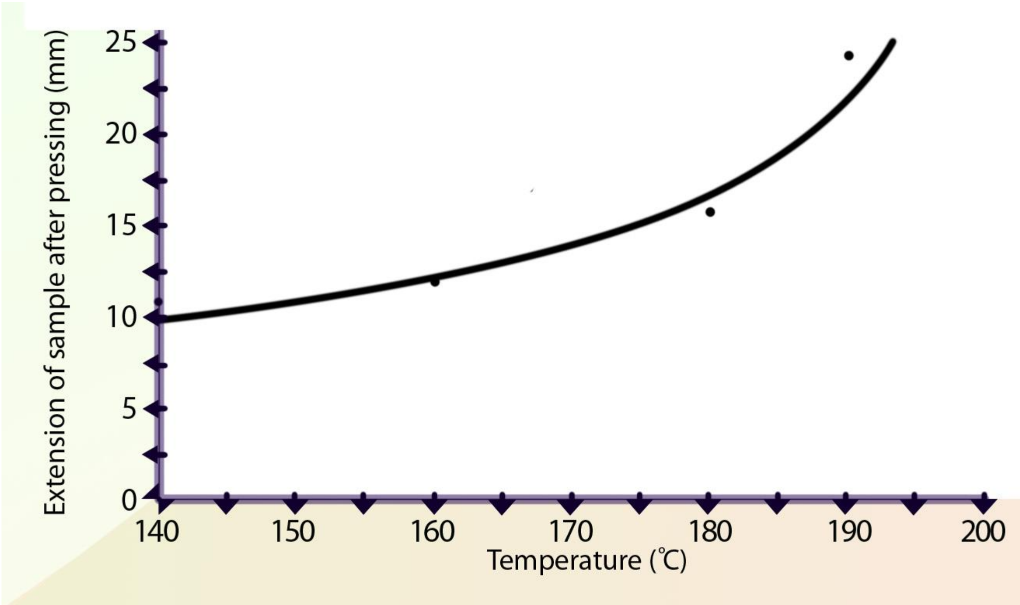

Figure 5.5, Sample extension due to temperature graph.

The graph in figure 5.5 may be inaccurate (due to low number of samples), however, the general trend suggests that as the temperature increases the veneer splits and spreads more to the point where at circa 200°C the wood fibres in the veneer are destroyed (as shown in experiment 2).

These results are to be expected, as the Biome will flow better at higher temperatures allowing the sample to spread more easily. The substance holding the fibres together will weaken at a higher temperature. This accounts for the increase in the number of splits in the veneer at higher temperatures.

It was observed that when the veneer starts to separate, it does so along the growth boundaries of the wood, it is presumed these regions are the weakest.

Samples 5C and 5E produced similar results in terms of the resulting size and thickness of the sample after pressing. There were differences in the behaviour of the veneer within the sample, the sample under greater pressure has many more splits. The overall results suggest that it is a combination of both heat and pressure that split the veneer.

Limitations

The full extent to which temperature and pressure interact during processing is not clear. Repeat experiments would provide more reliable data - as only a single sample is produced at each set of parameters. Natural variations in the birch wood will affect the properties during processing.

Categorising the outcome of the pressing exposes the limitations of analysing the films visually, as small bubbles and faults in the bonds between the fibre and the polymer matrix can not be observed. It would be advantageous to examine the structure of the films with a microscope, this is conducted in similar material studies (Kamath, 2005).

Counting the number of separations provides an indication as to what is happening during the process, however, this is not a definitive metric for measuring the properties in the samples created.

The films produced are small in comparison with any component that might be manufactured. Different behaviour may be observed in veneer/Biome films produced at an increased scale.

Conclusion

At increased temperature and pressure, greater separation of the fibres occurs. In these small square samples, the fibres separate laterally, to the point where the width of film which contains fibres increases by 40% - 50%. At the lower end of the pressure range the fibres do not split and at the higher pressure range the wood fibres are crushed. At the lower temperature range the Biome plastic is not molten and does not flow properly and as it is increased towards the recommended processing temperature, the fibres are destroyed. These results demonstrate that a full range of temperatures and pressures have been considered.

For subsequent tests it is concluded that a processing temperature range of 170°C to 190°C is used. The optimal pressure to be used is uncertain, but between 1.0MPa and 3.0MPa seems sensible for the 30mm x 30mm sample size used in this experiment.

5.2.2.3 Experiment 6 - pressure and scale investigation

Further variation of hot press parameters will provide an increased understanding of the veneer/Biome processing. Again, the method for creating samples will be to produce small films.

This experiment will study whether an optimal pressure can be established. For experiment 6 the scale of the samples are marginally increased. The differences observed in the resulting films are compared to the smaller samples produced in experiment 5.

Test conditions

For this experiment, 8 samples were produced at increasing pressures. This provides a larger data set than was produced in experiment 5. A wider range of pressures should provide a clearer progression of how the films spread under pressure. The following test conditions were kept consistent across experiment 6:

- Sample size - 40mm x 40mm birch veneer
- Layers - Veneer sandwiched between Biome sheets (consistent with exp. 5)
- Pre-heat time - 4 minutes (consistent with exp. 5)
- Press time - 5 minutes (consistent with exp. 5)
- Temperature - 190°C (consistent with exp. 5)
- Pre-pressed sample thickness - 1.0mm (0.6mm veneer, 2 x 0.2mm Biome). (consistent with exp. 5).

Results

The table 5.4 displays the results of varying the processing pressure using the 40mm x 40mm square samples (a larger sample size than used for experiment 5).

Sample	Conditions		Results		
	Pressure (MPa)	Temperature °C	Number of splits	Film thickness (mm)	Resulting film size L x W (mm)
6A	3.11	190	5	0.8	40 x 54
6B	6.35	190	8	0.7	40 x 62
6C	25.09	190	11	0.7	40 x 62
6D	31.3	190	11	0.75	40 x 60
6E	37.5	190	9	0.65	40 x 61
6F	43.77	190	13	0.7	40 x 62
6G	50.00	190	13	0.6	40 x 60
6H	56.23	190	15	0.6	40 x 61

Table 5.4, Experiment 6 parameters - variation of pressure

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Figure 5.6, Images of experiment 6 sample films

Analysis

The resulting films displayed in figure 5.6 show that - consistent with experiment 5 - at the increased pressures:

- More separated fibres are created in the films.

- Films become thinner.

Results table 5.4 shows that the maximum width extension of 12mm is reached at 6.35MPa. The amount the fibres spread at higher pressures is consistently 20mm - 22mm. This amounts to a width increase in the section containing wood fibres of around 50%. The use of pressure to process sample 6B is more than 8 times that used to process sample 6H suggesting that the fibres within the film will not travel any further than this 50% width increase.

The percentage increase in sample width is shown in the graph in figure 5.7. The results for experiment 6 (purple) are compared with those of experiment 5 (dashed blue). For the results for the two experiments to be comparable they have been normalised as a percentage increase in width - with the width measured as between the outer fibres in the sample.

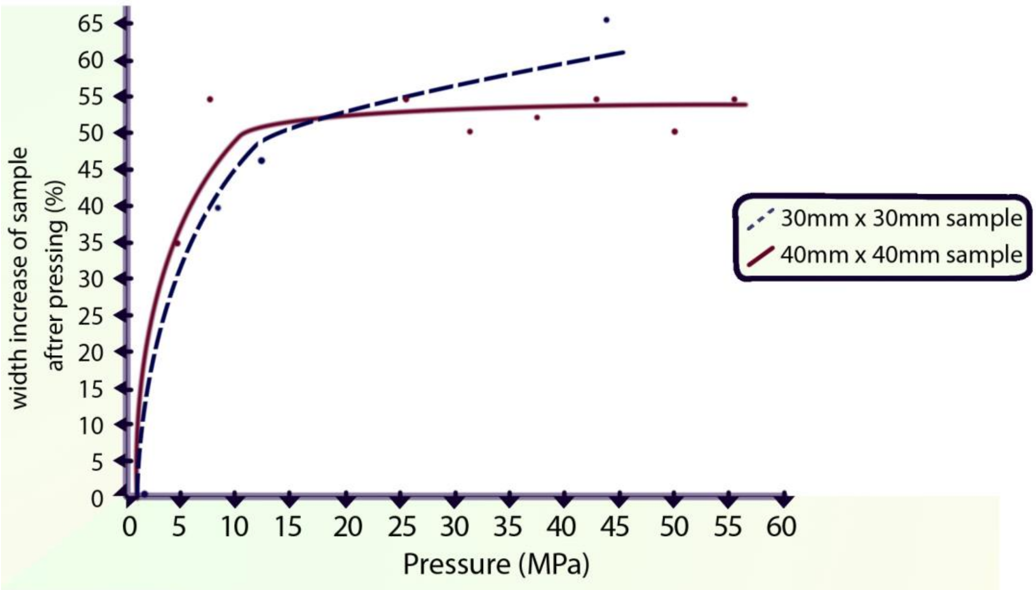

Figure 5.7, Graph comparing the pressure to the width increase when the scale of sample is increased.

The points on the graph in figure 5.7 are somewhat scattered, but they show a similar trend. A certain amount of pressure is required to start splitting the fibres, after which they separate at the growth regions in the wood. These pieces separate to increase the width of the sample by 45% to 55% (as well as some distortion to the shape).

The graph in figure 5.8 shows how the number of splits increases with the pressure.

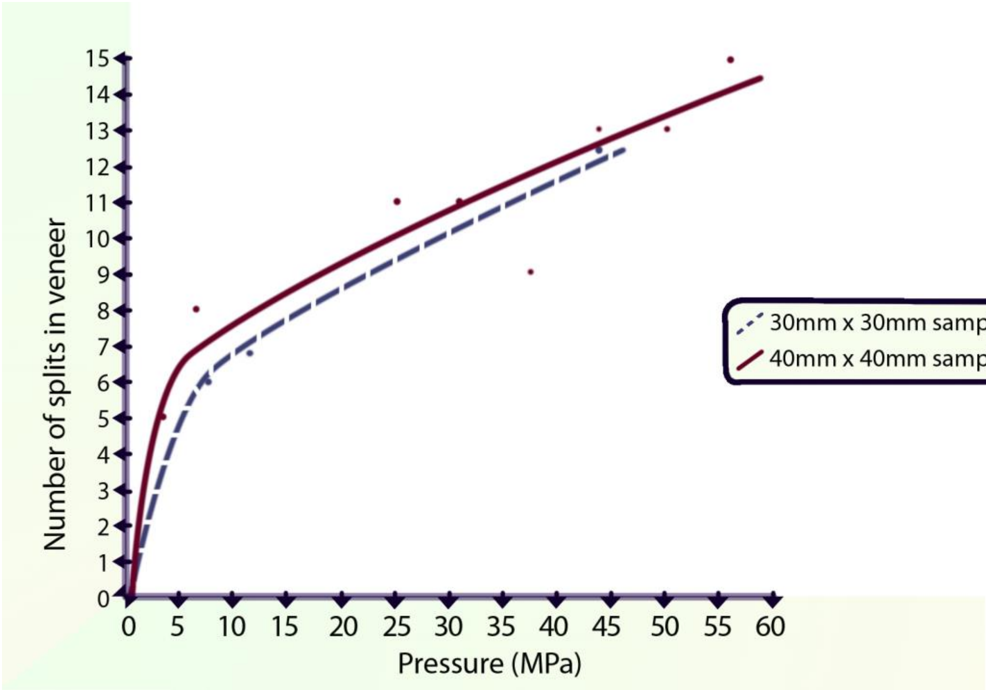

Figure 5.8, Graph comparing the pressure to the number of splits in the veneer when the scale of sample is increased.

It can be seen in figure 5.8 that under increasing pressure the wood veneer continues to be split. Overall the fibres in the sample cease to spread at 15MPa to 20MPa. At higher pressures the larger pieces separate into smaller bundles of fibres.

The 30mm square sample has less splits because there are fewer fibres. Both sets of results show a similar progression. The optimal pressure to use for creating a composite depends on how the mechanical properties are affected at higher pressures. Additional separated fibres dispersed in the Biome may be advantageous in creating a composite providing the fibres are not too damaged.

From the two graphs (figures 5.7 and 5.8) it appears that the separation of the fibres happens in 3 phases:

1. <u>0.4MPa to 4MPa</u> - Splitting - The molten Biome is forced between the fibres of the birch veneer.
2. <u>4MPa and 20MPa</u> - Spreading - A small number of initial splits - which occur at the growth boundaries - spread laterally, increasing the width of the area containing fibre. This region extends by 50%.

3. >20MPa - Pressure - Increasing the pressure further separates the bundles of fibres. There is no further spreading - there is no further increase to the overall size.

From experiment 6 it remains unclear how the length of fibres and the shape of the sample effect the separation process.

5.2.2.4 Experiment 7 – Aspect ratio

Experiment 7 investigates how the fibre separation is affected by the aspect ratio of the veneer sample. In experiments 5 and 6 square samples were pressed. This produced consistent results for the resulting size of films. During Experiment 7 the length and width of the veneer are investigated.

Test conditions

The total area of each sample is to be kept at 1600mm^2, however the length and width are varied.

Pressing conditions were kept consistent across experiment 7:

- Sample size - 1600mm^2 birch veneer
- Layers - Veneer sandwiched between Biome sheets (consistent with exp. 6)
- Pre-heat time - 4 minutes (consistent with exp. 6)
- Press time - 5 minutes (consistent with exp. 6)
- Pressure - 43.7MPa (consistent with exp. 6F)
- Temperature - 190°C (consistent with exp. 6)
- Pre-pressed sample thickness - 1.0mm (0.6mm veneer, 2 x 0.2mm Biome). (consistent with exp. 6)

The area of each sample is maintained at 1600mm^2, however a range of wide samples with short fibres and thin samples with long fibres were prepared.

Results

The results of experiment 7 are displayed in table 5.5.

	Conditions		Results	
Sample	Original width - across fibres (mm)	Original length - along fibres (mm)	post-press increase in width veneer/Biome region (mm)	percentage width increase
7A	160	10	2	1%
7B	80	20	17	21%
7C	53	30	20	38%
6F	40	40	22	55%
7D	30	53	19	63%
7E	20	80	20	100%
7F	10	160	11	110%

Table 5.5, Experiment 7 parameters - fibre width and length variation

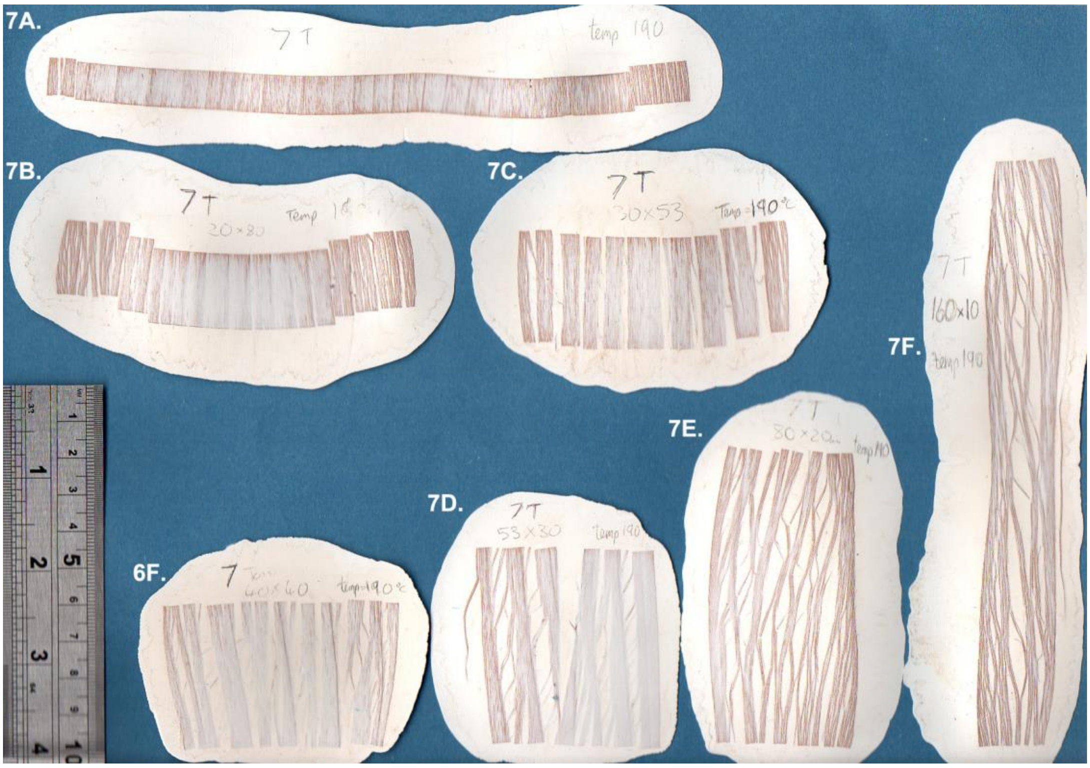

Figure 5.9, image of Experiment 7 sample films

Analysis

The width in the region containing wood fibres dramatically increases with narrower veneers suggesting that the separation of wood fibres is reliant on the number of fibres in the sample - which increase with width. The length of fibres in the veneer may not have a large influence on the resulting film size.

Sample	Conditions		Results		
	Pressure (MPa)	Temperature °C	Number of splits	Film thickness (mm)	Resulting film size L x W (mm)
6A	3.11	190	5	0.8	40 x 54
6B	6.35	190	8	0.7	40 x 62
6C	25.09	190	11	0.7	40 x 62
6D	31.3	190	11	0.75	40 x 60
6E	37.5	190	9	0.65	40 x 61
6F	43.77	190	13	0.7	40 x 62
6G	50.00	190	13	0.6	40 x 60
6H	56.23	190	15	0.6	40 x 61

Table 5.4, Experiment 6 parameters - variation of pressure

Figure 5.6, Images of experiment 6 sample films

Analysis

The resulting films displayed in figure 5.6 show that - consistent with experiment 5 - at the increased pressures:

- More separated fibres are created in the films.

5.2.2.5 Additional research

These characterisation experiments are a limited investigation into the veneer/Biome characteristics. An understanding of the separation of veneer fibres has been achieved. It is recognised that a further, more detailed investigation would provide an understanding of the mechanical properties beyond observations of the film samples. It is accepted that these limitations result in only partial insights into the veneer/Biome behaviour. Sufficient knowledge of the processing variables however, allows the veneer/Biome to be considered for the design and manufacture of a component.

It has been discovered that control of the processing conditions needs more accuracy than the available equipment allows. The analysis of this study has focused on what happens visually to the bundles of fibres within the film samples. Additional research would focus on using robust experimental design (Phadke, 1989). It would be beneficial to further development to investigate how the Biome and wood fibres are interacting at a microscopic scale. These methods would increase knowledge about the damage to the fibres, how they are bonding to the Biome and weaknesses in the structure.

5.2.2.6 Characterisation of veneer separation conclusion

This series of experiments has demonstrated the importance of a number of variables in the processing of the veneer/Biome material. It has been found that sandwiching birch veneer between sheets of Biome bioplastic separate the wood fibres in a promising manner – the fibres remain intact and aligned (Experiment 4). Through these experiments the mechanisms by which the fibres in the wood veneer separates is better understood.

As a result estimates in table 5.6 show the processing parameters which veneer/Biome should be processed:

Variable	Effect	Compromise	Sensible range
Temperature (°C)	Higher processing temperatures allow the Biome to flow better.	At the optimum temp for Biome processing (200°C) the fibres are damaged.	170°C - 190°C
Pressure (MPa)	Higher pressures separate more wood fibres.	Too much pressure damages the fibres	4MPa - 8MPa (depending on sample size)
Pre-heat (minutes)	Longer preheat times (up to 10 minutes) allow for a less violent splitting of veneer fibres.	Long preheat times lengthen processing time, enough time is needed for the heat to permeate through material.	5 - 15 minutes
Sample shape (mm^2)	The wider a sample is across the grain, the more pressure is needed to separate fibres. Larger samples (at low MPa) can be made if narrower	Large samples can not be processed using current equipment	100mm along grain x 50mm across grain (for a square sample allows 1.96MPa on a 10T press).

Table 5.6, characterisation of veneer/Biome film pressing.

Taking what has been learned during these experiments further, the next step is to apply the material to a component on the Aston EcoCar. Tensile testing of the resulting material can then be performed.

Any component to be designed and manufactured in the future is likely to be larger than the 40mm x 40mm samples prepared in this experiment. Moulding the material, and scaling up samples to a larger - more useful - size needs to be evaluated so that a part can be designed and manufactured using the hot press process.

Processing a part manufactured using veneer/Biome composite requires further development of the processing limitations - for example, the minimum radius on a corner in a mould, and the ability to process larger format films.

5.2.3 Investigating manufacturing using veneer/Biome

For components to be manufactured using veneer/Biome, the stacking and moulding of veneer/Biome needs to be investigated. The previous tests were useful in providing a better understanding of how the material behaves. The knowledge of processing parameters can now be applied.

This set of experiments will focus on larger films and the moulding process. Understanding the behaviour of the veneer/Biome material for this step in the manufacturing process will aid in the design of a mould and ensure a component can be designed.

<u>Aim</u>

Investigate how the veneer/Biome films can be processed into a useful composite for the design and manufacture of an EcoCar component.

<u>Objectives</u>

- Study how layers of films can be stacked in a mould.
- Investigate the processing of moulded veneer/Biome parts.
- Determine the minimum radius that veneer/Biome can be moulded with the fibres intact.
- Evaluate larger formats of veneer/Biome films.

5.2.3.1 Methodology

<u>Large format films</u>

Larger sample sizes of veneer/Biome film are created in order to generate a material suitable for layering into a mould. The scalability of producing films with separated fibres is evaluated. Manufacture of a part requires larger format films than were created during the characterisation experiments.

<u>Minimum Radius test</u>

A mould has been developed in order to test the minimum radius that veneer/Biome can be pressed in before the wood fibres break. A range of radii will be evaluated. The mould contains a series of decreasing half round sections for a 1mm thickness veneer/Biome composite sample to be moulded in. Figure 5.10 details the design of this mould.

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Figure 5.10, Image of the radius test mould, designed to test 1mm thickness sample of veneer/Biome.

The mould graduates from a radius of 12.5mm down to 3.2mm. This range will indicate the minimum radius than can be recommended when designing moulds for the veneer/Biome material.

5.2.3.2 Experiment 8 - Investigating an increase in the scale of film size

During experiment 7 it was observed how the samples containing longer fibres create a mesh pattern when pressed. Samples with shorter fibres separate in distinct bands. Further exploration of samples larger than 40mm x 40mm is required. Creating larger films will aid in the development of a scaled up process.

The manufacture of the component in this main study will be conducted on the lab press. In order to produce films for manufacture, the capabilities of the lab press (a 10 tonne hot press) needs to be investigated. Experiment 8 will investigate the optimum size of film able to be pressed using the current processing equipment.

<u>Experiment 8 methodology</u>

When producing the veneer/Biome films, the pressure available is a limiting factor. The maximum size of veneer/Biome sample that can be processed on the lab press is 300mm x 300mm. Using the full 10 tonnes available, the pressure on the sample will be 1MPa.

At 1MPa the layers of Biome and veneer do not split. When cooled the sample shrinks and cracks and the layers delaminate.

In order to manufacture the largest possible component it is proposed that:

1. Films with long fibres (running the length of the film) are pressed.
2. The long narrow films are placed side by side. This creates a 'sheet' by forming a larger area of long aligned fibres.
3. The 'sheet' can then be stacked with layers of similar 'sheets' and pressed into a component.

The processing time for the pressing of each film is approximately 1 hour. To limit the time required to manufacture a component it is desirable to reduce the quantity of films needed.
It is proposed that a maximum of 4 films are used to create a square 'sheet'. If 5 layers of veneer/Biome were used to mould a product, this would require 20 films to be pressed. Pressing 20 films (20 hrs) to create the material for manufacture of a component is an acceptable proposition.

The objective of experiment 10 is to discover the veneer size that will produce a film with the following characteristics:

- <u>The width is a quarter of the length:</u> A ratio of 1:4 would allow a square 'sheet' of 4 films to be prepared.
- <u>The fibres are evenly separated:</u> This allows small bundles fibres to be distributed in the composite.

<u>Test conditions</u>

The following conditions were kept consistent across experiment 8:

- Layers - Veneer sandwiched between Biome sheets.
- Pre-pressed sample thickness - 1.0mm (0.6mm veneer, 2 x 0.2mm Biome).
- Pre-heat time - 4 minutes
- Press time - 5 minutes
- Temperature - 190°C

<u>Results</u>

The results of experiment 8 are displayed in table 5.7.

Sample	Parameters			Results			
	Veneer size (mm)		Pressure (MPa)	Film size (mm)		L:W ratio (1:4 target)	Fibre splits per 10mm
	Length	Width		Length	width		
7E	80	20	43.7	80	40	1 : 2	2.5
8A*	110	20	24.5	143	38	1 : 3.7	3
8B	180	40	13.6	180	70	1 : 2.5	3
8C	230	30	14.2	230	65	1 : 3.5	2
8D	260	50	7.5	260	65	1 : 4	1.7

Table 5.7, Experiment 8 parameters and results

* An increase in length is observed due to fibres at 30° angle.

Figure 5.11, Image of experiment 8 samples.

The images of samples 7E, 8A and 8B in figure 5.11 show that the fibres have separated in an even fashion. Sample 8A has the same mesh pattern seen in sample film 7E. This appears to be a trait of the larger samples, with fibres in excess of 70mm long. This may be due to the structure of the wood and the weaknesses exploited by the processing.

Sample 8B displays even separation of fibres. The width increase of 75% demonstrates the desirable traits for a larger film, suitable for manufacture. In the larger samples 8C and 8D the fibres have not separated in an even manner. Sample 8D is of the desired dimensions but contains few separated fibres.

The increase in length allows for larger format films to be made, however this is limited by the maximum force produced by the press.

It is recommended that using the current 10 tonne press, the largest film that can be used for moulding a component is 200mm x 200mm. This is based on:

- 200mm x 35mm veneers pressed to create 200 long x 50mm wide films.
- Using 4 films placed side by side to create a 200 x 200 veneer/Biome 'sheet'.

Sample 8E - Pre-separating fibres.

An alternative method of producing evenly separated fibres with the veneer/Biome film is to pre-separate the fibres. The width across the grain of the wood is key to how much the fibres separate. The fibres in thinner strips of veneer may separate at lower pressures. If these can be formed into a large film in a single pressing, this would both increase the size of films that can be produced and reduce the number of pressings needed.

It is theorised that a large film can be produced by using thin strips of veneer (similar to sample film 7N) positioned next to each other.

Sample 8E was prepared by:

- Layers - 5mm wide veneer strips are placed 5mm apart side by side, sandwiched between Biome sheets.
- Total pre-press film size - 200 wide x 220 long
- Pre-pressed sample thickness - 1.0mm (0.6mm veneer, 2 x 0.2mm Biome).
- Pre-heat time - 4 minutes
- Press time - 5 minutes
- Temperature - 190°C
- Pressure - 1.8MPa

Results

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Figure 5.12, Experiment 8E Film.

As displayed in figure 5.12, the strips of veneer in sample 8E do not separate. It is suspected that when pressed, the Biome flows over the top of veneer rather than forcing its way in between the fibres.

Conclusion

A press able to apply more force would increase the scalability of the film sizes. A 20 tonne press would be able to produce veneer/Biome components that are the area of the platens (300mm x 300mm).

For testing the moulding capabilities (Experiment 9), a recommended standard size of film - that will separate under a sensible range of parameters - is required.

5.2.3.3 Experiment 9 - veneer/Biome moulding capabilities investigation

Previous development has focused on single veneer/Biome films so it can be understood how the wood veneer in the sample splits. To further develop a veneer/Biome composite these films need to be stacked in layers and pressed again.

A specific constraint on the design of parts to be made using veneer/Biome, is the minimum radius that the veneer/Biome can be pressed into before the fibres break. This will dictate how sharp the corners can be in a mould. More generally, this experiment will also highlight other challenges in the moulding process. The tests will be carried out using the minimum radius test mould described figure 5.10.

<u>Test conditions</u>

Veneer/Biome films are pressed before being stacked into the radius test mould described in figure 5.10. This test mould is then pressed producing the samples for analysis.

<u>Film production</u>

Films for layering into the mould were prepared using similar conditions for all of the following radius test mouldings. The films have been standardised so that the results of the moulding tests are comparable. These conditions were:

- Veneer size - 110mm (along grain) x 50mm (across grain)
- Pressure - 18 MPa
- Temperature - 195°C
- Preheat time - 5 minutes
- Press time - 10 minutes

The resulting films have a thickness of 0.6mm.

<u>Layering of films in radius mould</u>

These films are then cut into strips 110mm x 24mm. 3 layers of film are then stacked into the radius test mould in the following manner:

- Layer 1, The grain runs along the length of the mould.
- Layer 2, The grain runs across the width of the mould - at 90 degrees to layer 1.
- Layer 3, The grain runs along the length of the mould.

The direction of the grain is alternated, with the outer layers running the length of the mould so that the behaviour of the wood fibres can be observed.

Radius test mould pressing

Two samples were moulded using the radius test mould under the processing conditions in table 5.8:

Moulded Sample	Pressure (MPa)	Temperature °C	Preheat time (minutes)	pressing time (minutes)
9A	27.5	180	5	10
9B	35.3	220	10	10

Table 5.8, Radius test mould processing parameters

Results and analysis

After pressing, the fibres can be seen in the resulting sample. A portion of test sample 7A is shown in figure 5.13.

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Figure 5.13, Image of Sample 9A showing the 3.2mm, 5mm and 7.5mm radius sections.

In figure 5.13, where the material has been moulded to a radius of 3.2mm, it is observed that the fibres have broken at the crest of the curve. These broken fibres indicate that the curve is too sharp. On the 5mm and 7.5mm radius curves, the fibres in the moulding are intact. Similar results can be seen in figure 5.14, in sample 9B the fibres have broken when moulded to a radius of 3.2mm.

Figure 5.14, Image showing the fibres in samples 9A (top) and 9B (bottom).

For sample 7B higher temperature, increased pressure and longer heating period were used during processing. When comparing the two samples in figure 5.14 it is clear from the darker fibres in sample 7B that the higher temperature has significantly damaged the fibres. It can also be seen in the flat sections between the curves that the fibres are destroyed where they have been compressed.

From producing the two samples shown in figure 5.15, a number of issues in the moulding of the veneer/Biome composite can be observed. In figure 5.15, uneven fibres within the moulding can be seen. There are a number of broken fibres within the sample, some of these issues can be accounted for by inaccurate mould manufacture (inconsistent cavity thickness).

Figure 5.15, Image of sample 9A (front) and 9B (back)

More concerning than the manufacturing errors in the mould are the regions where the films have not been pressed together and films have failed during processing - shown in the figure 5.16.

Figure 5.16, Image of sample 9A showing regions of failure.

The higher temperature and pressure used in processing sample 9B offer improvement to the moulding problems of 9A (220°C is the optimal Biome processing temperature). The temperature increase, however, destroys the fibres.

Regions remain in sample 9B where the veneer/Biome layers have been broken during processing. This occurs because films are stretched as they are pressed into the mould, the fibres do not stretch and therefore break. This effect, where the fibres have been broken during processing is described as 'dragging'. If the Biome was more fluid, then the fibres could slide more easily into the mould when being processed. This 'dragging' issue will cause constraints in the moulding of the veneer/Biome composite, due to the limited movement of the fibres during processing.

During the preheat phase of the moulding process there was limited contact between the layers of veneer/Biome and the surface of the mould. This could lead to the sample not being thoroughly preheated. A lack of processing temperature affects both how the fibres move within the Biome as well as the radius to which the fibres can be moulded. Further work is required so that the sample is heated thoroughly before pressing.

Moulding conclusion

Improvements to mould design are required. A radius can be put along the edges of the moulding surface in an effort to prevent the described 'dragging' effect of the fibres. The inaccurate manufacture of the radius test mould contributed to the delamination issue. Future moulds need to be manufactured to a higher tolerance.

To further address the delamination issue, 'dragging' effect and layers sliding within the mould a further process step can be introduced. Layers of flat films can be pressed together to produce a pre-moulding 'blank'.

This test has successfully shown that veneer/Biome should be moulded into no less than a 5mm radius corner. The test has also highlighted some of the issues concerning the moulding process. Some of these issues can be solved through improving the mould. The most concerning problem is the 'dragging' issue, where the fibres break during moulding as the material is elongated when forced into the mould. There may be a constraint as to how far the veneer/Biome can be deformed during the moulding process, limiting the depth of the mould.

5.2.3.4 Manufacturing investigation conclusion

For designing a material, Initial basic testing and application of the material was a key starting point for further development (Chapter 4 - the pilot study). Through conducting this series of preliminary experiments, the processing behaviour of the material has been observed and is better understood. Investigating the material in this manner provides immediate information on the direction of development, highlighted the areas for improvement, indicated the areas which needed better understanding and signalled the limitations of how the material can be applied.

The exact strength and flexibility of the veneer/Biome material remains unknown. From the Biome datasheet, the pilot study and these materials experiments general properties of the material have been observed. The addition of wood fibres to the Biome bioplastic have improved the stiffness of the formulated composite. The veneer/Biome material can now be subject to a design and manufacture process. For an accurate evaluation of the materials properties, the exact properties will be tested on the material used for manufacture of the component.

It is therefore recommended that to mould a component using Biome and birch veneers the process described in figure 5.17 is used:

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Figure 5.17, Recommended veneer/Biome process flowchart

The process described figure 5.17 contains 26 listed parameters, choosing the levels of these variables in the manufacturing process will determine whether the final product is successful. By considering the results of the materials investigation, the levels in table 5.9 have been judged to offer the greatest chance of producing a successful product.

Recommended processing variables				
Process	Variable	Previously investigated	Rationale - possible effects	Acceptable range
Materials choice	Choice of plastic	Biome HT90 bioplastic	Properties selected in section 4 (materials selection)	HT90
	Extrusion variables	none	Externally supplied by Biome bioplastic	-
	Biome sheet thickness	0.2 - 0.3 mm thickness	Externally supplied by Biome bioplastic	0.25 $^{+}/-$ 0.1 (mm)
	Choice of wood	birch veneer	High availability of birch commercially.	Birch veneer
	veneer thickness	0.6 mm thickness	As supplied	0.6 (mm)
Film pressing	Film size	90 - 360mm^2	Affects the pressure needed to split wood fibres - press limitations of resulting part size. 20 tonne press required.	Max size 40mm (across grain) 280mm (along grain)
	Preheat time	0 - 15 mins	Heating through affects the severity of pressing	10 to 20 minutes
	Press time	0 - 10 mins	No great effect on outcome of film - could affect bond strength in sample	10 to 20 minutes
	Cooling time	0 - 50 mins	Affects ductility of sample - but unable to test	Heat removed, cooled to 100^{o}C
	Temp (^{o}C)	140°C - 200°C	Critical parameter for separating fibres	175 ^{o}C to 190 ^{o}C
	Pressure	0 - 12 MPa	Critical parameter for separating fibres - limited by press	10 to 20 MPa
	Biome to veneer ratio	1:1 (by material thickness)	Will affect the weight, strength and stiffness of resulting film.	1:1 - 2:1

stacking 'Biome/veneer' films to press 'blank'	Preheat time	0 - 15 mins	Heating through affects the severity of pressing on the fibres	10 to 20 minutes
	Press time	0 - 10 mins	No great affect on outcome of blank - could affect bond strength in sample	10 to 20 minutes
	Cooling time	0 - 50 mins	Affects ductility of sample - but unable to test	heat removed, cooled to 100^{o}C
	Temp (^{o}C)	140°C - 200°C	Critical parameter for bonding layers	175^{o}C to 190^{o}C
	Pressure	0 -12MPa	Critical parameter for bonding layers - limited by press	5 - 10 MPa
	Biome to veneer ratio	1:1 (by material thickness)	Will affect the weight, strength and stiffness of resulting film.	2:1 to 1:2
	number of layers	2 - 5 layers of films	Dependant on the thickness required	3 to 7 film layers
	orientation of fibres	none	Direction of fibres affects the resulting strength in a particular direction.	unidirectional layers stacked at 90^{0}
	thickness of blank	none	Dependent on part thickness	more than part thickness (4 to 6mm)
Pressing moulded part from blank	Thickness of part	none	flat part can be cut from blank, effect of extra pressing cycle has not been determined	3 to 4mm
	Preheat time	0 - 15 mins	heating through affects the severity of pressing	10 to 20 minutes
	Press time	0 - 10 mins	no great affect on outcome of film - could affect bond strength in sample	10 to 20 minutes
	Cooling time	0 - 50 mins	affects ductility of sample - but unable to test	Heat off, cooled to 100^{o}C

	Temp (ºC)	140°C - 200°C	critical parameter for bonding layers	175 ºC to 190 ºC
	Pressure	0 -12MPa	critical parameter for bonding layers - limited by press	1 to 20 MPa

Table 5.9, recommended processing variables.

These parameters will inform the design and manufacture of a 2016 Aston EcoCar component.

5.3 2016 EcoCar Wishbone design report.

5.3.1 Introduction

The sustainable design philosophy and the understanding that has been gained from the veneer/Biome materials experiments is now applied to a component. Continuing the M/D/M philosophy, the knowledge of the veneer/Biome material will be used to inform the design and manufacture of a component for the 2016 Aston EcoCar. This will be carried out using a product design process described in methodology section 3.5.

Applying the veneer/Biome composite material to the 2016 Aston EcoCar will provide evidence as to the usefulness of the material under development, identify the manufacturing challenges the material presents and allow analysis of the M/D/M process. The first stage of the design process is to assess the 2015 EcoCar design and 'frame the problem'.

5.3.1.1 2015 Aston EcoCar evaluation

The 2015 Aston EcoCar displayed in figure 5.18 was a partial success at the 2015 Shell EcoMarathon, however there were serious issues.

Figure 5.18 - The 2015 Aston EcoCar, a flawed concept?

Table 5.10 is a breakdown of the targets set for the EcoCar by the management team at Aston University and the vehicles performance at the competition.

Target	How target is accomplished	Performance	Comment
Build a vehicle	manufacture and assemble the car components in time for competition	5/10	Components were manufactured, but the car was not fully assembled.
Follow the 'Aston Wooden car' ethos	Where possible use wood and sustainable materials	6/10	There are a significant amount of welded steel components. Little consideration to full lifecycle of vehicle
Pass the SEM technical inspection	Follow competition regulations	9/10	The vehicle passed the technical inspection with no major contravention.
Enter the competition	Drive 10 laps of the Rotterdam track within 30 minutes on 1 ltr of fuel.	0/10	The car achieved 6 laps before running out of fuel.
Win an award	Impress with the design, or be the most fuel efficient in the class.	0/10	In order to qualify for awards, a qualifying time was needed.

Table 5.10, 2015 Aston EcoCar performance review

The issues with the structure and performance relating to the team are not considered in this study, however, it is understood that a lack of testing and project management contributed to the vehicles poor performance.

Problem statement

Whilst achieving the basic targets - building a car that passed the SEM technical inspection, the team of students failed to build a suitable car to compete in the competition. The problems with the car can be broken down into:

Lack of 'Wooden car' sustainability ethos.

- Aluminium was bonded to wood - not conducive to disassembly and recycling.

- The team gave more thought to the use of steel and aluminium as construction materials - rather than biodegradable wood.
- Steel components have been welded in such a way as to prevent disassembly.

Failure to register a time in order to be eligible for the awards.

- The car weighed in marginally under the 200kg upper limit (set for safety reasons).
- There was a lack of integration between parts - components only performed a single function, overcomplicating the construction, and missing the opportunity to reduce weight.
- It has been speculated that the vehicle's rolling resistance was too high.

5.3.1.2 Design Proposal

There are three main areas where the veneer/Biome composite can provide a solution to the issues raised in the 'Problem statement':

1. Reduce weight.
2. Increase performance.
3. Improve the sustainable Aston 'wooden car' ethos.

It is proposed that a structural component be manufactured using the veneer/Biome.

<u>Aim</u>

Design a structural part on the 2016 Aston EcoCar using the veneer/Biome composite material.

<u>Objectives</u>

- Assess the options for applying the veneer/Biome composite and Identify a suitable component to be manufactured using this material.
- Conduct a review of the current component.
- Design a part that showcases the advantages of the veneer/Biome composite (biodegradable, structural and weight saving).
- Make a veneer/Biome component.
- Prove scalability of production.
- Evaluate the success of the component.

5.3.1.3 Designing using the veneer/Biome

Consideration to the final use of the material through its development has been given attention, further to this, the design of the component needs to take into account the material through the design process.

What has been learned in the materials development stage and the pilot study will inform the application and manufacture of the product designed in this phase. Ultimately the way the material is used will have an impact on the form of the product.

The following knowledge needs to be taken into consideration during this product design phase:

Material’s advantages.

- Lightweight moulded pressings,
- Strength,
- Stiffness achieved through moulding,

Processing restrictions.

- The bed size of the press is 300mm x 300mm,
- Minimum radius of moulded corners,
- Maximum depth of mould,
- Maximum thickness of the material.

These parameters will be detailed in the design specification - bringing together the materials and the design, which aids the manufacturing process.

Designing the part using the strengths of the material is an important part of the M/D/M approach.

5.3.1.4 Methodology

Product design process

The process used to develop the new component to be manufactured using the veneer/Biome material will follow the standard product design process described in figure 3.5

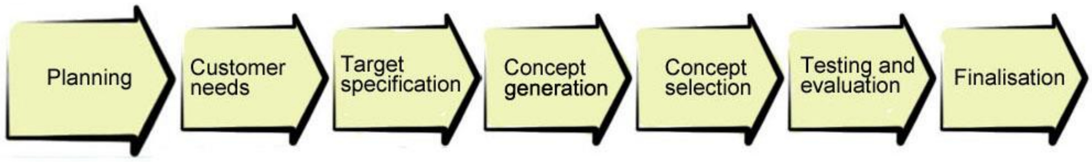

Figure 3.5, Generic product design process (Ulrich & Eppinger, 2008)

The process is tailored slightly with regards to the nature of the development project - utilising the appropriate design tools to structure the development. For example, the estimated load on the component is modelled to select the concept.

Benchmarking

The original component used on the Aston EcoCar at the 2015 Shell Ecomarathon competition is used in a benchmarking process. The performance and characteristics of the original component are measured and analysed, so that the new design can be measured against the original component (Ulrich & Eppinger, 2008 p.107).

Physical testing

Physical testing of the veneer/Biome component will provide vital data pertaining to the success of the veneer/Biome composite. This set of tests will be in the form of a performance test on the Aston 2016 EcoCar.
The performance of the design is critical to the success of the project and the material being developed. If the performance of the material can be shown to work, then the material can be said to have been a success.

5.3.2 Area of application

A number of factors are taken into consideration in order to make a decision as to what components will be designed using the veneer/Biome material.

Consideration factors

Material processing constraints.

1. The components will be limited in size. The veneer/Biome components will be manufactured on a 20 tonne 300mm x 300mm hot press.
2. Due to budget constraints, the moulds required will need to be simplistic to allow them to be manufactured for the limited budget.
3. The characteristics of the material limits the moulded radius to 7mm and the depth of the moulding to 25mm.

Suitability of application.

1. The application must demonstrate the advantages of the material - structural, lightweight and mouldable.
2. An exterior part of the vehicle.
3. Ideally the veneer/Biome component will replace one where less sustainable materials have been used.
4. The accessibility of the components to be replaced - removable original components and installation of the replacement.

Overall impact

1. As a showpiece component, the aesthetics of the design are notable.
2. The visibility of the component on the vehicle.
3. The function of the component should be easily recognisable.

As with an earlier pilot study, a number of suitable areas on the Aston EcoCar have been considered for the application of the veneer/Biome material. The options for the new component are:

a) A component of the frame supporting the chassis (as with the pilot study).
b) A supporting bracket for the door.
c) An interior structure supporting the dash or steering column.
d) A wheel upright, housing the bearings for the wheel shaft.
e) A front wishbone.

From the pilot study a number of lessons were learned. The main conclusion affecting this selection process is that a manageable scale of production is needed to successfully manufacture a component using current available equipment. A single moulded component will be designed to reduce the complexity of the design, allowing better evaluation of the material.

The decision on which area to apply the veneer/Biome needs to be ambitious enough to provide as much data as possible, yet also be realistic enough to be feasible. The options for the new component 1 through 5 are subjectively scored (based on experience with processing the material, the pilot study and designing and building the Aston EcoCar). A weighting has been given pertaining to the importance of the consideration factor. The options are scored against the consideration factors (processing constraints, suitability and impact) in the selection table 5.11.

		Option				
		a	b	c	d	e
Materials processing	1	1/20	17/20	17/20	12/20	17/20
	2	5/10	5/10	5/10	1/10	7/10
	3	13/20	5/20	10/20	2/20	15/20
Suitability of application	1	17/20	10/20	8/20	20/20	15/20
	2	10/10	5/10	0/10	10/10	10/10
	3	0/10	5/10	2/10	10/10	10/10
	4	0/5	5/5	5/5	3/5	5/5
Overall impact	1	8/8	3/8	1/8	7/8	2/8
	2	5/5	4/5	0/5	2/5	1/5
	3	6/8	3/8	3/8	6/8	7/8
Total		65/116	62/116	48/116	73/116	**89**/116

Table 5.11, Area of application selection table

In consideration of the manufacture and suitability of the component to be designed, the prominent candidate for redesign is the front wishbone.
The application on the 2016 Aston EcoCar chosen as most appropriate is the front wishbone.

5.3.3 Design Brief

The front wishbone forms part of the suspension system, linking the bottom of the upright (where the wheel is mounted) to the chassis. This is a load bearing component, on the exterior of the car and does not follow the 'Aston wooden car' ethos on the 2015 EcoCar.

Figure 5.19 displays the components in the front suspension and wheel mount assembly. Highlighted in this image is the Front upright assembly of the 2015 Aston EcoCar.

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Figure 5.19, 2015 Aston EcoCar front upright assembly

A functional wishbone will need to be designed to meet the sustainable Cradle to Cradle design goal.

5.3.3.1 Project scope

The system in need of replacement consists of the linkage between the bottom of the upright and where this attaches to the chassis. The boundaries of this system are shown in red in figure 5.20a and 5.20b.

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Figure 5.20a, Top view of the design system boundary.

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Figure 5.20b, Front view of the design system boundary.

The areas highlighted in figures 5.20a and 5.20b for the new wishbone design are limited by:

- The bottom of the upright and the position of the M8 post,
- The ideal height of the pivot mount on the chassis (level with the M8 post),
- The bottom of the chassis - for ground clearance.
- The most forward point of the chassis,
- The position of the brake disc when the wheels are turned.

The illustration in Figure 5.20c demonstrates how turning the wheel affects the area to situate the wishbone (shown in red).

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Figure 5.20c, Illustration showing the constraints caused by the movement of the wheels

These considerations need to be taken into account during the design process.

Aim

Design a sustainable wishbone component for the 2016 Aston EcoCar.

Objectives

- Perform the function of spacing the bottom of the upright from the chassis, while allowing the vertical movement of the suspension.
- Transfer the lateral load placed on the upright through to the chassis.
- Moulded using the sustainable veneer/Biome composite material - demonstrating the materials structural, light-weight and mouldable properties

- be manufactured in-house at Aston University
- Achieve a weight reduction.

The moulds created for processing will mean that a small batch of wishbones will be manufactured. At least 2 wishbones are expected to be produced and installed on the 2016 Aston EcoCar. The EcoCar project runs on a yearly cycle for entry into the SEM. The wishbone subassembly needs to be manufactured and put together in time for the full construction of the 2016 EcoCar.

To prove the effectiveness of the material and manufacturing process, the part will be evaluated against the original 2015 wishbone component. Physical testing will be performed as proof of material and concept.

5.3.4 Benchmarking

In order to design a sustainable replacement wishbone for the 2016 Aston EcoCar, analysis is required of existing wishbone designs. To fully consider how the 2016 wishbone will be designed, a full range of alternatives need to be reviewed. As the previous Aston EcoCars have been built for a similar purpose (and to SEM rules), the wishbones designed for the 2014 and 2015 cars will provide a benchmark for improvement. For a broader perspective of the alternatives, a production car wishbone will also be benchmarked.

The data gathered from this analysis will inform the design of concepts for the new 2016 Veneer/Biome wishbone. The concepts can then be measured against the benchmarks to establish where improvements have been made.

5.3.4.1 Benchmark 1 - 2014 Aston EcoCar wishbone

The 2014 Aston EcoCar was designed by student members of the Aston University SEM team. This 2014 EcoCar design displayed in figure 5.21 will be analysed for materials and performance.

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Figure 5.21, Left: 2014 EcoCar wishbone, right: 46 component parts.

Key performance issue for the 2014 Aston EcoCar (also concerning the 2014 wishbone design) were:

1. The weight of the vehicle.
2. complex and inefficient assemblies.
3. Lack of component integration.

Component parts

The 2014 EcoCar wishbone consists of a number of parts manufactured from four materials - aluminium, steel, stainless steel and birch ply. The assembly of the wishbone has been broken down to provide an understanding for improving upon and measuring against the current product.

The 2014 EcoCar wishbone design contains a total of 46 components, these are detailed in table 5.12.

Pivot Bracket				
Component	Material	Component weight (g)	Number of component	Total weight (g)
M8 Nut	stainless steel	5	6	30
M8 Bolt (60mm)	stainless steel	24	2	48
M8 Bolt (35mm)	stainless steel	16	4	64
Large washer	stainless steel	6.5	12	78
Pivot bracket	Aluminium	75	2	150
		Pivot Bracket weight: 370g		
Wishbone				
Component	Material	Component weight (g)	Number of component	Total weight (g)
Outer 9mm Ply	BB Birch Ply	170	2	340
Middle 9mm Ply insert	BB Birch Ply	152	2	304
Pivot Block	Aluminium	51	2	102
Bearing housing	Aluminium	95	1	95
M8 spherical bearing	Steel	8	1	8
M6 Bolt (mm)	stainless steel	9	4	36
M8 Bolt (mm)	stainless steel	16	2	32
M6 Nut	stainless steel	2	4	8
M8 Nut	stainless steel	5	2	10
		Wishbone weight: 935g		
		Total weight: 1305g		

Weight by material	
Material	weight (g)
Steel	8
Stainless steel	306
Aluminium	347
Birch Ply	644

Table 5.12, breakdown of 2014 EcoCar wishbone components.

Performance

Considering the design of a sustainable, light-weight vehicle, there are aspects regarding the 2014 EcoCar wishbone performance where lessons can be taken forward for future reference.

Improvements could be made regarding:

- 46 is a large number of components - a wishbone could be designed with half this number of components.
- The brackets in the pivot assembly showed signs of failure indicating a flaw in the design.
- The number (and subsequent weight) of stainless steel - nuts, bolts and washers - could have been minimised.
- The weight of each wishbone - 1.3Kg - is considerable.
- Regarding the attachment of the wishbone to the chassis, very little integration with other components has been considered.
- The design has not been optimised.

Positive aspects of the design include:

- The full disassembly of component parts is conducive to recycling.
- A substantial part of the wishbone is biodegradable.

5.3.4.2 Benchmark 2 - 2015 Aston EcoCar wishbone

The wishbone for the 2015 Aston EcoCar was conceived by student members of the Aston University Shell Ecomarathon team. The 2015 design displayed in figure 5.22 will be analysed for materials, cost and performance.

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Figure 5.22 - 2015 Aston EcoCar wishbone.

Key performance issue for the 2015 Aston EcoCar (which also applies to the wishbone component) were:

1. The weight of the vehicle.
2. Excessive use of steel components.
3. complex and inefficient assemblies.

Component parts

The 2015 EcoCar wishbone consists of a number of parts manufactured from four materials - aluminium, steel, stainless steel and brass. The assembly of the wishbone has been broken down to provide an understanding for improving upon and measuring against the 2015 EcoCar wishbone component.

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Figure 5.23, An exploded drawing of the 2015 front suspension wishbone.

As can be seen in figure 5.23, the current wishbone design contains a total of 31 components, these are detailed in table 5.13.

Pivot Bracket				
component	material	component weight (g)	Number of component	total weight (g)
M8 Nut	stainless steel	5	6	30
M8 Bolt (75mm)	stainless steel	30	2	60
M8 Bolt (60mm)	stainless steel	24	4	100
Internal bracket	Steel	28	2	56
Pivot bracket	Aluminium	123	2	246
		Pivot Bracket weight: 492g		
Wishbone				
component	material	component weight (g)	Number of component	total weight (g)
Large washer	stainless steel	6.5	4	26
Bush	Bronze	8	4	32
Pivot Tube	Steel	20.5	2	41
Arm	Steel	77	2	154
Bearing housing	Steel	30	1	30
M8 spherical bearing	Steel	8	1	8
Circlip	Steel	0.1	1	0.1
Weld	Steel	40	1	40
		Wishbone weight: 331.1g		
		Total weight: 823g		

Weight by material	
Material	weight (g)
Steel	329
Stainless steel	216
Aluminium	246
Brass	32

Table 5.13, breakdown of 2015 EcoCar wishbone components.

<u>Costing</u>

The costing method is a simplified version of that described by Ulrich and Eppinger (2008; p235 – 243).

In addition to the weight, the viability of the veneer/Biome component can be measured by monetary production cost compared with the original. The following cost estimate has been drawn up. For a suitable comparison to be made with regards to the tooling and production, it will be assumed that a batch of 200 components are manufactured. This represents a production run of 100 vehicles. Labour costs are assumed to be at £20 per hour based on 2016 UK average labour costs of 22 Euros (Eurostat, 2017). The cost of materials for specialised parts has been approximated due to lack of pricing at the quantities used. The cost of machines, and the time and equipment used to design the components is not taken into account.

The cost of components is detailed in table 5.14, the standard parts (nuts, bolts and washers) have been costed at 2016 prices (sourced from RS components).

Standard parts				
Component	Unit cost (£)	Quantity	Cost per car (£)	Sub tot
M8 Bolt (75mm)	0.38	4	1.50	
M8 Bolt (60mm)	0.46	8	3.70	
M8 Nut	0.02	12	0.24	
large washer	0.08	8	0.36	
M8 spherical bearing	2.66	2	5.32	
circlip	0.01	2	0.02	£11.14
Specialised part				
Component	Materials cost (£)	Quantity	Cost per car (£)	
internal bracket	.50	4	2	
pivot bracket	3	4	12	
bush	2	8	16	
pivot tube	.50	4	2	
arm	1	4	4	
bearing housing	1	2	2	£38.00
Manufacturing cost				
Activity	Hourly rate (£)	Time (hrs)	cost per car (£)	Sub tot
Manual (drilling, sawing and bending sheet)	20	2	40	
Assembly	20	0.5	10	
Welding	20	0.25	5	
turning	20	0.5	10	£65
		Estimated total cost		£114

Table 5.14, 2015 Ecocar wishbone broad cost of production

The majority of the costs arise from manufacturing bespoke components, making the manufacture of the 2015 wishbone expensive. This cost could be reduced by fitting more standard component parts.

<u>Performance</u>

The original 2015 EcoCar wishbone was fitted to the vehicle and taken to the SEM competition, and as the car has completed this trial it can be assessed in regard to the overall performance of the vehicle itself.

Positive aspects:

1. Passed the technical inspection allowing the vehicle to compete on track.
2. Did not fail under operating conditions (when the car was on track).
3. provided a stiff spacing between the chassis and the front wheel upright.
4. Allowed ample movement of the spherical bearing for the suspension system to work as designed.

Areas for improvement:

1. the weight of the system (along with most components of the car) is excessively heavy - the Aston EcoCar weighed just under the maximum weight allowed.
2. The sustainable 'wooden car' design ethos was not followed, the majority of the wishbone cannot be disassembled for re-use or recycling.
3. The pivot brackets could have been better integrated into the chassis.
4. The brackets in the pivot assembly showed signs of failure indicating a flaw in the design.
5. The number of components (31 in total) could be reduced.

5.3.4.3 Benchmark 1 and 2 discussion

Comparison

The 2014 EcoCar wishbone weighs considerably more than the 2015 design. The majority of this weight increase can be accounted for by the amount of plywood. An advantage to the 2014 design is the ability to disassemble the components for disposal or reuse.

Limitations

The 2014 and 2015 Aston EcoCar wishbones are efforts by members of the Aston EcoCar team to resolve the front suspension. It is recognised that the using the EcoCar designs as a benchmark has limitations.

1. The quality of the original concepts are debatable. Due to inexperience, it can not be expected that a final year BEng student will follow a full design process and optimise the design of this component.
2. As a one-off fabrication, consideration has not been given to scale of manufacture.

It is useful to consider examples from the automotive industry.

5.3.4.4 Benchmark 3 - Production car comparison

To gain a broader perspective, a further production car wishbone is analysed. Although the solutions from industry may be inappropriate for use on a sustainable EcoCar that weighs considerably less, the mass-produced wishbones are:

1. In full production
2. Represent many years of development on vehicles.
3. Are commercial, mass produced products.

Benchmark - Small/medium sized production car.

The wishbone chosen for benchmarking a production car is from a small/medium sized Alfa Romeo, Figures 5.24a and 5.24b display the component.

Figure 5.24a, Wishbone from Alfa Romeo.

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Figure 5.24b, Left – Alfa Romeo ball joint; Right – pivot bracket.

Designed for the Alfa Romeo 145, 146, 155 and GTV models, the wishbone displayed in figure 5.24 was fitted to these production cars between 1992 and 2004. The curb weight of an Alfa Romeo 155 is 1400Kg.

<u>Component parts</u>

Due to the construction method it is not possible to disassemble the alfa wishbone, therefore the weight of each component is approximated. Identifying the materials was also an issue as none were labelled. As well as creating an inconvenience for this process, these issues also cause problems when reclaiming the material at the end of the products life. A breakdown of the alfa wishbone components is provided in table 5.15

Pivot bracket				
Assumed to be integrated into the chassis				
Wishbone				
Component	Material	Component weight (g)	Number of component	Total weight (g)
Main wishbone cast	Steel	2056	1	2056
Bush	steel	250	2	500
Ball joint	Stainless steel	70	1	70
Captive Nut	Stainless steel	20	4	80
Pivot brackets	Galvanised steel	350	2	700
Seals	Rubber	30	1	30
Ball joint cover	PVC	5	1	5
		Wishbone weight: 3451g		
		Total weight: 3451g		

Weight by material	
Material	Weight (g)
Steel	2056
Galvanised steel	216
Stainless steel	246
Rubber	32
PVC	5

Table 5.15, Breakdown of Alfa Romeo wishbone components

Costing

A pair of wishbones are available for purchase for between £20 and £30. These are available as obsolete spare parts. The materials and manufacturing costs are unavailable, it is therefore assumed that the cost to produce these parts is less than the £20 price they were bought for. The EcoCar cost estimates and the production car spare parts price are not directly comparable but provide an indication to the relative costs.

Performance

The Alfa Romeo wishbone performs a similar function to the part being designed for the 2016 EcoCar. The construction is considerably more heavy duty because of the higher weight, faster speed and 12.5 year life span of the car it is designed for.

The design features:

- The linkages that attach to the chassis consist of bushes.
- A ball joint where the wishbone attaches to the wheel upright, allows the upright to move vertically with the suspension and to turn with the steering.
- An Asymmetric shape, allowing for loading but also taking packaging and use of material into account.
- The wishbone is built mostly of steel and is not designed for disassembly into its component materials.

It is notable that the design of wishbone spans 4 different models of car, allowing for efficiency in the manufacture and parts supply. The longevity of this design (12.5 years) and considering similar components are still in production, demonstrates how progress in the design and manufacture of such components is sluggish.
It could be argued that the design is optimised and does not need to change, but, the manufacture and disposal of these components could (and should) have less impact on the environment.

5.3.4.5 Benchmark conclusions

This analysis of previous designs, aids understanding of the issues discussed in the problem statement. The benchmarking is useful later in the process to provide performance targets in the specification and also to grade concepts during evaluation.

<u>Materials comparison with EcoCar benchmarks.</u>

The weight of the vehicles and the different forces during use make a direct comparison between benchmark wishbones unrealistic. The weight of the Alfa Romeo model – 1400 kg is 7 times greater than the 200kg Aston EcoCar. Assuming a production car can simply be scaled down, a proportional target weight for the 2016 wishbone would be 500 g. The weights and materials used for the benchmark wishbones are compared in figure 5.25.

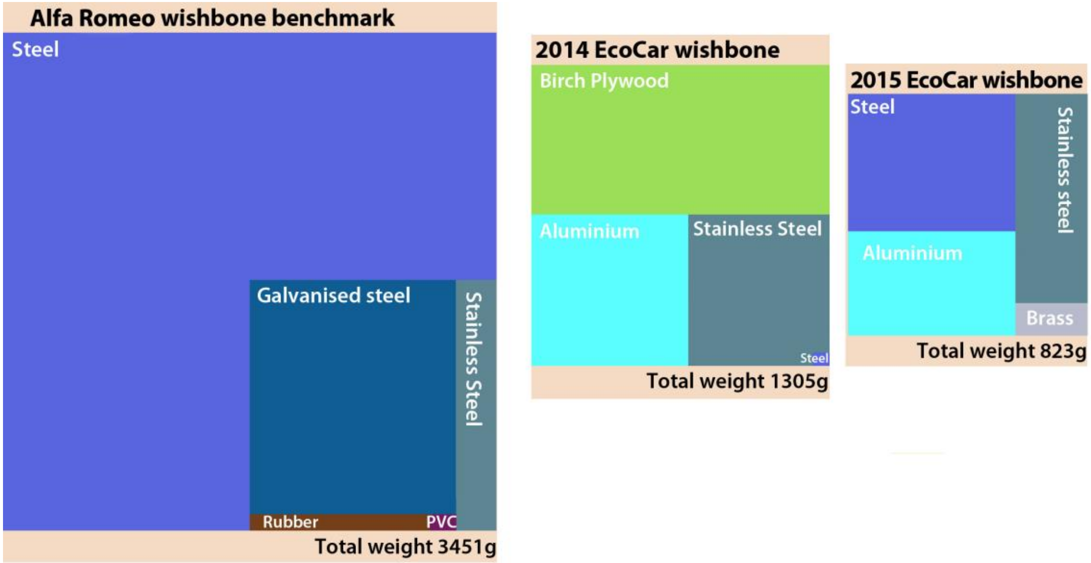

Figure 5.25, Comparison of benchmark materials by weight.

The diagram in figure 5.25 shows that the alfa wishbone contains more steel than the EcoCar wishbones. The 2014 EcoCar wishbone weighs more than the 2015 EcoCar wishbone due to the plywood construction.

This M/D/M study is applied to a similar vehicle as the 2014 and 2015 Aston EcoCars. The 2016 vehicle has similar design goals and will again be entered into the SEM. The previous Aston EcoCar and wider automotive products provide valid comparisons to inform the design of a new sustainable wishbone.

5.3.5 Vehicle loading

To aid the design process a representative load acting on the wishbone needs to be calculated.

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Figure 5.26, the wishbone is subject to loading during braking and cornering of the vehicle.

As illustrated in figure 5.26, the maximum amount of force applied to the wishbone occurs when the car is travelling at top speed and brakes are applied while cornering.

5.3.5.1 Vehicle information

The maximum force acting on the wishbone can be calculated using the information in table 5.16.

Variable		Value	Unit	Assumption
Top speed	(u)	8.5	m/s	A top speed estimate of 30kmph. Based on an average speed of 25kmph required to complete 2016 SEM track in 43 mins.
Minimum Turning radius	(r_{min})	6	m	SEM rules - Article 47; d. (p.22) [1]
Friction coefficient: tires on road	(μ)	1		Worn Tires at 50km/h [2]
Total vehicle weight car + driver	(m)	250	kg	the car contains 1 driver and no passengers
Chassis weight		135	kg	Based on targeted weight of 2016 Aston EcoCar
Drivetrain weight		45	kg	Using the same 2015 Aston Ecocar fuel cell, motor and housing – positioned above rear wheel.
Driver weight		70	kg	SEM rules - Article 20; a. (p.22) [1]
Wheel base		2000	mm	Based on the wheel base of 2015 Aston EcoCar
Track width		1000	mm	SEM rules - Article 45; d. (p.22) [1]
Wheel radius	(r_w)	280	mm	Using the same wheels as the 2015 Aston EcoCar
Ride height		100	mm	SEM rules - Article 45; g. (p.22) [1]
Vertical distance from the axle to the bearing bracket.	(Z_1)	160	mm	Using the same upright assembly as the 2015 Aston EcoCar

Vertical Distance between the wheel axle and wishbone	(Z_2)	90	mm	Using the same upright assembly as the 2015 Aston EcoCar
horizontal distance between the wishbone and wheel centreline	(y_1)	70	mm	Using the same upright assembly as the 2015 Aston EcoCar

Table 5.16, assumed figures for wishbone loading calculations

[1] Shell (2016)

[2] Rief (2014) p.19

From SEM rules

SEM rules Article 51; d. states that “The effectiveness of the brake system will be tested during vehicle inspection. The vehicle must remain immobile with the Driver inside when it is placed on a 20 percent incline with the main brake in place.” (Shell, 2016 p.24)

SEM rules Article 47; d. states that “The turning radius must be 6 m or less. The turning radius is the distance between the centre of the circle and the external wheel of the vehicle. The external wheel of the vehicle must be able to follow a 90° arc of 6 m radius in both directions.” (Shell, 2016 p.23).

Simplifying assumptions

Zero rolling resistance

No load damping provided by tyres or suspension

Vehicle coordinate system

Figure 5.27, vehicle coordinate system

Figure 5.27 displays the vehicle coordinate system, this is used when referring to directions in relation to the vehicle.

5.3.5.2 Forces acting on the wishbone

To determine the strength required in the wishbone component the loading during operation needs to be calculated. The loading on the wishbone is applied in the horizontal direction (X) - due to braking and acceleration of the vehicle and the Lateral direction (Y) – due to the vehicle cornering. The wishbone is designed to be free to move in the vertical direction (Z). The forces on the right-hand wishbone – F_1 (due to braking) and F_2 (due to cornering) are described in the figure 5.28. The maximum force on the wishbone occurs during braking while cornering.

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Figure 5.28, Wishbone braking and cornering forces model.

The loading on the vehicle is required in order to determine the magnitude of F_1, F_2, R_A and R_B as displayed in figure 5.28. The loading has been simplified in order to estimate the forces from the available information.

The magnitude of the loads on the wishbone is affected by the weight distribution of the vehicle. As the vehicle corners and brakes – illustrated in figure 5.29 - the distribution of the vehicles weight changes.

Figure 5.29, vehicle cornering and braking affects weight distribution.

Braking and cornering loads are assumed to act at the vehicles centre of mass (CoM). By calculating the weight distribution on each wheel the magnitude of these dynamic loads on the wishbone can then be calculated.

5.3.5.3 Centre of mass

The centre of mass for the vehicle is needed to calculate the dynamic loads on the vehicle. An estimate for the CoM of the 2016 EcoCar is based on the 2015 EcoCar. The CoM is calculated using the component weights measured in the Lifecycle Inventory (in section 2.5). These have been simplified into 5 segments:

Driver: **70kg**

Chassis, (vehicle interior, chassis and bodywork): **93kg**

Front axle, (1/2 brake system, front uprights, front wheels and steering): **22Kg**

Rear axle, (1/2 brake system, rear subframe, rear wheels): **20 Kg**

Drivetrain, (fuel cell, control systems, electric motor and gearing): **45kg**

Assumptions

- The 2016 vehicle weighs a similar amount to the 2015 EcoCar.
- The vehicle and driver is symmetrical (down the centre of the vehicle).
- The 2016 vehicle reuses 2015 EcoCar components – Drive train (fuel cell and motor), wheels, brake system, steering and front uprights.
- The 2016 vehicle will have a similar vehicle architecture to the 2015 EcoCar – central driving position, wooden monocoque chassis with a rear support structure.

- The fuel cell, motor and housing are positioned centrally (left to right) above rear axle with the CoM located 600mm above ground (based on 2015 EcoCar).
- The driver weighs 70 kg and is seated centrally, on the floor of the vehicle equidistant between wheel base (based on 2015 EcoCar). The CoM is located in the torso of the driver - a 50th percentile UK adult male, data from Pheasant & Haslegrave, (2005).
- The weight of chassis and interior components are evenly distributed (simplified to a 1m x 1m x 2m object) and therefore the centre of mass for the chassis segment is located at the geometric centre.

Centre of mass calculation

The CoM for each segment of the EcoCar vehicle have been plotted in figure 5.30.

Figure 5.30, The centre of mass for the 5 segments of the vehicle

The centre of mass for each segment in figure 5.30 is measured from the datum – located at the point where the rear left tire is in contact with the ground. The coordinates and relative mass for each segment are displayed in table 5.17.

Segment (i)	Relative mass: m_i (%)	Horizontal CoM distance: X_i (mm)	Relative horizontal CoM (mi·xi)	Vertical CoM Distance: Zi (mm)	Relative vertical CoM (mi·Zi)
Driver (red)	28.0	1000	28000	- 550	- 15400
Chassis (blue)	37.2	1200	44640	- 600	- 22320
Front axle (black)	8.8	2000	17600	- 280	- 2464
Rear axle (black)	8.0	0	0	- 280	- 2240
Drivetrain (green)	18.0	0	0	- 600	- 10800
			Σ 90240		Σ - 53224

Table 5.17 Centre of mass coordinates for each segment.

<u>Combined CoM Location</u>

Horizontal CoM location (X_{CoM}) = 90240/100 = 902.4mm ≈ **0.9m**

Vertical CoM location (Z_{CoM}) = - 53224/100 = - 532.24mm ≈ - **0.5m**

Lateral CoM location (Y_{CoM}) = **0.5m**

5.3.5.4 Braking force

The braking force on the wishbone has been calculated using the vehicle inspection test scenario – described in Article 51 of SEM rules (Shell, 2016: p.24). The braking force (F_B) has been calculated using the weight of the car on an incline - translated to the diagram displayed in figure 5.31.

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Figure 5.31, Vehicle braking diagram.

Assumptions:

1. No rolling resistance or friction in the bearings.
2. The ramp is a rough surface

SEM rules state that the brakes must hold the vehicle on a 20 percent incline, converting to degrees:

$$\theta = Tan^{-1}(.20) \; = \; 11.3°$$

Resolving for the braking force F_B holding the car:

$$F_B \; - \; mg \; Sin\theta = \; 0$$

As m is the total mass of the vehicle:

$$F_B \; = (250{\times}9.8) \sin 11.3$$

F_B = **480N**

The deceleration due to braking (A_{brake}) can be calculated using:

$$A_{brake} = \frac{F_B}{m} = \frac{480}{250} = \; \mathbf{1.92 \; ms^{-2}}$$

5.3.5.5 Horizontal Load Distribution

The horizontal load distribution during braking can be calculated using the static and dynamic loads on the vehicle.

<u>Static load distribution</u>

The diagram in figure 5.32 displays the forces affecting the static horizontal load distribution.

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Figure 5.32, static load distribution

Assuming equilibrium, and summing forces in the z direction:

$$\sum F_z = R_{rear} + R_{front} - mg = 0$$

$$\therefore mg = R_{rear} + R_{front}$$

To find the distribution of the vehicle load between the front (R_{front}) and rear (R_{rear}) axles we take moments about the point at which either the front or rear wheels contact the road. Assuming clockwise moments are negative and the vehicle is in equilibrium.

$$\sum M = 0$$

taking moments about the rear:

$$\sum M = R_{rear}x_{rear} - mgx_{com} + R_{front}x_{front} = 0$$

As the distance x_{rear} from the rear wheel = 0, and the distance x_{front} = $x_{wheelbase}$, then substituting and rearranging for R_{front}:

$$\sum M = R_{front}x_{wheelbase} - mgx_{com} = 0$$

$$R_{front} = \frac{mgx_{com}}{x_{wheelbase}}$$

and since,

$$mg = R_{rear} + R_{front}$$

$$R_{rear} = mg - R_{front}$$

and the mass acting on the front and rear axles can be calculated from:

$m_{front} = \frac{R_{front}}{g}$ and, $m_{rear} = \frac{R_{rear}}{g}$

m_{front} = **112.5** kg

m_{rear} = **137.5** kg

So, at rest a higher proportion (55%) of the vehicles weight acts on the rear axle.

Effect of Load transfer under braking

It can be assumed that the car experiences a constant deceleration of A_{brake} due to braking and friction of the tyres on the road. The diagram in figure 5.33 displays the forces affecting the load transfer under braking.

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Figure 5.33, load transfer due to braking

Taking moments about the point where the rear wheel contacts the road when the car is braking, and assuming the centre of mass is on the centreline of the car at a height above the ground z_{CoM} (calculated in table 5.17).

$$\sum M = -R_{\substack{dynamic \\ front}} x_{wheelbase} + mA_{brake} z_{com} = 0$$

which can be rewritten as:

$$R_{\substack{dynamic \\ front}} = \frac{mA_{brake} z_{com}}{x_{wheelbase}}$$

Combining the static and dynamic loads,

$$R_{front\_total} = R_{\substack{dynamic \\ front}} + R_{front}$$

and

$$R_{rear\_total} = R_{rear-} R_{\substack{dynamic \\ front}}$$

$R_{rear\ total}$ = **125** kg

$R_{front\ total}$ = **125** kg

Under braking the weight is evenly distributed between the front and rear axles.

5.3.5.6 Lateral load distribution

The lateral load distribution during cornering can be calculated using the static and dynamic loads on the vehicle.

Static load distribution

The diagram in figure 5.34 displays the forces affecting the static lateral load distribution.

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Figure 5.34, static lateral load distribution

Assuming equilibrium, and summing forces in the z direction:

$$\sum F_z = R_{left} + R_{right} - mg = 0$$

and, taking moments about the left tyre, where positive moments are anti-clockwise

$$\sum M_{left} = R_{right} y_{right} - mg y_{com} = 0$$

since y_{right} = track width

$$R_{right} = \frac{mg y_{com}}{y_{track\_width}}$$

R_{right} = **125** Kg

R_{Left} = **125** Kg

As the vehicle components and driver are mounted centrally along the centre line of the vehicle, the weight is evenly distributed between left and right.

Lateral Load transfer under Cornering

As the car takes a left hand bend of radius (r) at a velocity (u) then the car is accelerated towards the centre of the bend by an acceleration ($A_{centripetal}$). The diagram in figure 5.35 displays the forces affecting the load transfer.

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Figure 5.35, load transfer under cornering

The centripetal acceleration ($A_{centripetal}$) can be found from:

$$A_{centripetal} = \frac{u^2}{r_{min}}$$

Taking moments about the point where the left wheel contacts the road. The dynamic load change as a result of cornering can be found by incorporating the moment induced by $A_{centripetal}$ acting on the car at height z_{com}.

$$\sum M = R_{\substack{dynamic \\ right}} y_{track\_width} - mA_{centripetal} z_{com} = 0$$

Rearranging to find $R_{dynamic\ right}$:

$$R_{\substack{dynamic \\ right}} = \frac{mA_{centripetal} z_{com}}{y_{track\_width}}$$

So the total load on the right hand side of the car as a result of cornering is:

$$R_{right\ total} = R_{right} + R_{\substack{dynamic \\ right}} = R_{right} + \frac{mA_{centripetal} z_{com}}{y_{track\_width}}$$

and:

$$R_{left\ total} = R_{left} - R_{\substack{dynamic \\ right}}$$

R_{Left_total} = **-38** kg

R_{right_total} = **288** kg

The vehicle will become unstable when experiencing lateral load transfer while taking a bend with a radius of 6m at top speed (as $R_{left\ total}$ is negative).

For stability, the resultant vector comprising gravity and lateral acceleration must fall within the track width of the car – described in figure 5.36.

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Figure 5.36, Resultant stability vector due to cornering

The vehicle remains stable when the vector falls within the track width. The limit of stability is where the vector falls outside the width of the car.

Since y_{CoM} and $\frac{1}{2}$ track width are both 0.5m, when $A_{centripetal}$ exceeds g, θ_a is greater than 45° and the car will roll.

As such the worst case lateral acceleration (before the vehicle rolls) is when:

$$A_{centripetal} \ = \ g = 9.8\ ms^{-2}$$

At top speed (8.5 ms^{-1}) the vehicle would be on the limit of stability turning a bend of 7.4 m radius. To turn a corner of 6 m radius, the vehicle should not exceed speeds of 7.6 ms^{-1}. When $A_{centripetal}$ = 9.8 ms^{-2}:

R_{Left_total} = 0 Kg

R_{right_total} = 250 Kg

5.3.5.7 Load distribution while cornering and braking

The combined load distribution of the vehicle for braking while cornering (from sections 5.3.6.5 and 5.3.6.6 around a left-hand bend shown in figure 5.37 is set out in the table 5.1

Figure 5.37, load distribution segments

segment	distribution	Load (kg)	Lateral force (F_C) due to $A_{centripetal}$ (N)	Horizontal force (F_B) due to A_{brake} (N)
Front left (Fl)	0%	0	0	0
Front right (Fr)	50%	125	1225	240
Rear left (Rl)	0%	0	0	0
Rear right (Rr)	50%	125	1225	240

Table 5.18, dynamic load distribution

5.3.5.8 Lateral load on the wishbone (F_2)

Using the dynamic loads in table 5.18 the lateral load on the wishbone (F_2) can be calculated. The diagram in figure 5.38 displays the lateral forces affecting wishbone.

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Figure 5.38, Diagram of lateral forces acting on the front right of the EcoCar

It is assumed that the location of the wishbone on the 2016 Aston EcoCar is in a similar position to the 2015 arrangement. The vertical distance from the axle to the bearing bracket (Z_1) is 160mm, the minimum distance between the axle and the wishbone (Z_2) is 90mm and the distance between the wishbone and wheel centreline (y_1) is 70mm.

The frictional force ($F_{f\_front\_right}$) acts at the point the front right wheel is in contact with the ground due to the lateral force on the front right ($F_{C\ front\_right}$) from table 5.18.

$$F_{f\_front\_right} = F_{\mathrm{C\ front\_right}} = 1225\ \mathrm{N}$$

The reaction force where the front right wheel is in contact with the ground (F_{r_wheel}) is the load of the vehicle on the front right tyre from table 5.18:

$$F_{r\_wheel} = R_{front\_right} = 1225\ N$$

The sum of the forces on the upright assembly displayed in figure 12 in the y direction is:

$$\sum F_y = -F_{f\_front\_right} + F_{top\_y} + F_2 = 0$$

Including the reaction force of the wheel (F_{r_wheel}) and taking moments about F_{top_y}:

$$\sum M = -\ F_{f\_front\_right}\ (r_{wheel} +\ Z_1) +\ F_2(Z_1 +\ Z_2) + (F_{r\_wheel} \times y_1) = 0$$

Rearranging for F_2

$$F_2 = \frac{F_{front\_right}\ (r_{wheel} + Z_1) - (F_{f\_wheel} \times y_1)}{Z_1 + Z_2}$$

F_2 = 1813 N

5.3.5.9 Horizontal load on the wishbone (F_1)

The diagram in figure 5.39 displays the horizontal forces (in the x direction) affecting wishbone.

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Figure 5.39, Diagram of braking forces acting on the front right of the EcoCar.

As the car travels in the x direction, the wheel rotates anticlockwise. The braking force on the front right wheel ($F_{B\ front\_right}$ from table 5.18) acts in a clockwise direction to prevent this rotation. The frictional force between the tyre and the road surface ($F_{fr\_horizontal}$) acts in opposition to $F_{B\ front\_right}$. Since $F_{B\ front\_right}$ has been calculated at the point the wheel is in contact with the ground and assuming the wheel does not skid:

$$F_{B\,front\_right} = F_{fr\_horizontal} = 240 \text{ N}$$

The sum of the forces on the wishbone in the x direction is:

$$\sum F_x = -F_{B\,front\_right} + F_{top\_x} + F_1 = 0$$

Taking moments about F_{top_x}:

$$\sum M = -F_{B\,front\_right}\,(r_{wheel} + Z_1) + F_1(Z_1 + Z_2) = 0$$

Rearranging for F_1,

$$F_1 = \frac{F_{B\,front\_right}\,(r_{wheel} + Z_1)}{Z_1 + Z_2}$$

F_1 = 422 N

5.3.5.10 Wishbone load

The forces acting on the wishbone – F_1 and F_2 – are illustrated in the diagram in figure 5.40.

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Figure 5.40, Loading of the wishbone due to cornering and braking forces (F1 and F2)

The magnitude of the reaction forces where the wishbone attaches to the chassis (R_A and R_B) can be expressed using the following terms:

Taking moments about R_A:

$$\sum M_A = (-R_B d_X) + (+F_1 L_y) + (+F_2 d_{XA}) = 0$$

Rearranging to find R_B:

$$\mathbf{R_B} = \frac{(\mathbf{F_1 l_y}) + (\mathbf{F_2 d_{XA}})}{\mathbf{d_X}}$$

Taking moments about R_B:

$$\sum M_B = (+R_A d_X) + (+F_1 L_y) + (-F_2 d_{XB}) = 0$$

Rearranging to find R_A:

$$\mathbf{R}_A = \frac{(\mathbf{F_2 d_{XB}}) - (\mathbf{F_1 l_y})}{\mathbf{d_X}}$$

To minimise R_A and R_B in the 2016 wishbone design, the distance between points A and B (d_x) should be maximised. To evenly distribute F_1 and F_2 between R_A and R_B, the ideal geometry for the 2016 wishbone would be asymmetrical.

The forces modelled are approximations, for example the lateral damping effect created by the tyres and the rubber block suspension have not been included in the calculations. The accuracy of the modelled forces (F_1 and F_2) is low, however, all estimates have been based on maximum loads.

5.3.6 Needs analysis

The 2016 EcoCar wishbone needs to perform in a number of ways, both in terms of the context of the research project and as a component for the Aston EcoCar. These ‘Needs’ (as described on p72 of Ullrich and Eppinger, 2008) have been discerned from the previous analysis of EcoCar wishbone designs (the benchmarks), similar products on the market (production car benchmark) and the problem area itself (detailed in the design brief).

Sustainable design

1. The wishbone has a low impact on the environment.
2. The wishbone is simple to disassemble.
3. The wishbone is consistent in style to automotive parts
4. The wishbone is constructed in a manner complimenting the material.

Material and manufacture

1. The wishbone is moulded using Veneer/Biome.
2. The wishbone can be manufactured using the hot press process.
3. Where fixings are required standard parts are used where possible.
4. The wishbone can feasibly be manufactured in time for the SEM.

Performance

1. The wishbone attaches to the chassis and the wheel upright of the Aston EcoCar.
2. The wishbone secures the wheel upright in the correct position.
3. The wishbone allows the wheel upright to move vertically.
4. The wishbone does not interfere with other parts of the vehicle.
5. The wishbone performs at the SEM competition.
6. The wishbone survives under loading.
7. The wishbone does not lose integrity before end of life.
8. The wishbone can be installed and removed using Aston EcoCar team equipment.
9. The wishbone contributes as little weight to the vehicle as possible.

The wishbone design also needs to reflect the fact it is the outcome of the research project. The finished artefact needs to demonstrate the material in an impressive manner - the wishbone needs to express the potential of the material in a considered way.

The 'Needs' will be used to evaluate the concepts, with the aim of selecting the most appropriate wishbone design. A weighting will be applied to the importance of each need. This selection process is subjective, and the following Target Specification will be used to refine the chosen concept for production.

5.3.7 Target specification

Sustainable Design				
No.	Metric	Imp.*	Unit	Ideal value
1	Use of veneer Biome material	5	-	70% - 100%
2	Impressive representation of the material	1	-	yes
3	Damage environment less than original	4	-	80%
4	Designed for disassembly	1	Sec	<300
5	Follow Materials Design methodology	4	-	yes
Material and Manufacture				
No.	Metric	Imp.*	Unit	ideal value
6	Process on the 'hot press' in University Lab	2	MPa	<2
7	Max size of component	2	mm	<300 x 300
8	Minimum radius size for moulding	5	mm	>10
9	Depth of mould	4	mm	<10
10	Thickness of material	3	mm	2 - 5
11	Number of components	1	-	<31
12	Accuracy of the mould	5	mm	+/- 0.25
Performance				
No.	Metric	Imp.*	Unit	Ideal value
13	Attach to M8 post on 'wheel upright'	2	-	yes
14	Withstand the lateral force under braking	5	N	>5620
15	Vertical travel at 'wheel upright' end	4	mm	> 20
16	Distance from pivot to 'wheel upright'	4	mm	150
17	Keeping the wheel vertical	5		
18	Distribute force into chassis	3		
19	Not deflect, holding wheel in correct position	5	mm	<2
20	Weigh less than original	4	g	<600
21	Meet Shell competition regulations.	5	-	pass
22	Not interfere with ground clearance or wheel	4	-	yes

Table 5.19, Target specification

* abbreviation - importance of metric

The target specification will be used to inform the ideation of concepts, as well as to evaluate the resulting development and manufacture.

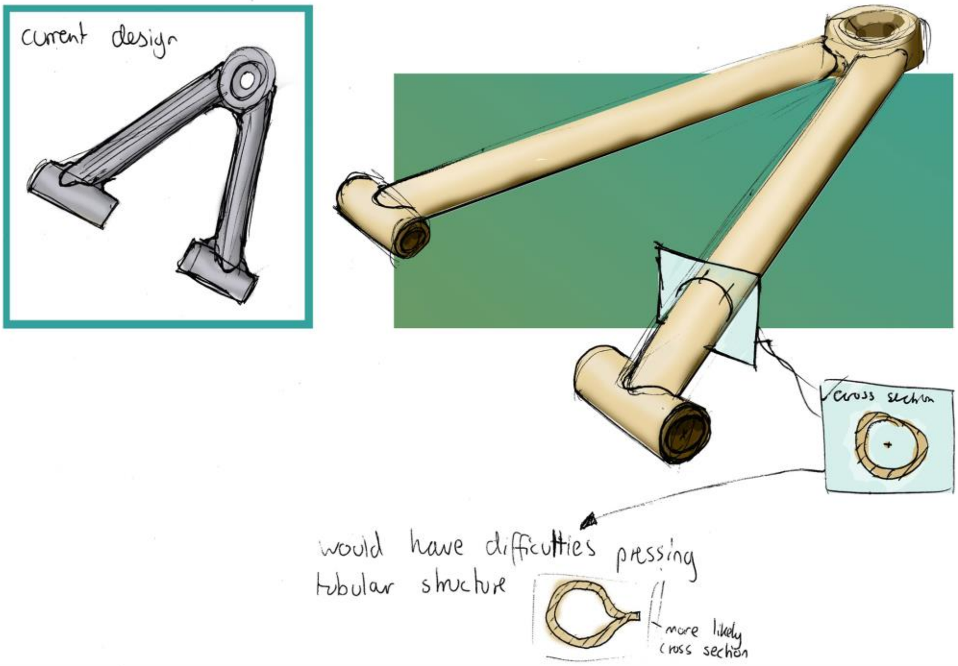
5.3.8 Concept generation

There are 5 elements to the design:

1. The linkage to the M8 post on the upright.
2. The wishbone attachment to the M8 post linkage.
3. The moulded wishbone - spanning from the upright linkage to the chassis.
4. The mechanism that allows the upright to move vertically.
5. The mounting to the chassis.

The aim of this concept generation exercise is to fully explore the possibilities for a wishbone that can be manufactured using the Veneer/Biome composite. A number of concepts have been conceived. Sketches of 20 concepts are detailed in figures 5.41a to 5.41k:

Concept 1
Replicate current design using new material



Concept 2
Similar in style to current design - pressing and radii considered

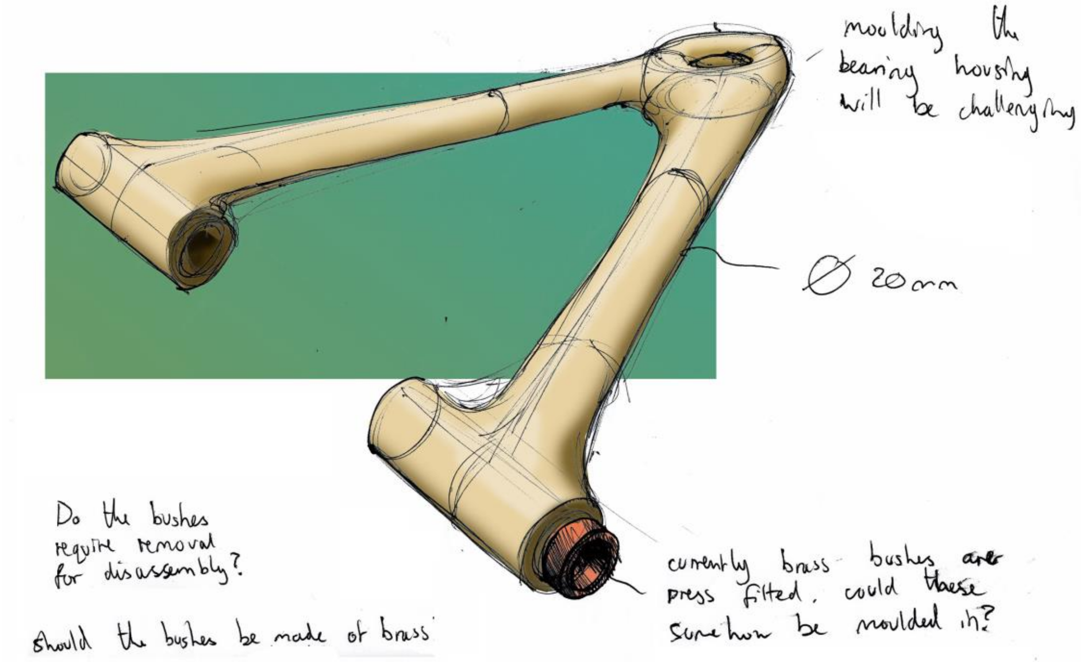
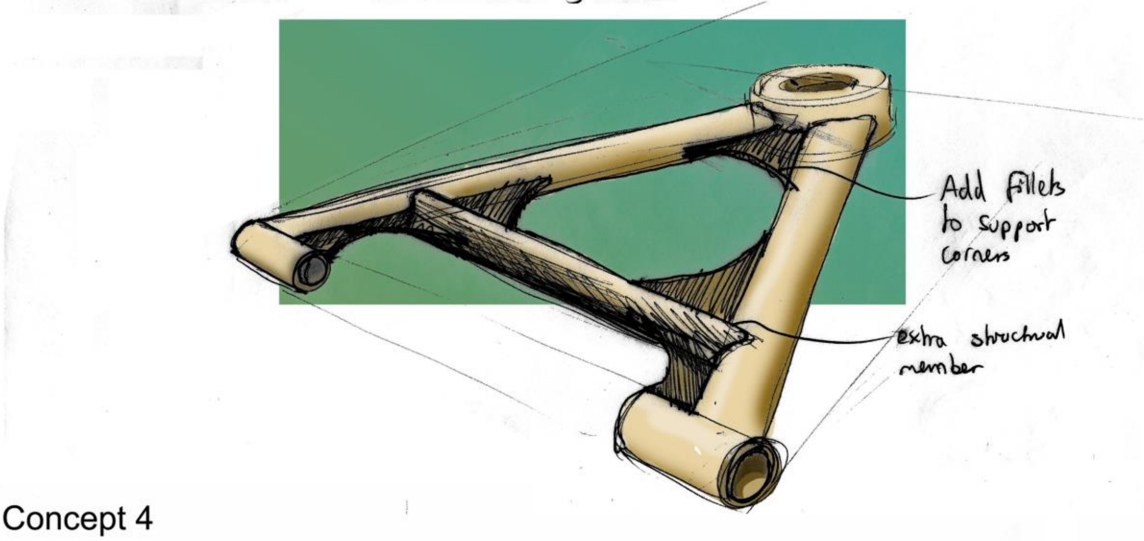


Figure 5.41a, Wishbone concepts 1 and 2.

Concept 3
Strengthened current design

- Design is improvement on original structure
- Design doesn't showcase the novel material or process (could be fabricated using steel)



Concept 4
2 stage moulding of Veneer/Biome 'tubes'

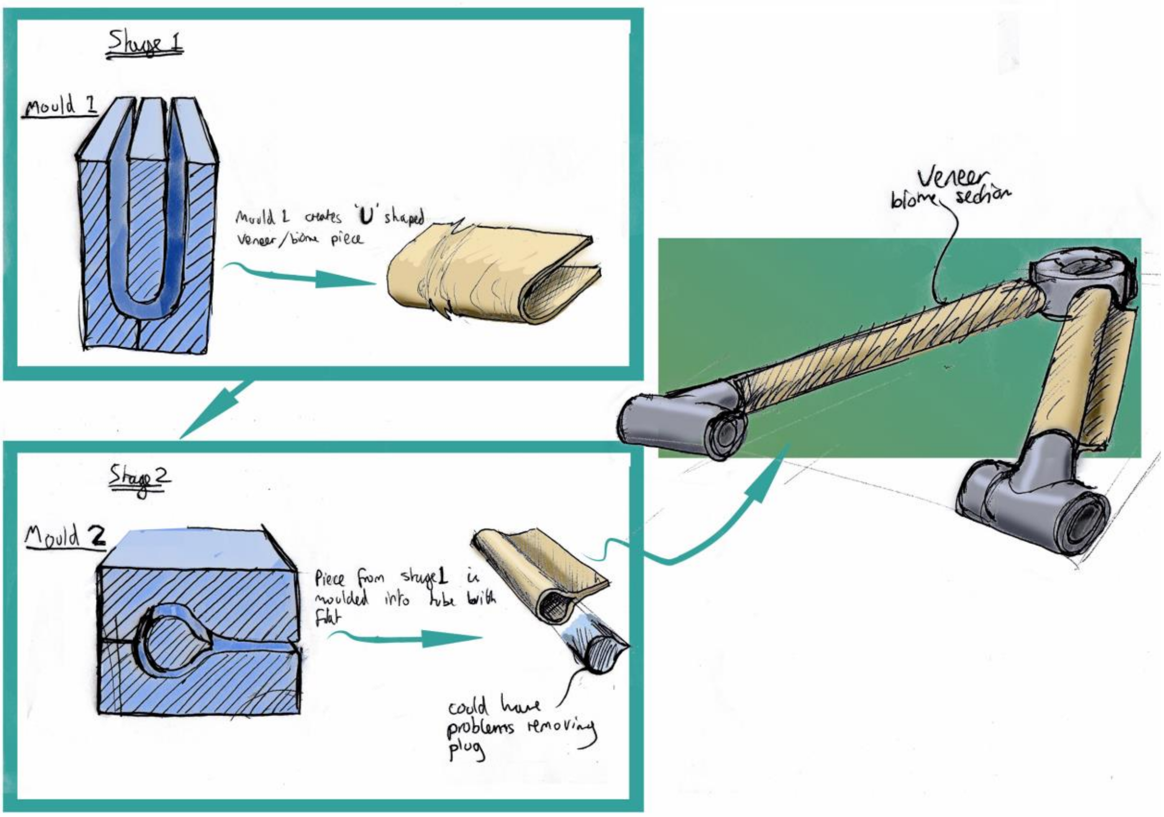
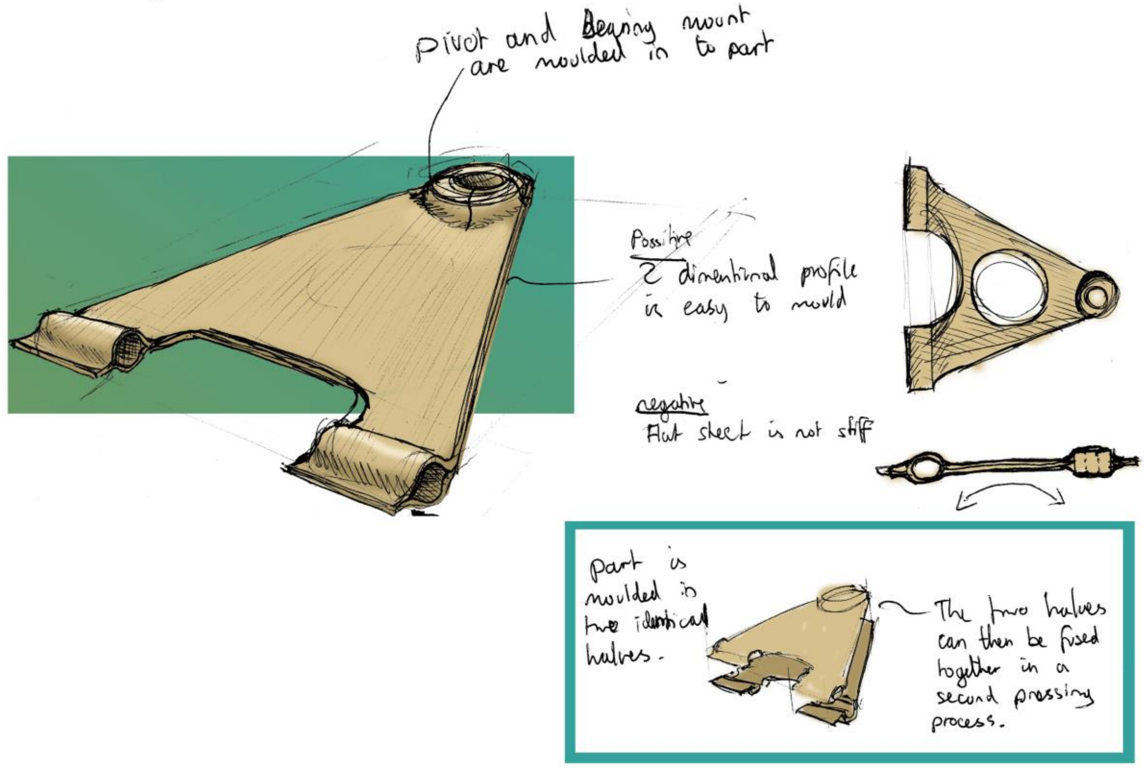


Figure 5.41b, Wishbone concepts 3 and 4.

Concept 5
'Flat' moulding



Concept 6
Moulded design with stiffening features

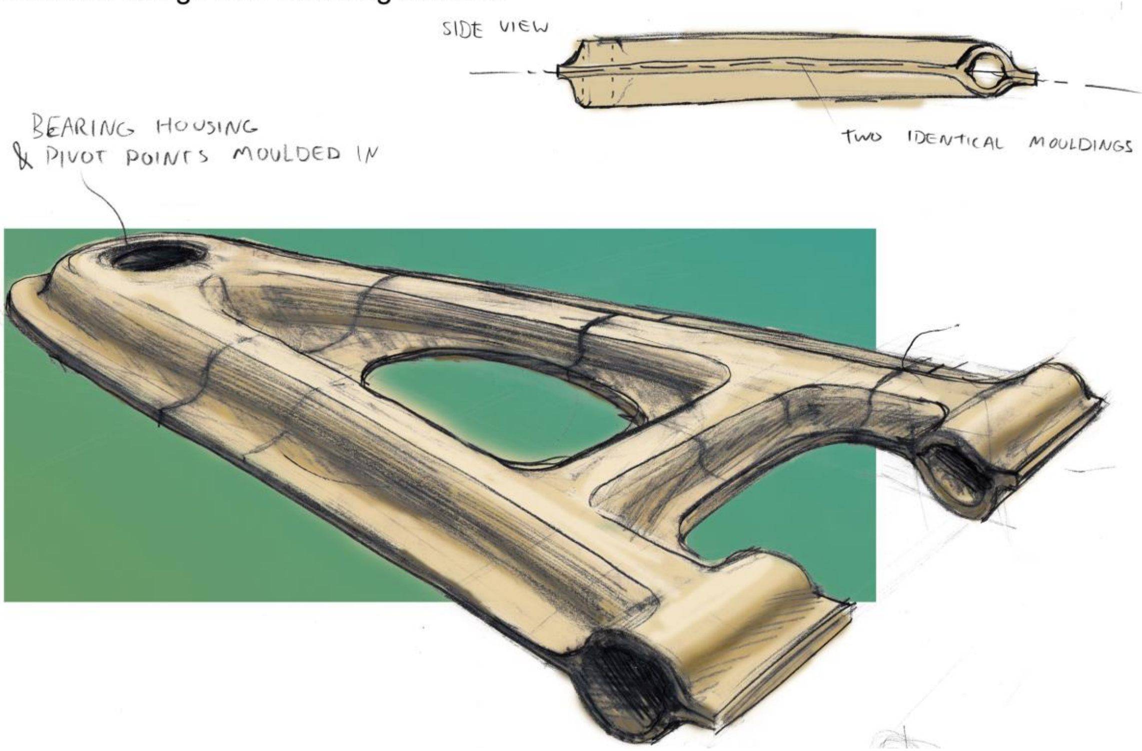
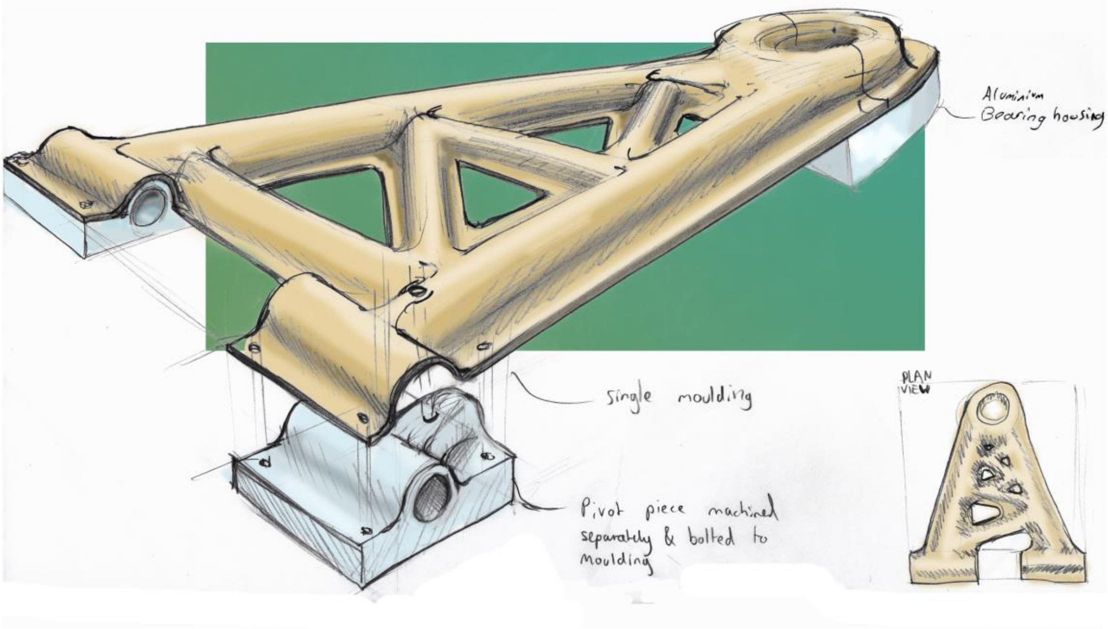


Figure 5.41c, Wishbone concepts 5 and 6.

Concept 7
Single moulding, bolted fixings for disassembly



Concept 8
Aesthetic moulded structures

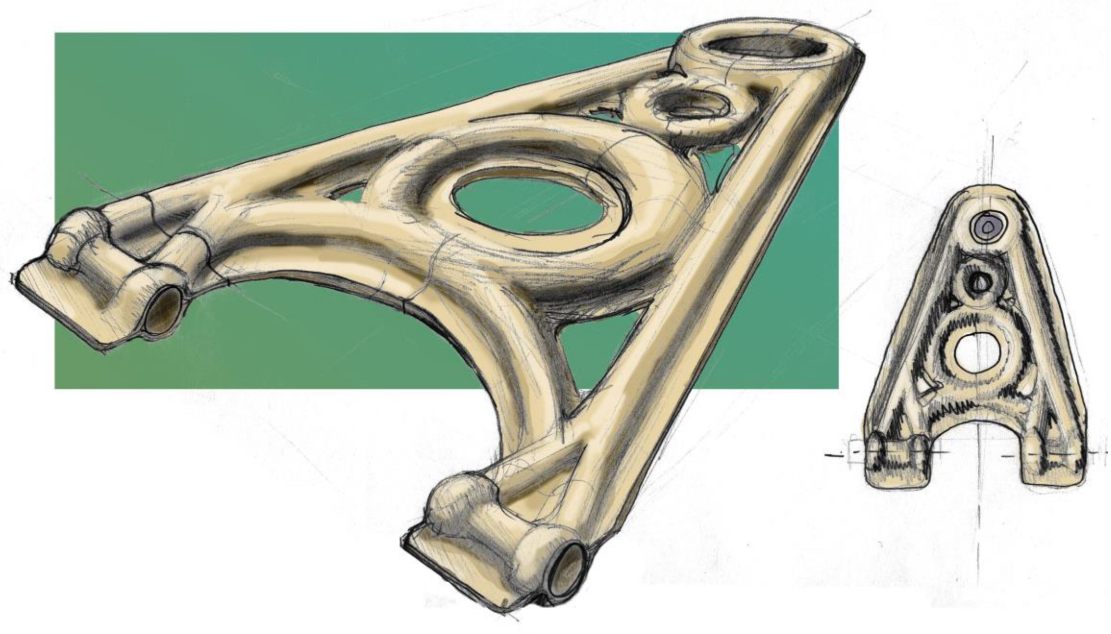


Figure 5.41d, Wishbone concepts 7 and 8

Detail design - upright joint.

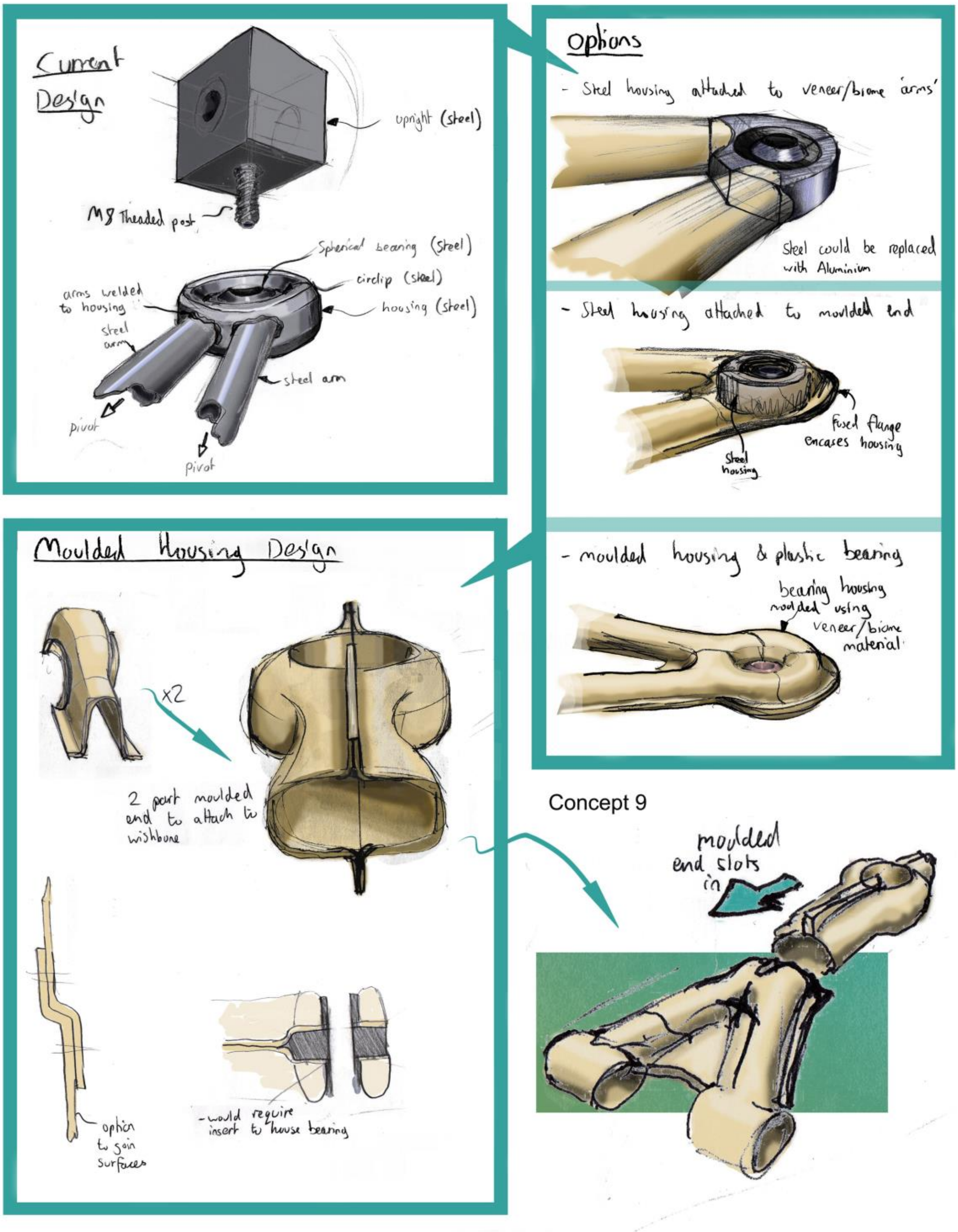
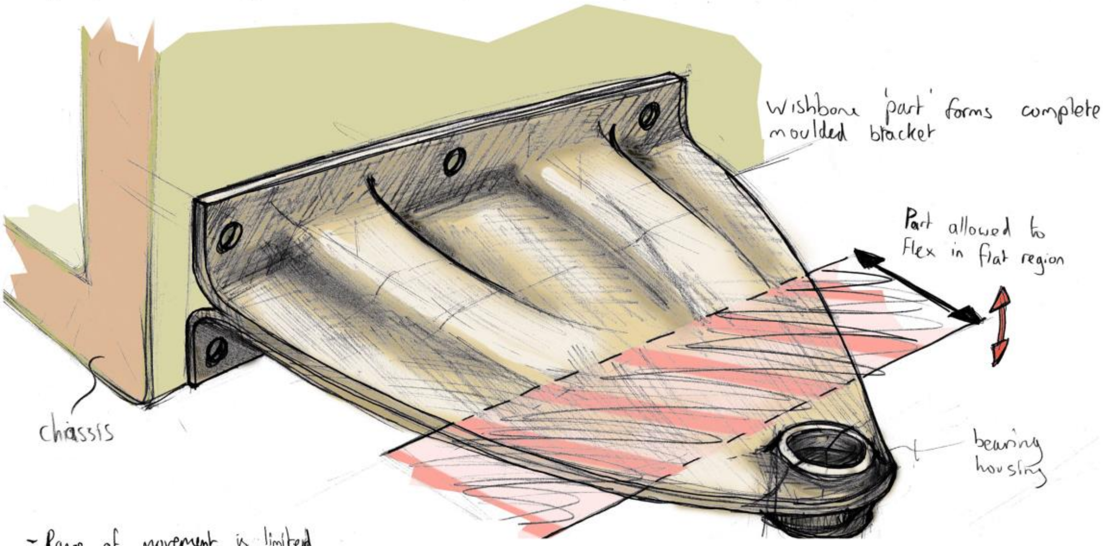


Figure 5.41e, Wishbone detail design - upright joint and concept 9.

Concept 10
single part - flexing wishbone component



- Range of movement is limited
- Fatigue on part unknown as material is new

Concept 11
Moulded bracket design with rubber 'hinge'

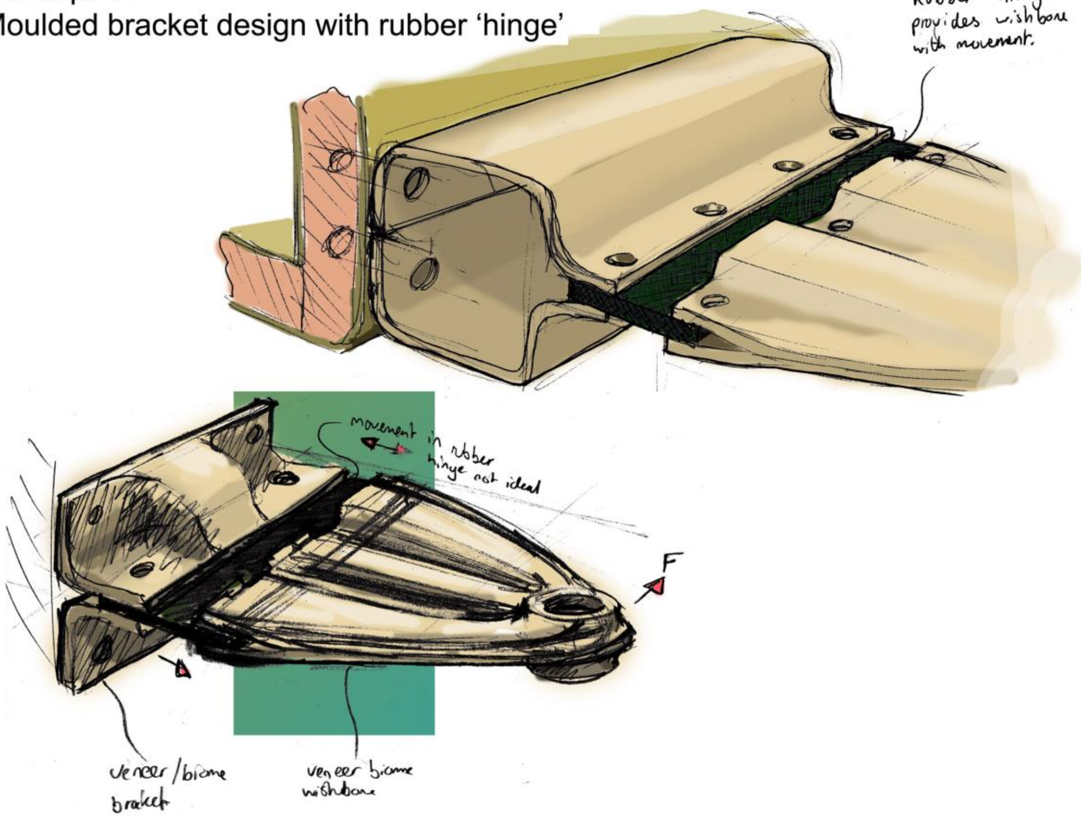
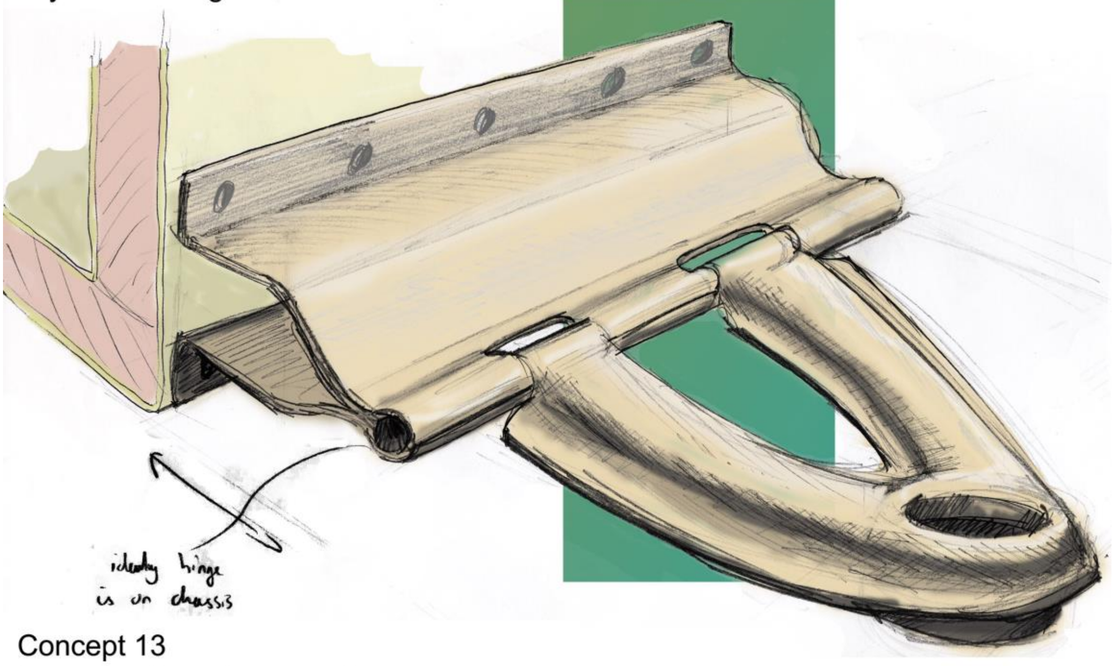


Figure 5.41f, Wishbone concepts 10 and 11

Concept 12
Asymetric design



Concept 13
Moulded Biome/Veneer hinge and bracket

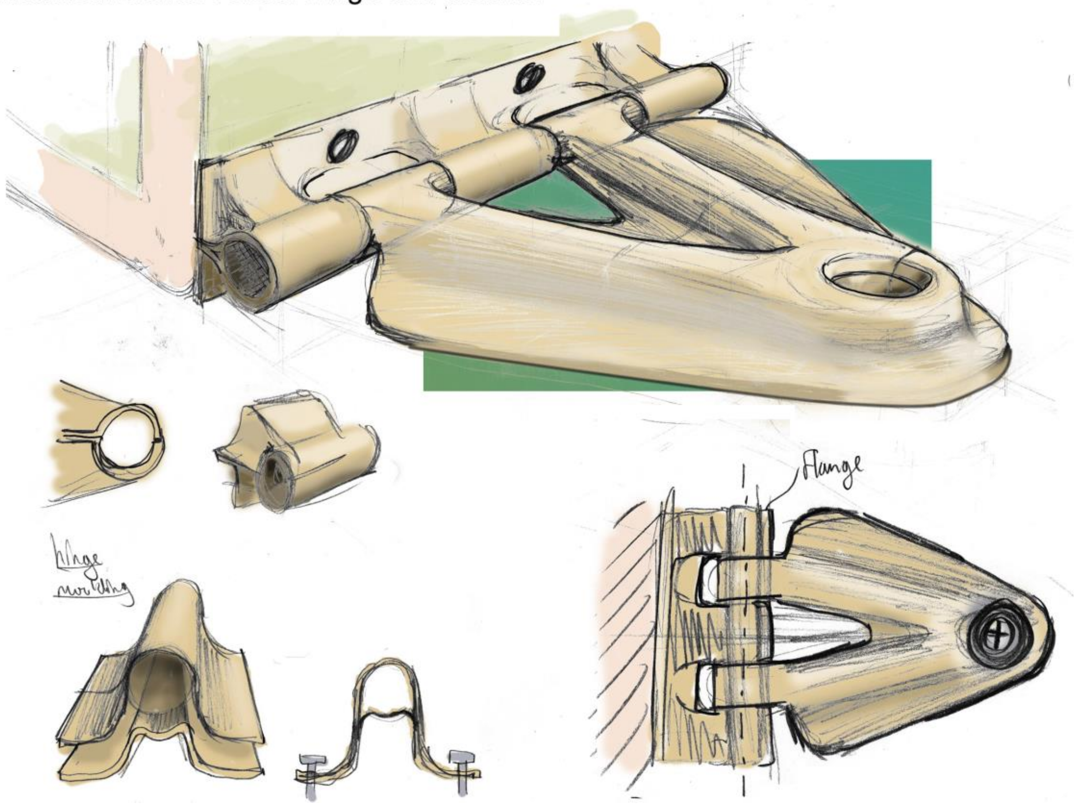
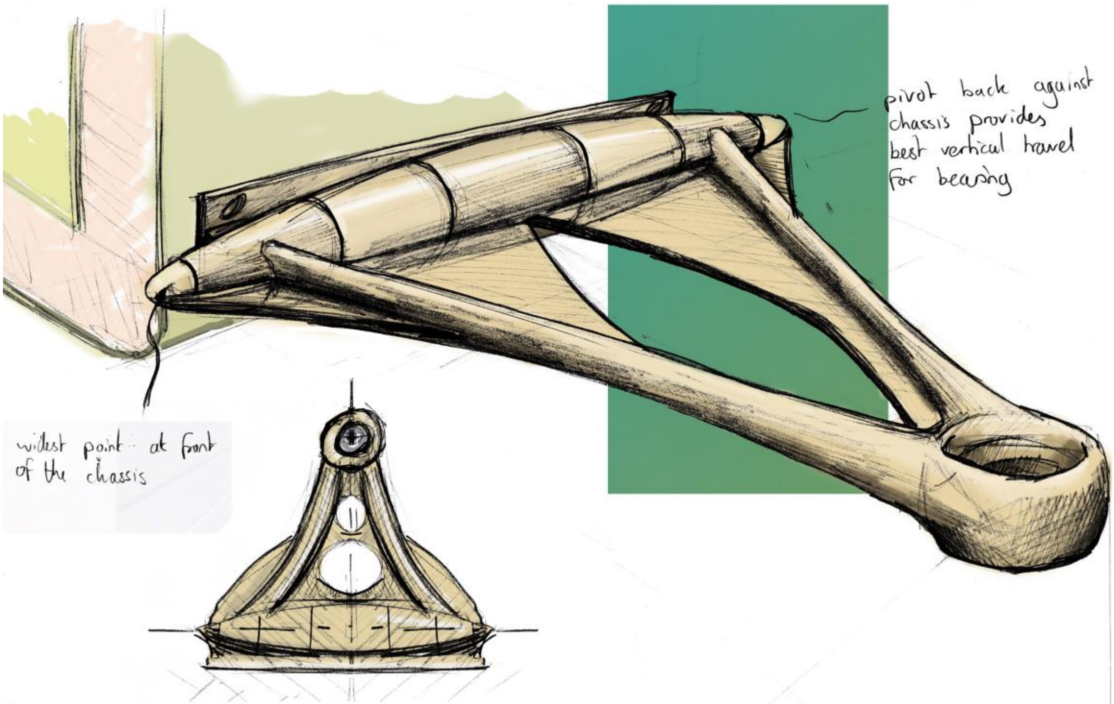


Figure 5.41g, Wishbone concepts 12 and 13

Concept 14
stylised moulded wishbone



Concept 15
Standard parts and wooden joints

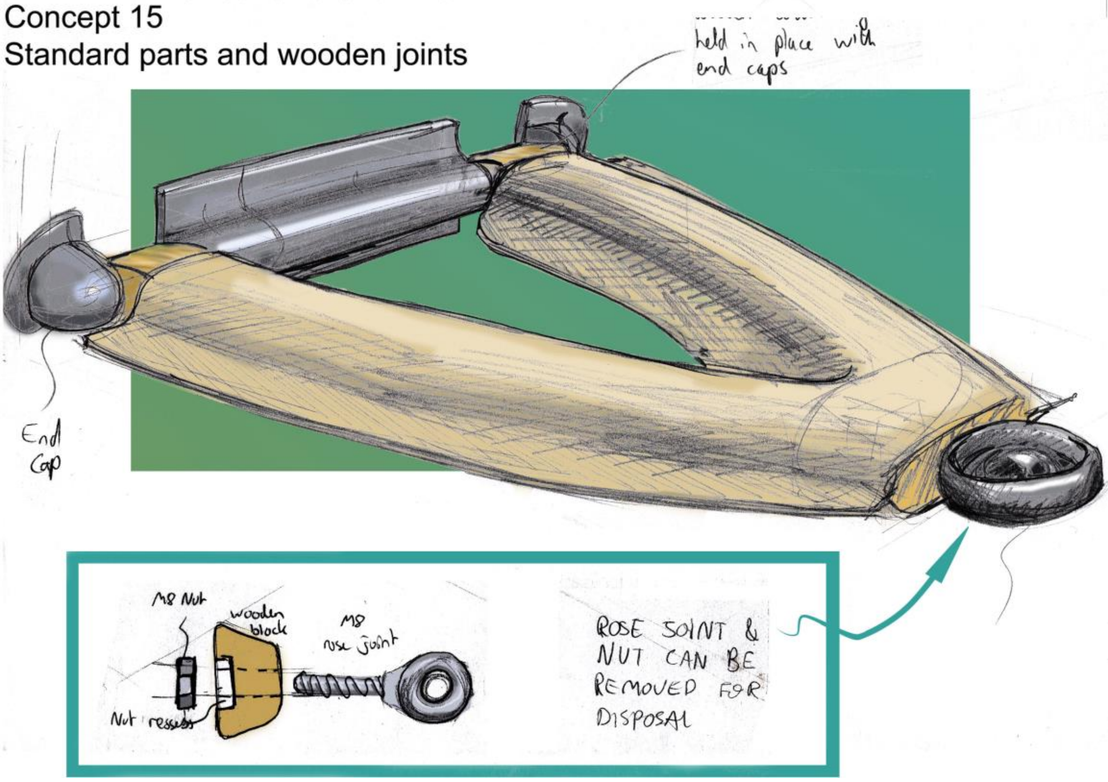
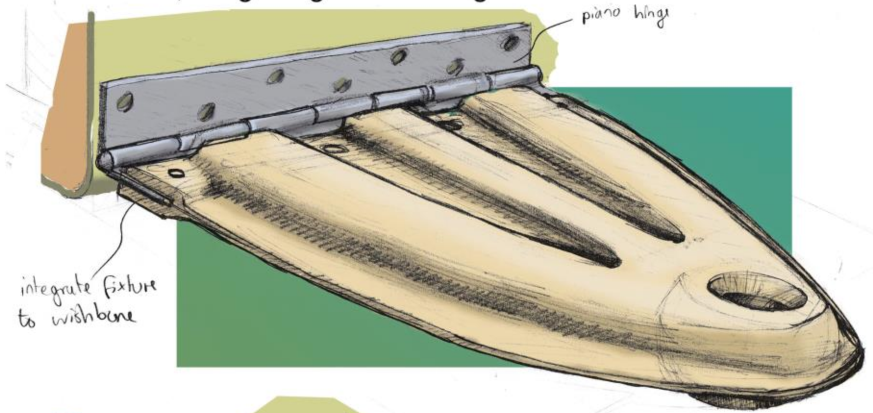
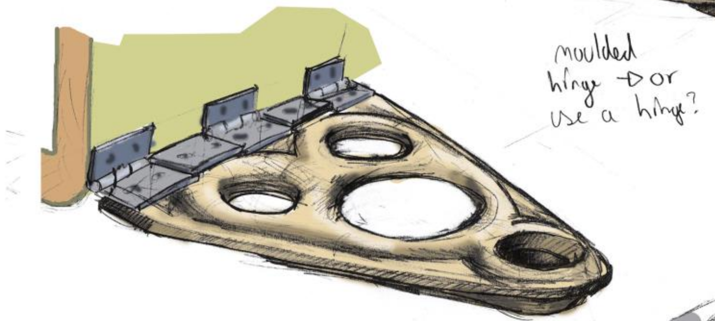


Figure 5.41h, Wishbone concepts 14 and 15

Concept 16
Moulded wishbone, integrating a metal hinge.





Concept 17
Moulded hinge wishbone with clevis joint

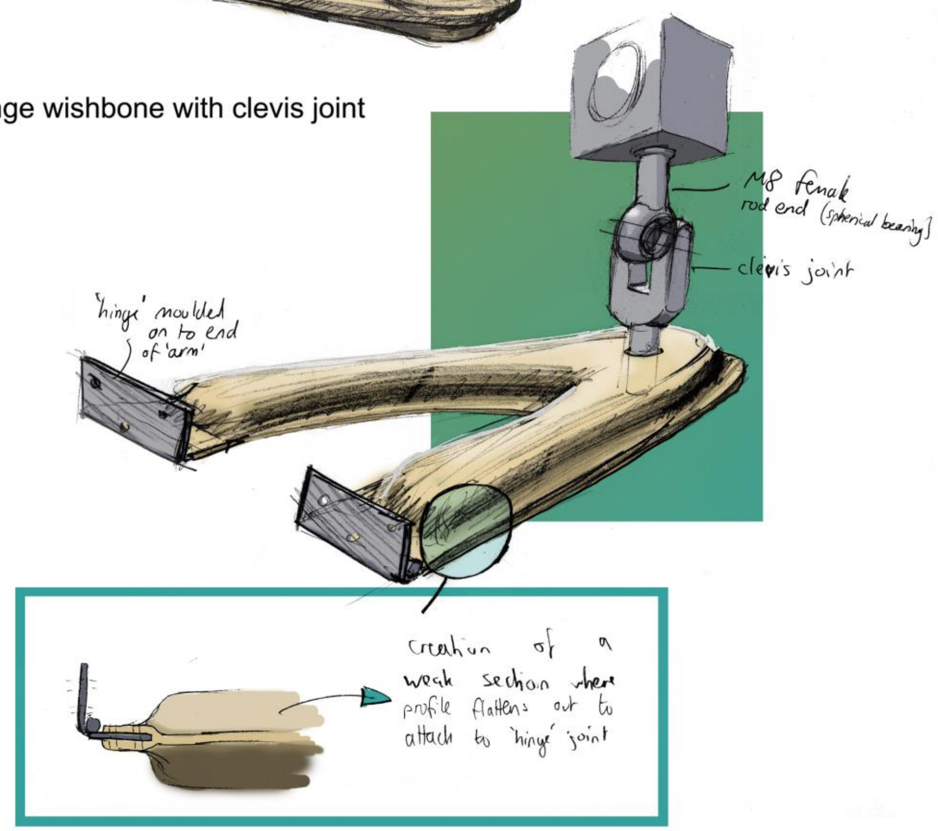
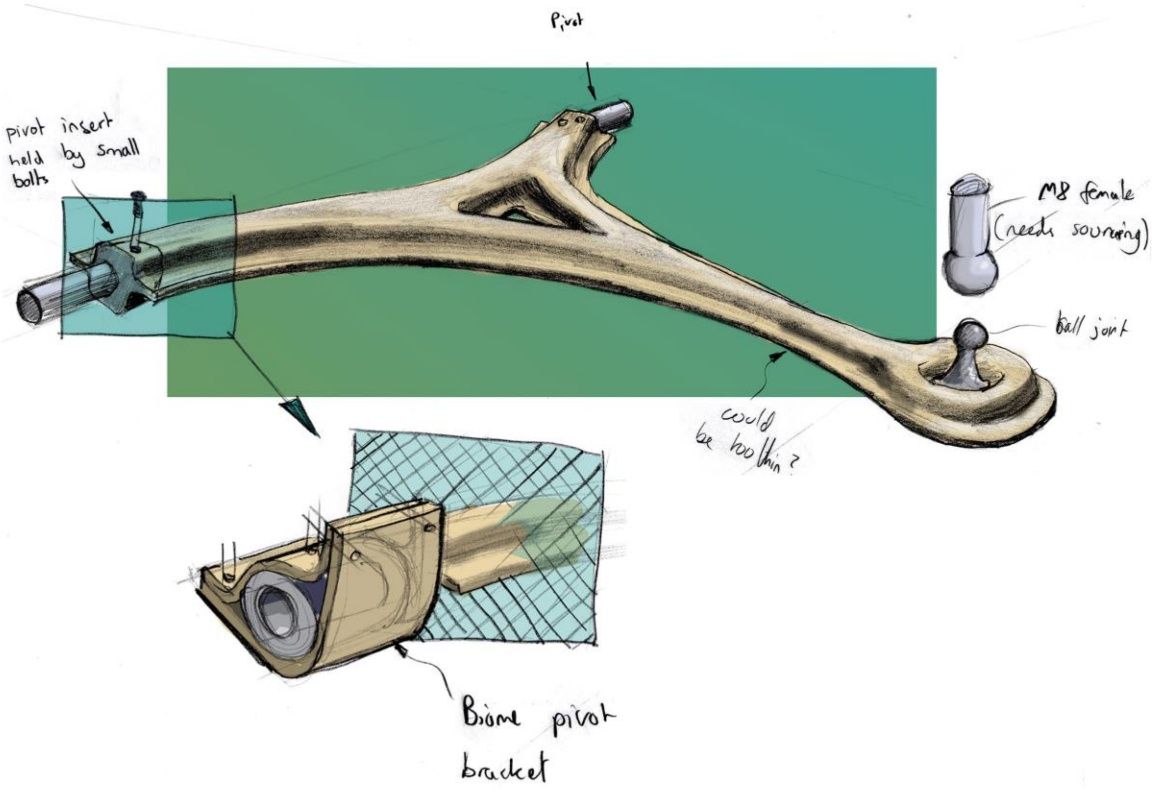


Figure 5.41i, Wishbone concepts 16 and 17.

Concept 18
Pivot mounted in chassis cutout, ball joint conection to wheel upright



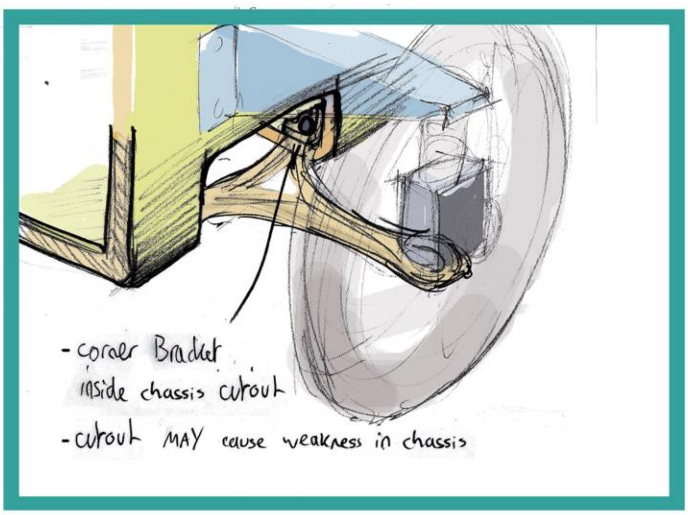
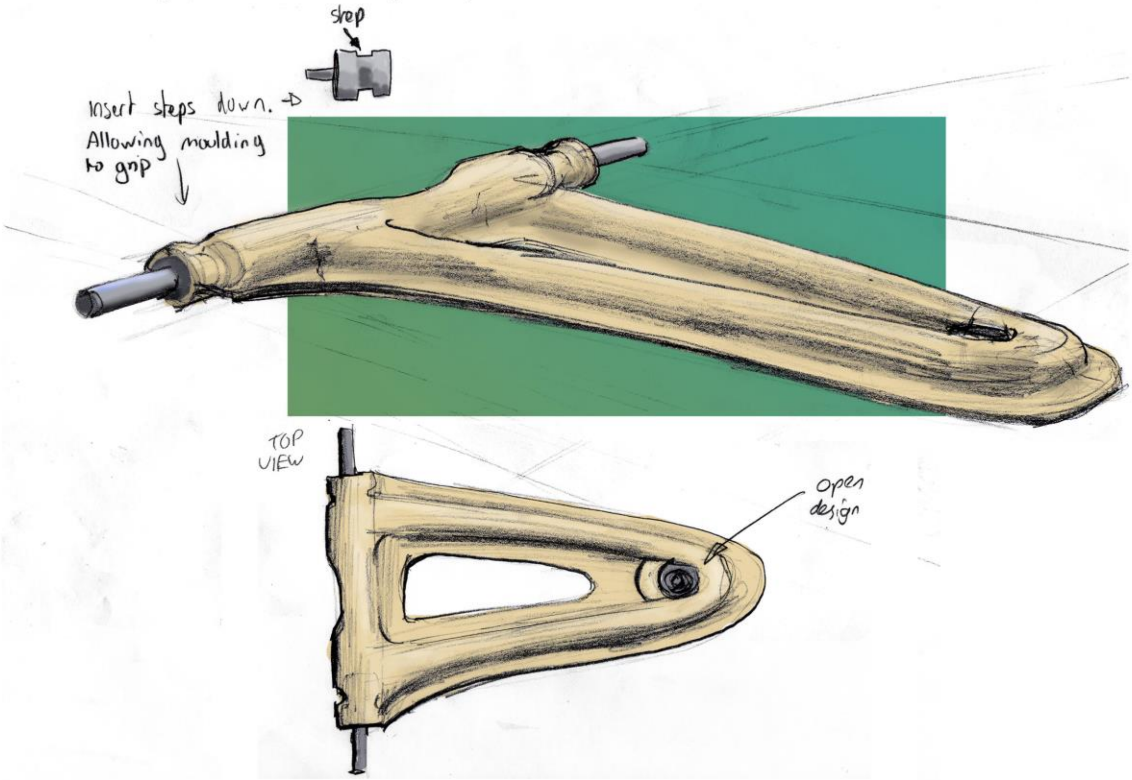


Figure 5.41j, Wishbone concepts 18

Concept 19
Narrow design with moulded pivot point



Concept 20
Design with moulded flange

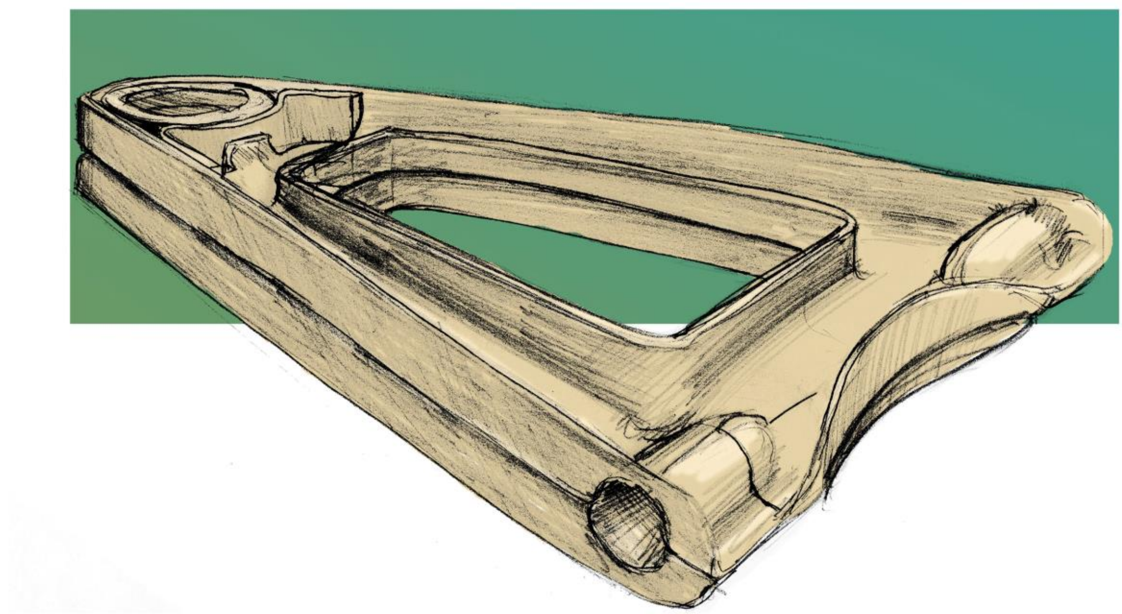


Figure 5.41k, Wishbone concepts 19 and 20.

A total of 20 concepts have been sketched out in figures 5.41a to 5.41k. Each concept displays differences in both geometry and attachment to various fixtures. This has been achieved through consideration of the benchmarks and the previous investigation of the veneer/Biome material. The important part of this process was to fully explore the range of possible designs using a 'broad brush' approach as described on p109 of Ulrich and Eppinger (2008).

Concepts 1, 2, 3 and 4 are of a similar design to the 2015 wishbone (used as a benchmark). Creating the tube sections will prove difficult - considering the pressing process - a more suitable form could be a 'flatter' design with pressed features (Concepts 5).

Concept 5 draws from an idea to press together two similar mouldings - creating a 'clam shell' component. Processing the mouldings in this way is developed in the remaining concepts where further features such as flanges for stiffness, and moulded inserts are considered.

Concepts 1 to 20 need to be narrowed down and developed further in an effort to reach the optimal design.

5.3.9 Concept selection

To select a final design from these concepts, each concept will be scored against the needs analysis (section 5.3.6). This is a subjective method, based on experience gained from the pilot study and points raised through the benchmark analysis. A weighting has been given to the scores to reflect the importance of each criteria. The most promising concepts are highlighted. Perceived flaws with some high scoring concepts will require further consideration. A matrix evaluation similar to Milton and Rodgers (2013) ‘matrix evaluation’ (p.152) method is used in Table 5.20 to select the most promising concepts – using the benchmark 2014 and 2015 EcoCar wishbones as points of reference.

Needs (+weighting)	Benchmarks 2014	2015	Concepts 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Sus Design																						
1 (score _/5)	3	1	4	4	4	2	4	4	3	4	4	5	5	5	5	5	3	4	3	4	4	4
2 (score _/1)	1	0	0	0	0	0	1	1	1	0	0	1	1	1	1	0	1	1	1	1	0	0
3 (score _/1)	0	1	1	1	0	0	0	1	0	1	0	0	0	0	1	1	1	0	0	1	1	1
4 (score _/4)	1	3	0	0	0	1	3	4	3	4	3	4	2	3	4	4	3	3	3	3	3	4
Total for section (_/11)	5	5	5	5	4	3	8	10	7	9	7	10	8	9	11	10	8	8	7	9	8	9
Material & manufacture																						
1 (score _/8)	-	-	7	7	7	2	7	7	5	8	6	8	7	8	8	8	4	6	7	8	8	8
2 (score _/8)	-	-	0	0	1	5	6	8	8	7	7	7	6	6	7	4	7	8	8	8	8	8
3 (score _/2)	2	1	1	1	1	0	1	1	0	1	1	2	0	1	1	1	0	2	2	1	1	1
4 (score _/10)	10	8	0	0	1	9	10	8	7	6	2	8	6	6	6	2	9	8	8	6	8	8
Total for section (_/28)	12	9	8	8	10	16	24	24	20	22	16	25	19	21	22	15	20	24	25	23	25	25
Performance																						
1 (score _/8)	6	6	6	6	6	6	6	6	6	6	6	7	7	7	7	7	7	7	7	8	6	6
2 (score _/8)	6	7	7	7	7	7	7	7	7	7	7	8	0	8	8	8	8	8	8	8	7	7
3 (score _/8)	6	5	6	6	6	6	6	6	6	6	6	4	6	4	5	6	7	7	7	8	7	6
4 (score _/5)	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
5 (score _/10)	10	8	2	3	8	6	5	6	6	6	5	2	0	4	6	4	7	9	6	4	8	9
6 (score _/5)	3	4	2	4	2	3	3	4	4	4	2	3	2	3	3	4	4	5	4	1	3	4
7 (score _/3)	3	3	0	0	1	1	2	2	2	2	1	0	1	1	1	1	2	3	2	0	2	3
8 (score _/5)	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4	5	5
9 (score _/5)	0	1	2	2	2	0	3	3	2	3	3	4	4	4	4	3	3	3	3	4	4	4
Total for section (_/57)	44	44	35	38	42	39	42	44	43	44	40	38	30	41	44	43	48	52	47	42	47	49

Table 5.20, Concept selection matrix – concepts scored against the needs analysis criteria listed in 5.3.6

At this point the fixings and linkages to be used has not been explored in depth. A number of methods have been considered in a general fashion and suitable components will be selected once the geometry of the moulded component is finalised. Four high scoring concepts chosen to take forward are concepts 6, 16, 19 and 20.

5.3.9.1 Stress analysis

Maximum loading on the wishbone occurs when braking while cornering (calculated in section 5.3.5). These maximum loading conditions on the right-hand wishbone – F_1 (due to braking) and F_2 (due to cornering) - act at point P as described in the figure 5.42. To select a geometry for the moulded veneer/Biome wishbone component, the stress in the wishbone under these maximum loading conditions is modelled for concepts 6, 16, 19 and 20.

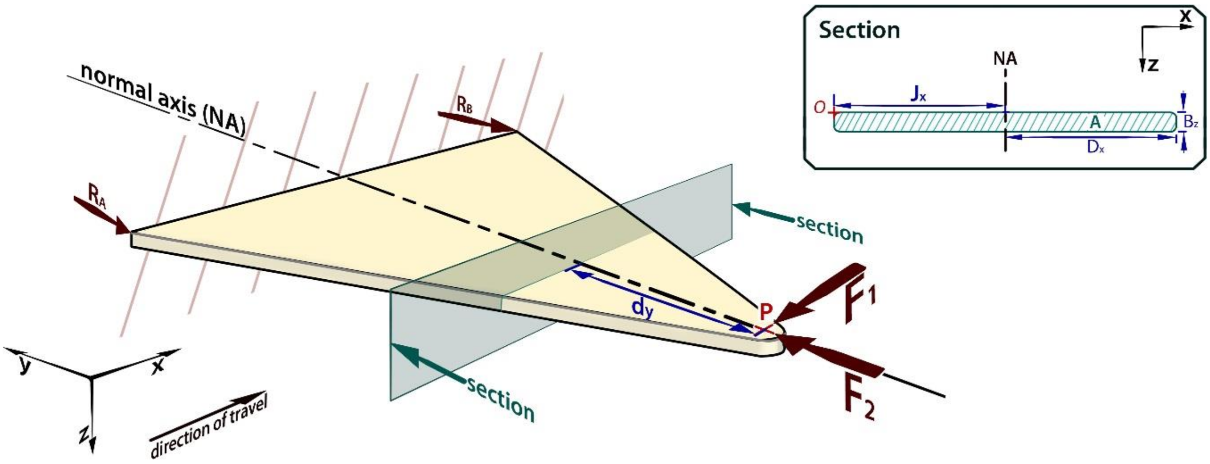


Figure 5.42, wishbone diagram for stress modelling.

As the wishbone is designed to move freely in the vertical direction (Z), the loading on the wishbone is applied in the {x,y} plane. The stresses caused by F_1 and F_2 within each concept can be analysed at cross sections (taken at intervals). performance of each concept geometry can then be used to select an optimal geometry for the moulded wishbone component.

<u>Concept geometry</u>

From the sketches in concept generation section 5.3.8 the geometry of the four chosen concepts are detailed in figures 5.43a, 3b, 3c and 3d. Plan views of each of the four chosen concepts is illustrated, with cross sections AA, BB, CC, and DD taken at a distance (L_y) from point P (as illustrated in figure 5.42). Sections are taken at 50mm intervals perpendicular to the normal axis. For each concept, a wall thickness of 3 mm (for each moulding) has been applied and for ease of calculation radii have been eliminated.

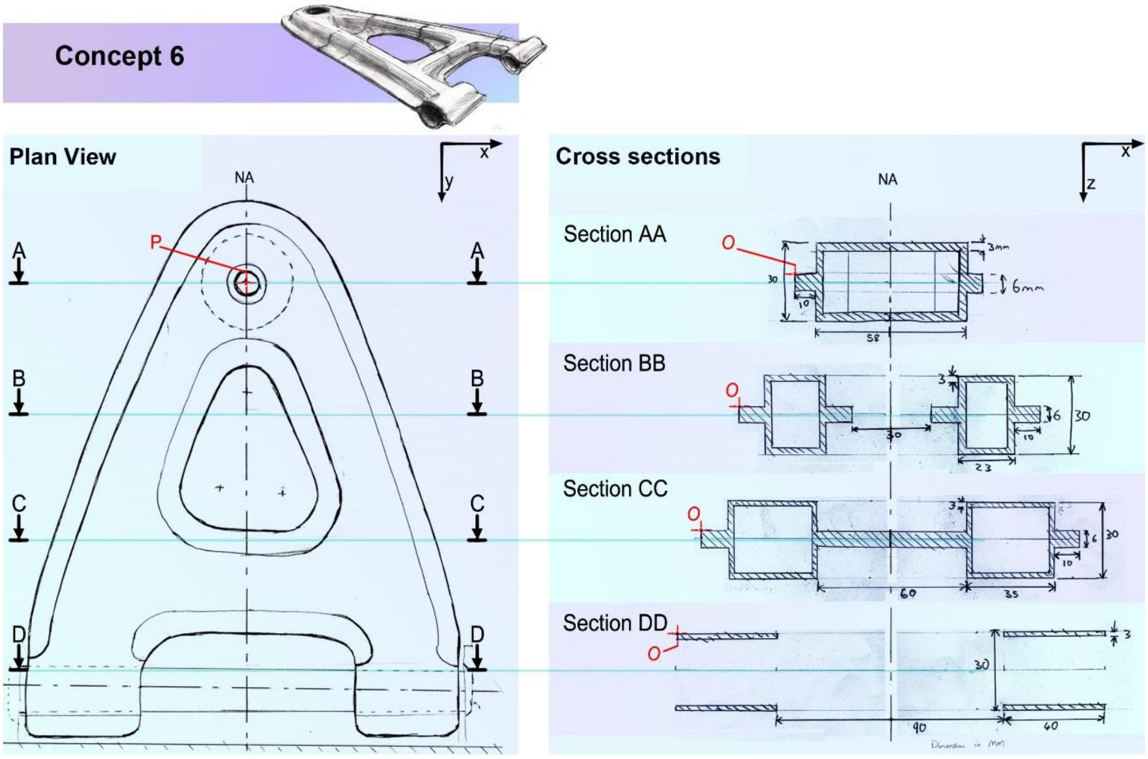


Figure 5.43a, Plan and section view of concept 6.

The Forces F_1 and F_2 act at point P, where the normal axis and section AA intersect.

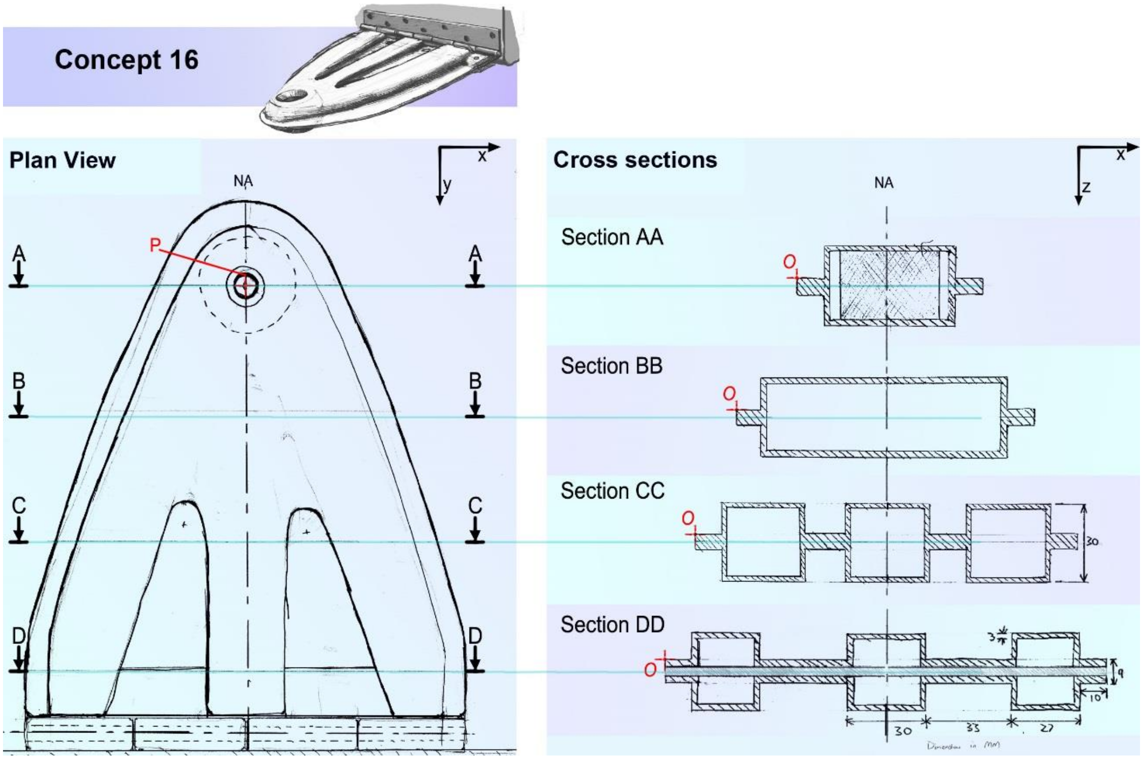


Figure 5.43b, plan and section views of concept 16

For concepts 19 and 20 (shown in figures 5.43c and 5.43d) the overall depth of the component was increased from 30mm to 40mm.

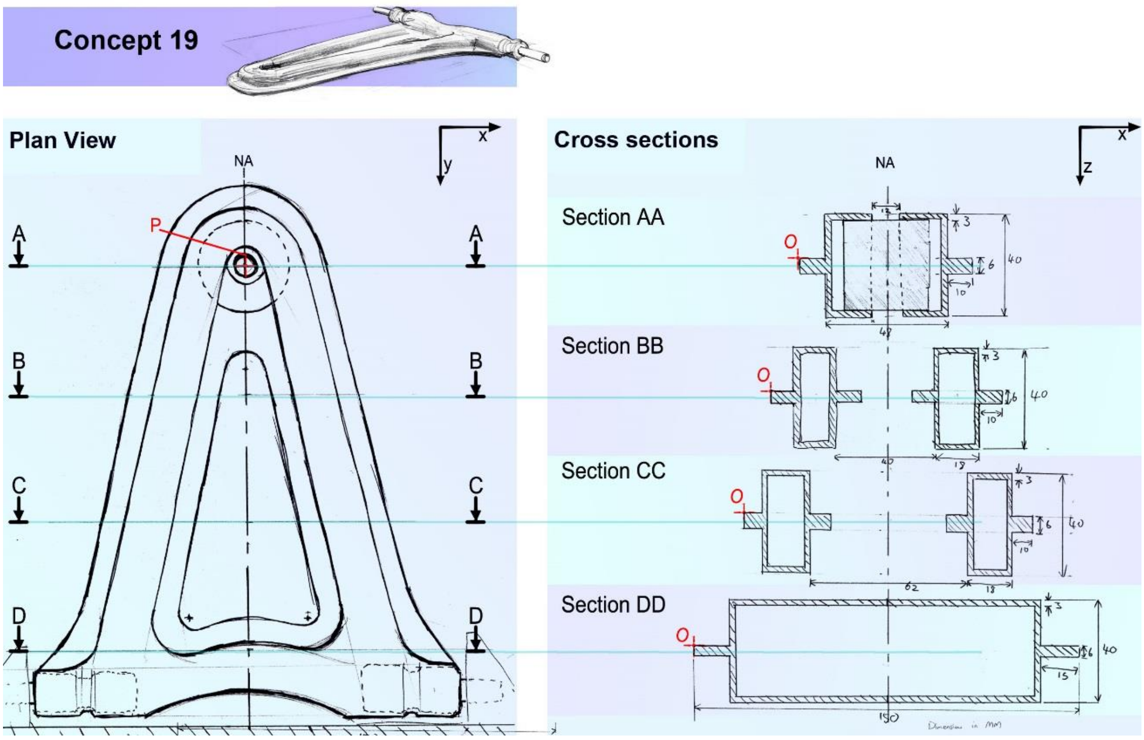


Figure 5.43c, plan and section views of concept 19

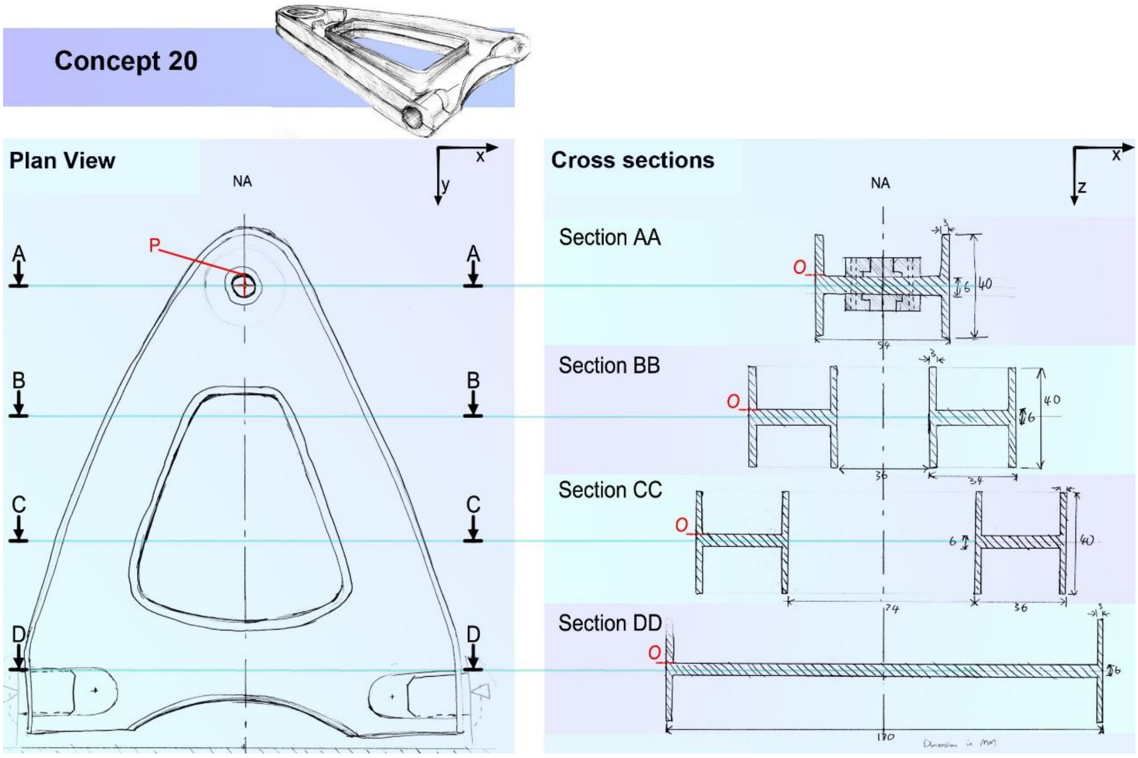


Figure 5.43d, plan and section views of concept 20

From the dimensions in figures 5.43a, 5.43b, 5.43c and 5.43d the cross-sectional area (A) has been measured and second moment of area (I) has been calculated.

The cross sections are reduced into rectangular segments, and for each segment the second moment of area has been calculated using the formula:

$$I = \frac{B_z \, {D_x}^3}{12}$$

Where B_z is the thickness of the material in the z direction, and D_x is the distance from the normal axis (as displayed in figure 5.42). The values calculated for I and A for each concept is displayed in table 5.21.

<u>Stress analysis</u>

To model the stress, the forces F_1 and F_2 (calculated in section 5.3.5) are used where:

F_1 = 422 N

F_2 = 1813 N

The stresses induced by F_1 and F_2 are calculated at point *O* in each of the cross sections of the wishbone concepts using the following formulae:

As the cross sectional planes are parallel to the direction of F_1, the shear stress (τ_{xy}) due to F_1 can be calculated using:

$$\tau_{xy} = \frac{F_1}{A}$$

Since there is no direct stress acting on the sections in the x direction (σ_x):

$$\sigma_x = 0$$

Direct stress acting on sections in the y direction (σ_y), is caused by direct stress due to F_2 and the bending stress due to F_1:

$$\sigma_y = \frac{F_2}{A} + \frac{M\,J_x}{I}$$

Where $M = d_y F_1$

Measurements of figures 5.43a, 5.43b, 5.43c and 5.43d have been applied to these formulae, the results have been compiled in table 5.21.

	Section	Distance to point P: d_y (mm)	Cross sectional area: A (mm^2)	Second moment of area: I (mm^4)	Shear stress: τ_{xy} (MPa)	Direct stress in the x direction: σ_x (MPa)	Direct stress in the y direction: σ_y (MPa)
Concept 6	AA	0	612	-	0.7	0	2.96
	BB	50	804	1,179,652	0.52	0	1.11
	CC	100	1188	2,411,244	0.36	0	1.38
	DD	150	480	2,092,000	0.88	0	2.75
Concept 16	AA	0	564	-	0.7	0	3.21
	BB	50	834	1,065,250	0.51	0	1.21
	CC	100	1308	2,283,412	0.32	0	1.40
	DD	150	1434	1,273,232	0.29	0	4.29
Concept 19	AA	0	540	-	0.8	0	3.36
	BB	50	864	804,752	0.49	0	1.31
	CC	100	864	1,460,528	0.49	0	1.77
	DD	150	1104	2,385,792	0.38	0	2.06
Concept 20	AA	0	528	-	0.8	0	3.43
	BB	50	816	1,137,232	0.52	0	1.03
	CC	100	840	2,699,040	0.50	0	1.23
	DD	150	1224	3,878,992	0.34	0	1.46

Table 5.21, Concept geometry

Principal Stress in wishbone concepts

To calculate the principal stresses in the wishbone concepts a Mohr's circle analysis is conducted. For each cross section, point *O* (illustrated in figure 5.42) is located within the cross section, at the maximum distance (J_x) from the normal axis. The principal stress (maximum stress for cornering while braking) at point *O* can be calculated by considering the plane {x,y}.

As σ_y is in compression, the stress boundary conditions can be described by the diagram in figure 5.44.

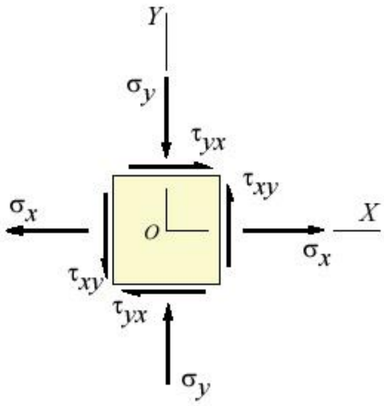


Figure 5.44 stress boundary conditions

Following the sign convention, the values for direct and shear stress from table 5.21 are used to plot Mohr's circle diagrams. A method developed by Naik (2015) has been used to generate the Mohr's circle plots with Excel, these graphs are displayed in figure 5.45. Direct stress in compression is shown as negative, and in tension as positive on the x axis. Positive shear is considered to act in a clockwise direction, and is plotted on the y axis.

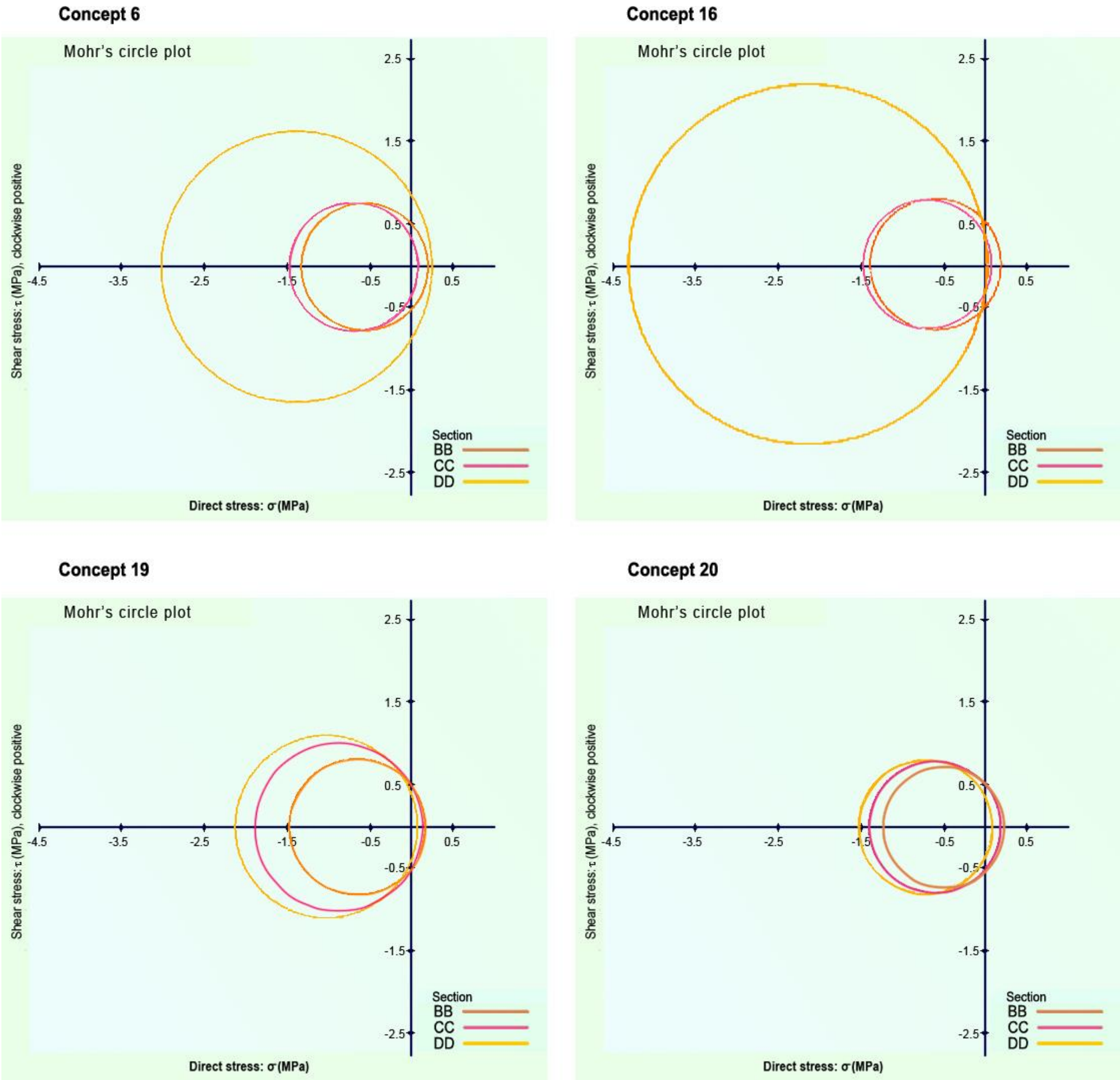


Figure 5.45, Mohr's circle plots for concepts 6, 16, 19 and 20.

The maximum and minimum principal stresses at point *O* in the cross sections of the concepts are listed in table 5.22.

	Section BB			Section CC			Section DD		
	σ_{Max}	σ_{Min}	τ_{Max}	σ_{Max}	σ_{Min}	τ_{Max}	σ_{Max}	σ_{Min}	τ_{Max}
Concept 6	0.2	-1.3	0.8	0.1	-1.5	0.8	0.3	-3.0	1.6
Concept 16	0.2	-1.4	0.8	0.1	-1.5	0.8	0.0	-4.3	2.2
Concept 19	0.2	-1.5	0.8	0.1	-1.9	1.0	0.1	-2.1	1.1
Concept 20	0.2	-1.2	0.7	0.2	-1.4	0.8	0.1	-1.5	0.8

Table 5.22, Principal stress at point O in concept cross sections.

Discussion

It is accepted that the forces and stresses are subject to inaccuracy as a result of simplification of load case and geometry. Since all geometries have been simplified in the same manner they can be considered comparable. Therefore, principal stress analysis can be used to evaluate the concepts and select the optimal geometry from concepts 6, 16, 19 and 20.

From the tensile tests performed in the Pilot Study, the estimated yield stress for the veneer/Biome sample was 50 MPa. In the four concepts under consideration the maximum stress is under 5 MPa. This shows the designs should be within the limits of the material. The maximum direct stress for all four concepts is under compression, this is as expected due to the loading conditions.

In concept 6, the comparatively large principal stresses (both direct and in shear as displayed in table 5.22) in section DD are due to the low cross sectional area. Large stresses in section DD of concept 16 are due to the low moment of inertia value.

Concept 19 is 10mm narrower at section BB in comparison to concept 6. As the shape of the sections are similar, the higher stress in concept 19 is due to the narrow shape. The lowest and most consistent levels of stress are displayed in concept 20 (illustrated in figure 5,45).

Concept 20 emerges as the optimal geometry to apply the loads as modelled. This is due to a greater amount of material at a distance from the neutral axis in comparison to the other concepts.

As a result of the stress analysis, the geometry of Concept 20 will be taken forward as the basis of the final design for the moulded wishbone component.

5.3.9.2 Biome/veneer component geometry

The basic geometry of concept 20 (a triangular shape with flanges along the rim) is to be adopted. Further developments are required to address issues raised in the selection matrix, and to better meet the target specification.

Issues regarding concept 20 that need resolving:

1. There is a need for further moulded stiffening structures.
2. Encased (moulded in) steel pivots create disassembly issues.
3. The moulded Veneer/Biome hinges are unachievable with the equipment and resources available.
4. Standard parts are desirable for the pivots and upright attachment. (Pahl & Beitz, 2007: p.374)
5. The complexity of the required mould is a concern.
6. The radii and draft angles for moulding need to be considered.
7. The depth of the mould is a consideration - to be kept as shallow as possible to preserve the fibres in the material, but needs to be deep enough so that the wishbone performs.
8. accurately positioning the wheel.
9. weight.

The linkage from the wishbone to the wheel upright and the pivot points need to be defined. The linkages and pivots considered during concept generation will be combined with the chosen geometry (concept 20). These will then be evaluated to select the most appropriate option.

5.3.9.3 Combination

Concept selection focused on the geometry of component proposed to be moulded. The upright linkages and pivot mechanisms most appropriate for use with concept 20 need to be considered.

<u>Linkage and pivot criteria</u>

1. General considerations for both pivot and linkage

   a) Feasibility.
   b) Rigidity.
   c) Disassembly.
   d) Sustainability.
   e) Standard parts - minimizing machining required and lowering cost.
   f) Standardise materials - for ease of recycling and reuse.
   g) Weight

2. The linkage from the wishbone to the upright will:

a) Allow the steering arm to turn the upright assembly freely.
b) Allow the upright to move vertically in an arc
c) Secure to an M8 post
d) Attach to the flat surface of H section (concept 20) of the wishbone.
e) Transfer loads through the centre of the wishbone

3. The mechanism that attaches to the chassis and allows the wishbone to move vertically will:

a) Be integrated with the chosen wishbone concept.
b) Transfer load from the wishbone to the chassis
c) Attach as close to the chassis as possible - minimizing horizontal movement along the wishbone arc of travel.
d) Allow the upright to move vertically (in an arc).

Table 5.23 evaluates the various pivot mechanisms and upright linkages considered during concept generation. These linkages and pivot mechanisms will be scored either positively or negatively with regard to compatibility with concept 20. The most suitable combination of upright linkage and pivot will be matched to the chosen design – concept 20.

Concept		**General considerations**							**Wishbone to upright linkage**					**Total score**
Upright linkage	Attachment to wishbone	1a	1b	1c	1d	1e	1f	1g	2a	2b	2c	2d	2e	
Spherical bearing (steel)	Moulded veneer/ Biome housing	-	-	-	-	--	+	+	+	=	+	-	+	-1
	Fabricated steel or aluminium housing	+	+	+	-	-	=	-	+	+	+	-	+	+3
	Moulded veneer/Biome housing with steel insert.	=	=	-	=	-	+	=	+	=	+	=	+	+2
	Wooden block	-	-	+	+	-	+	=	+	-	+	=	+	+2
Rose joint	Male clevis joint	+	+	+	-	+	+	-	=	-	+	+	-	+3

	fabricated wooden, steel or aluminium block	+	=	=	=	-	-	-	+	+	+	-	+	+1
Female ball joint	Male ball joint	+	+	+	-	+	+	=	+	+	+	+	-	+7
Female clevis joint	Male clevis joint	+	+	+	-	+	+	-	=	-	+	+	-	+3
Concept		**General considerations**							**Wishbone to chassis linkage**					**Total score**
Pivot	Attachment to wishbone	1a	1b	1c	1d	1e	1f	1g	3a	3b	3c	3d		
Moulded veneer/ Biome tube	Steel or aluminium bracket and pivot bolt arrangement	-	-	-	+	-	+	-	+	-	-	+		-3
Fabricated steel or aluminium housing		+	+	+	-	-	-	-	-	-	-	+		-3
Moulded steel insert	Steel rods attached to the chassis pin the wishbone in place	-	+	-	+	-	+	+	+	+	+	+		+5
Built in Flex	Moulded Veneer/Biome bracket	-	-	+	+	=	+	+	+	-	+	-		+2
Moulded Biome/ veneer hinge		-	+	-	+	-	+	+	+	-	-	+		+1
Steel hinge		+	+	+	-	+	+	-	=	+	+	+		+6

Table 5.23, Combination table considering upright linkage and pivot mechanism.

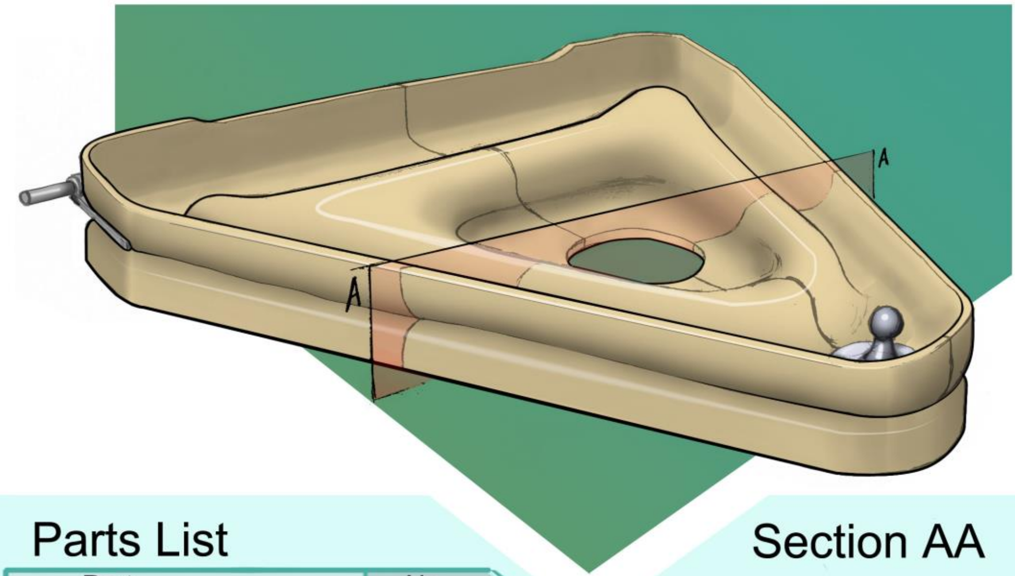
The combination table 5.23 takes into account the feasibility and appropriate attachment to the concept 20 geometry. the highest scoring concepts are feasible and appropriate for use with concept 20. The following parts have been selected:

- A stainless steel axial ball joint.
- Stainless steel flag hinge pivots.

Compromises have been made regarding the sustainability and weight. An effort will be made to source the lightest and 'least bad' components.

5.3.10 Final Concept

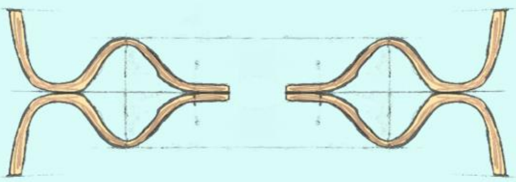
The final concept illustrated in Figure 5.46 combines aspects from several of the listed concepts.



Parts List

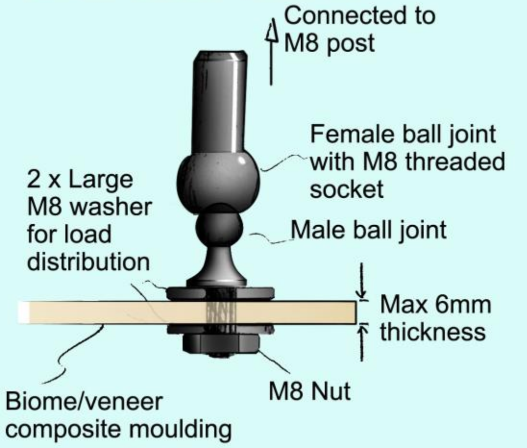
Part	No.
M8 Axial Ball Joint	1
Large M8 Washer	2
M8 Nut	1
Biome/Veneer Moulding	2
Flag Hinge (Left)	1
Flag Hinge (Right)	1
M5 Bolt (20mm)	6
M5 Washer	12
Total Components	26

Section AA



Design consists of 'H section' with moulded rib features to further improve the stiffness of the structure.

Ball Joint Detail



Top View

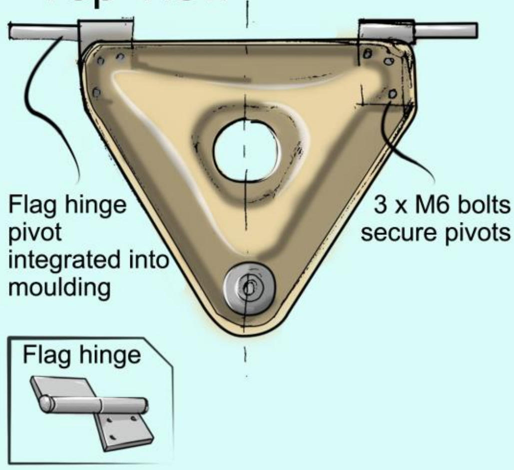


Figure 5.46, Final concept.

The flanges from concept 20 and the moulded structures from concept 7 provide stiffness across the structure.

The ball joint has been favoured as it provides a simple solution without complex moulding. Intricate moulds will prove difficult to achieve as the mouldable minimum radius is 10mm.

Lift off flag hinges allow the pivot pin to be mounted close to the chassis. This pivot pin is attached to a plate which can be imbedded within the veneer/Biome moulding. As the plate is hidden, the hinge provides a neat integrated solution.

The final moulded part will be created from two moulded pieces. This is proposed to be manufactured in the following process:

Stage 1. A 2 part aluminium male and female mould is pressed to create two 3mm thick Veneer/Biome 'trays'.

Stage 2. Two male moulds are reused to press the two 'trays' back-to-back.

Stage 3. The pivot and ball joint linkages are secured.

5.3.10.1 Standard parts

The use of commercial off the shelf components allows the linkages and fixtures to be low cost, with a short lead time (Pahl & Beitz, 2007: p.374). All parts are made from stainless steel. Table 5.22 details the source of parts to be used in the final design:

Component	**Quantity**	**Source**	**Stock number**
Flag Hinge (40 x 30 x 3)	2	RS components	347-8355
M8 Axial Ball Joint (incl. M8 nut)	1	Springfix Linkages	R3506.R006
M8 Washer (outside diam 24)	2	RS Components	797-6250
M6 Hex Socket button Screw	6	RS Components	232-8271
M6 Nut	6	RS Components	189-591
M6 Washer (outside diam 12.5)	12	RS Components	189-658

Table 5.22, List of standard parts for wishbone assembly

Along with the 2 moulded veneer/Biome components, these added fixings and linkages bring the total number of components to 31. This number is at the upper end of the (less than 31) target due to a design approach allowing for disassembly for the end of life separation of materials.

5.3.10.2 Predicted Weight

The weight of the stainless steel fixings totals 424 grams (excluding the fixings to the chassis), this presents a challenge with the target for the total wishbone weight being under 600 grams. Although the weight target may be missed, a compromise in this area ensures a robust product able to fully test the material of interest - the veneer/Biome composite. Future iterations of the wishbone may comprise steel components of reduced size.

The technical details of the wishbone need to be completed in order for the wishbone to be made. The next step for the M/D/M strategy is to bring together the design and materials so that the wishbone can be completed.

5.4 Veneer/Biome wishbone Manufacture

Two wishbones are required for the 2016 Aston EcoCar.

In order to manufacture the wishbones using the veneer/Biome material a mould will be required. This mould needs to be suitable for use on the university lab press under conditions set out in the design specification. The mould needs to produce a minimum of 4 parts.

5.4.1 The lab press

The press for manufacturing the wishbone components consists of 2 x 10 tonne hydraulic rams, pressing lower and upper heated platens shown in the figure 5.47.

Figure 5.47, Lab press, maximum pressure 20T, maximum temp 230°C.

The following constraints of the lab press need to be taken into consideration:

1. The press has a bed size of 280mm x 380mm.
2. The maximum stroke of the hydraulic rams is 183mm.
3. 340mm between vertical supports.
4. Maximum gap between bed plates of 200mm

5.4.2 The Mould

The manufacture of the mould is subject to the pressing equipment used as well as the cost of tooling and materials. A number of compromises have therefore been made:

Heating - The mould is to be heated by the platens located on the press beds. As the mould varies in depth, the temperature at the surface of the mould will vary by an estimated 5-10°C. This temperature difference is not ideal, leading to a certain amount of estimation as to how long to pre-heat the mould, and at what temperature to set the thermostats.
An infrared thermometer will be used to check the temperature of the moulding surface (before inserting the material into the mould), this will aid the accuracy of the manufacturing parameters.

To manufacture a component using more accurate conditions and evenly heating the moulding surface, a mould could be constructed with elements and thermostats located within the mould, close to the moulding surface. The resources for doing this were not available.

Die set - The standard tooling for pressing a part such as this wishbone would include a die set, however, a die set cannot be attached to the press platens. As this moulding is one of a kind, for a short run of wishbone components, it has been decided not to invest in a die set. The function the die set performs - to guide the male and female moulds to the correct location will be conducted by 3 pillars located in bushes set into the base of the moulds.

Materials - as the mould will only need to press eight to ten parts, it will be made using aluminium. Aluminium has better thermal conductivity (as it will be heated from the platens) compared to steel, it will also take less time to machine the mould.

Complexity - To manufacture the part, a 2-part mould with open sides is required. The part needs to be modelled in CAD in order that an accurate mould can be machined.

A CAD model is necessary, and is built using the press constraints as guidelines.

5.4.3 Development of a CAD model

The final concept sketch was combined with the list of standard parts for an initial CAD model of the wishbone part to be constructed. Final detailing of the design needs laying out, such as integrating the pivot and upright linkages to the moulded shape. It was clear that to realise the final design, some modification is needed. An iterative approach is taken to further development of the wishbone part using the Solidworks CAD package. This CAD development will allow a mould to be manufactured by CNC milling, ensuring the cavity is of an even thickness to the required tolerance and surface finish.

The geometry of the initial CAD model displayed in figure 5.48 differs slightly from the final concept sketch (figure 5.46), undulations evident in the final concept would cause excessive stretching of the veneer/Biome during moulding, so a simpler form was chosen.

As per the design specification, a minimum inside radius of 10mm was used on all corners of the modelled part:

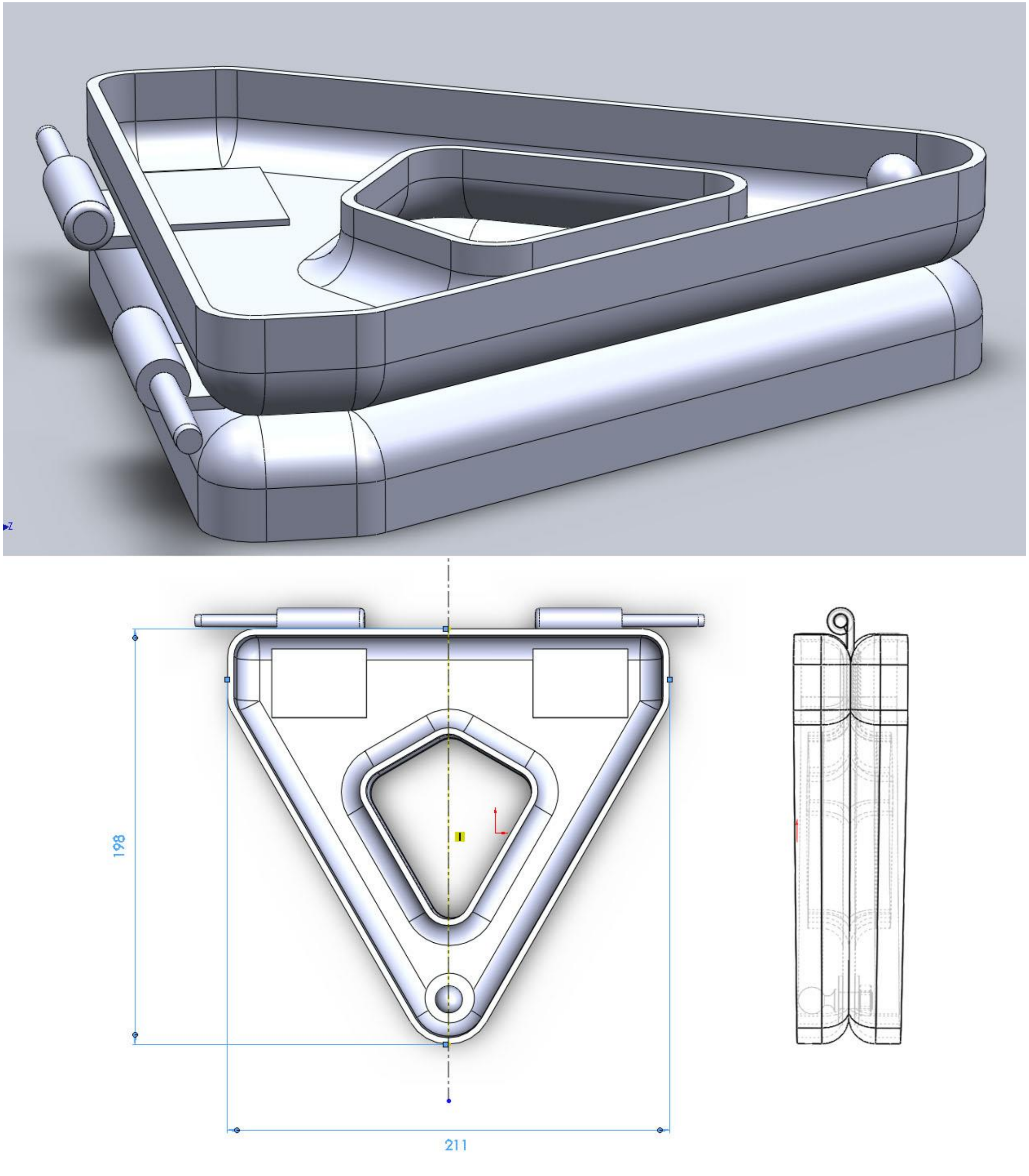


Figure 5.48, Wishbone CAD version 1.

The initial model needed further refinement, deliberation was needed regarding:

- Interfaces with the pivots and ball joint - requiring flat surfaces for washers.
- The internal geometry - stiffening ribs to improve the structure and strengthening the structure in the area between pivot points.

- The rear vertical face may interfere with the pivot. The pivot brackets (flag hinges) may need to protrude further out. Ideally the moulded section and the pivot is as close as possible while allowing the necessary range of movement. This will be tested using an assembly model.

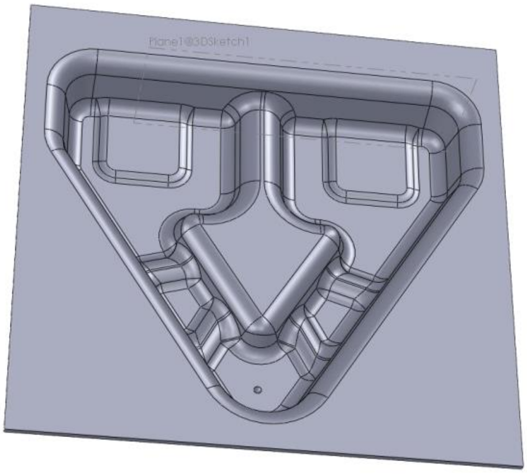


Figure 5.49, Wishbone CAD version 2.

The modelled shape in figure 5.49 represents the 3mm cavity between the male and female moulds. Further alterations to 'CAD version 1' included:

- A radius along the rim of the feature. - During the moulding test (experiment 9), sharp edges broke the fibres. The material will stretch as the mould closes, as the fibres do not stretch, they will either be 'dragged' into the mould, or break. It is desirable to have long unbroken fibres moulded within the part. A radius along the rim of the feature allows fibres to be 'dragged' into the moulded feature.
- Draft angles - In order to release the part from the mould intact, it is estimated a draft angle of at least 10° is required.

Only one mould can be manufactured due to budget restrictions. Once the mould is machined, further changes can not be implemented, for this reason a conservative approach to design is adopted. As this is a prototype material and component, the radii on the corners will be as large as possible and the depth of the mould will be kept as shallow as possible. The integration of the pivot plates needs to be sufficiently robust and secure.

The radius along the rim of the feature causes problems with the mouldable depth. The depth of the moulded feature would be increased to a point where during moulding, the wood fibres would be stretched too far. For this reason the walls of the feature were reduced - producing a more shallow feature. To recover this lost depth, trimming of the moulded part is likely to include a portion of the radius along the rim.

A second issue with the radii was a loss of definition within the part. After reviewing the moulding tests completed in experiment 9 (section 5.2.3) a less conservative minimum radius would achieve an improved result overall. The inside radii were reduced from 10mm to 7mm. The final CAD assembly is displayed in figure 5.50.

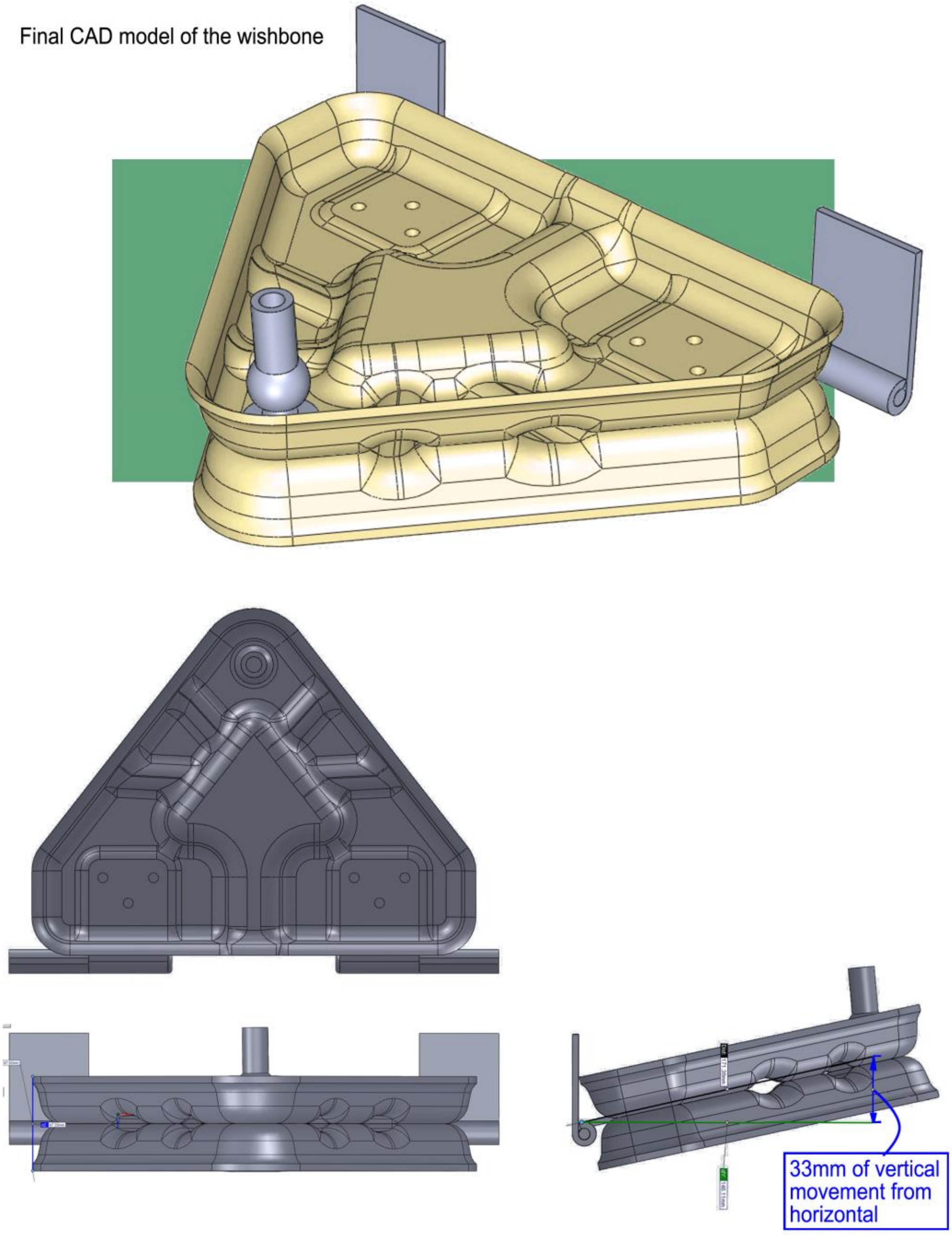


Figure 5.50, Finalised CAD model of wishbone design.

5.4.4 Final CAD design stress evaluation

To evaluate the design before manufacture, a stress analysis is conducted on the finalised design.

<u>Material strength</u>

For the purposes of this stress analysis, the estimated strength of the material is assumed to be **50 MPa** as measured during the tensile test conducted during the pilot study in section 4.3.3.

5.4.4.1 Principal stress at cross sections

The method used in section 5.3.9.1 is applied to the final design to calculate the principal stress at cross sections.

The geometry of the final CAD model is displayed in figure 5.51.

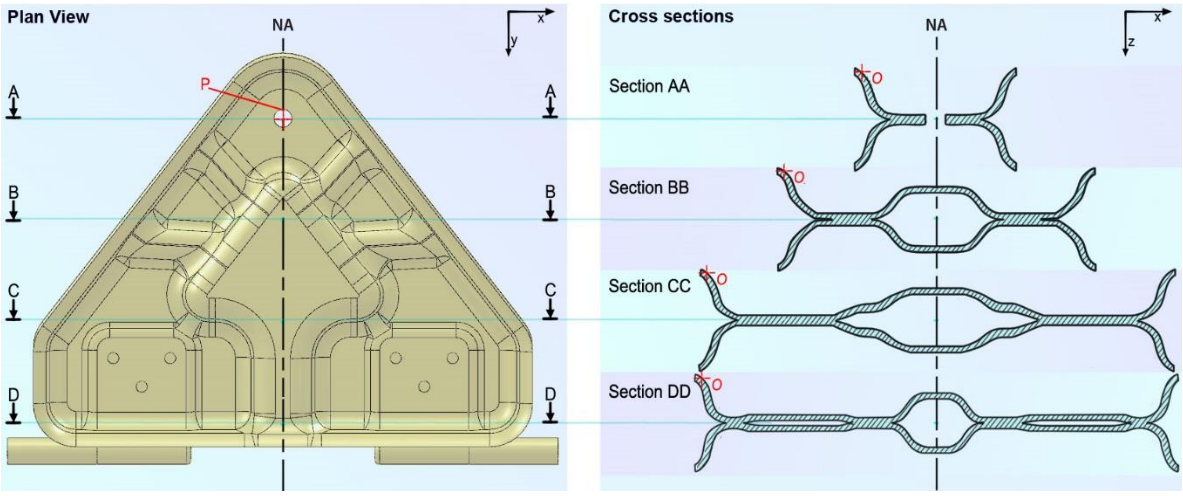


Figure 5.51, Finalised design plan view and cross sections.

Both the area and second moment of area of the cross sections are measured using the CAD model. The second moment of area is calculated about the normal axis (labelled NA in figure 5.51) the results are displayed in table 5.23.

Section	Distance to point P: d_y (mm)	Cross sectional area: A (mm^2)	Second moment of area: I (mm^4)	Shear stress: τ_{xy} (MPa)	Direct stress in the x direction: σ_x (MPa)	Direct stress in the y direction: σ_y (MPa)
AA	0	567	342873	0.7	0	3.2
BB	45	1045	2,070,963	0.4	0	0.7
CC	90	1612	6,760,664	0.3	0	0.7
DD	135	1641	7,625,494	0.3	0	0.9

Table 5.23 - Stress calculations for final design

To evaluate the geometry, the final wishbone CAD model is compared to the analysis of the chosen concept (concept 20) conducted in section 5.3.9. The principal stress is calculated using a Mohr's circle (displayed in figure 5.52)

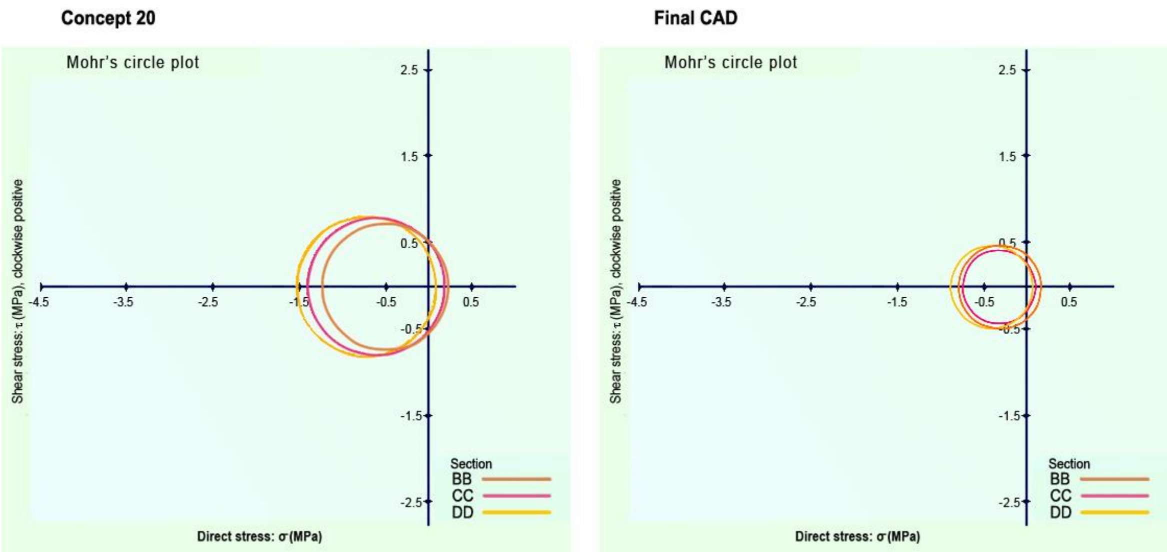


Figure 5.52, Mohr's circle diagrams for concept 20 and the final CAD design.

The principal stresses are displayed in table 2.

	Section BB			Section CC			Section DD		
	σ_{Max}	σ_{Min}	τ_{Max}	σ_{Max}	σ_{Min}	τ_{Max}	σ_{Max}	σ_{Min}	τ_{Max}
Concept 20	0.2	-1.2	0.7	0.2	-1.4	0.8	0.1	-1.5	0.8
Final CAD	**0.2**	**-0.8**	**0.5**	**0.1**	**-0.7**	**0.4**	**0.1**	**-0.9**	**0.5**

Table 5.24, Principal stress in concept 20 and final design.

The increased depth and width of the component is an improvement on the original concept 20 geometry. The principal stress in the wishbone is within the materials capabilities (50 MPa).

5.4.4.2 Applied loads

The applied loads on the wishbone are illustrated in figure 5.53.

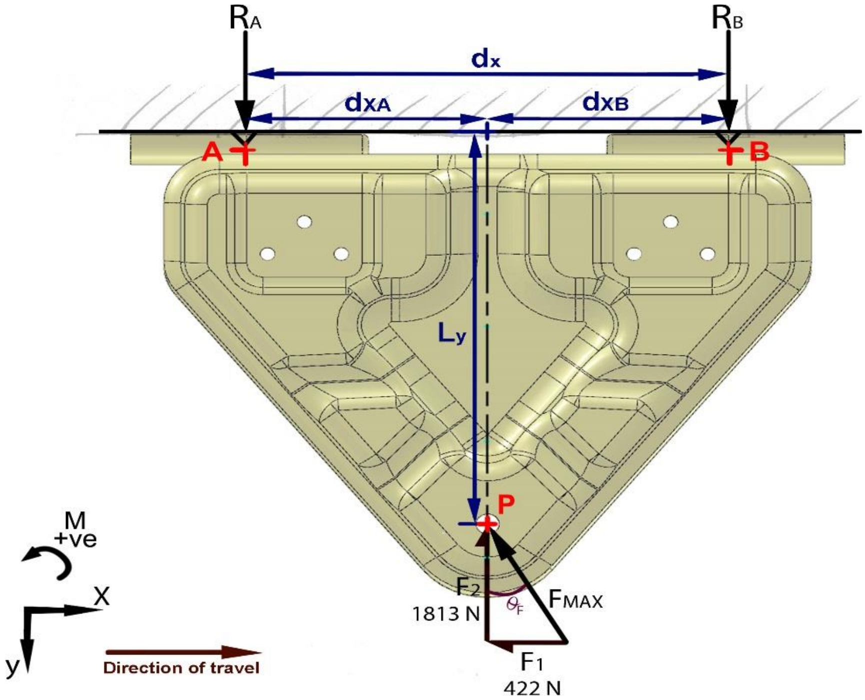


Figure 5.53, Loading of the wishbone at points A, B and P

Figure 5.53 illustrates the applied loads at the linkage points A and B - where the wishbone is attached to the chassis via a hinge, and point P - where the ball joint attaches the wishbone to the upright.

The loads at points A, B and P are calculated as follows:

<u>Point P</u>

The maximum force (F_{Max}) at point P (shown in figure 5.53) occurs when braking while cornering. This force can be calculated as a vector of the forces F_1 and F_2 calculated in vehicle loading section 5.3.6.

$$\tan\theta_F = \frac{F_2}{F_1}$$

θ_F = 76.9°

and since,

$$\sin\theta = \frac{F_2}{F_{Max}}$$

F_{Max} = 1861 N

<u>Points A and B</u>

From the vehicle loading section 5.3.6, R_A and R_B (illustrated in figure 5.53) can be calculated using the following formula:

$$R_A = \frac{(F_2 d_{XB}) - (F_1 L_y)}{d_X} \quad \text{and} \quad R_B = \frac{(F_1 L_y) + (F_2 d_{XA})}{d_X}$$

Using the measurements from the final CAD model illustrated in figure 5.53, L_y = 155 mm, d_X = 165 mm, d_{XA} = 82.5 mm d_{XB} = 82.5 mm. Therefore:

R_A = 946 N

R_B = 510 N

5.4.4.3 Bearing stress

The applied load acts on bolted joints across the thickness of the wishbone (t_z) which is consistent at 6mm (both veneer/Biome components have a uniform thickness of 3mm). The position of these joints is described in figure 5.54.

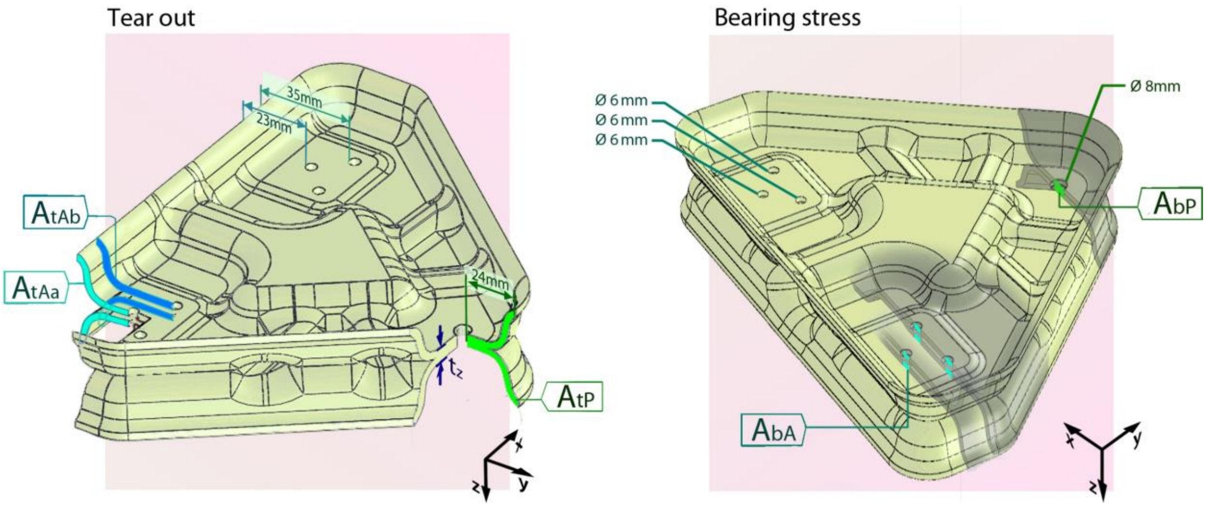


Figure 5.54, Bearing load cutaways.

Stress at point P

The stress at point P is a result of F_{MAX} acting at the interface between the ball joint and the veneer/Biome wishbone component.

Fracture in tension

If the ball joint is secured too close to the edge of the wishbone then the force applied will cause the ball joint to tear through the veneer/Biome material. The tear out area (A_{tP}) - measured from the ball joint to the closest edge as illustrated in figure 5.54 - has been measured on the CAD model as 218mm^2. Although the maximum force (F_{MAX}) is under compression the maximum tensile force cannot exceed this value, therefore the tear out stress can be calculated by:

$$\sigma_{tear\_P} = \frac{F_{Max}}{A_{tP}}$$

σ_{tear_P} = 8.5 MPa

Bearing stress

The ball joint is attached to the veneer/Biome component via an M8 threaded shaft, the force acting on the wishbone (F_{MAX}) produces a bearing stress in the veneer/Biome component across the area (A_{bP}) described by the diameter of the shaft (8mm) across the thickness of the material (t_z) (as illustrated in figure 5.54). The bearing stress can be calculated as:

$$\sigma_{bearing\_P} = \frac{F_{Max}}{A_{bP}}$$

$\sigma_{bearing}$ = 38.8 MPa

Stress at points A and B

As the arrangement of components at points A and B are the same, the stress will be calculated at ‘point A’ because the load (R_A) is higher.

Fracture in tension

Three M6 bolts attach each pivot bracket at point A, these bolts are located 23mm and 35 mm from the nearest edge.

The tear out area (A_{tAa} and A_{tAb}) - measured from 6mm diameter bolt holes to the closest edge as illustrated in figure 5.54 - has been measured on the CAD model as:

A_{tAa} = 208mm^2
A_{tAb} = 280mm^2

The tear out stress at this point is calculated by:

$$\sigma_{tear\_A} = \frac{R_A}{A_{tAa} + (2 \times A_{tAb})}$$

σ_{tear_A} = 1.2 MPa

<u>Bearing stress</u>
The pivot joints are attached to the veneer/Biome component via an M8 threaded shaft, the force acting on the wishbone at point A (R_A) produces a bearing stress in the veneer/Biome component across the area (A_{bA}) described by the diameter of the 3 x 6 mm diameter bolts across the thickness of the material (t_z) (as illustrated in figure 5.54). The bearing stress can be calculated as:

$$\sigma_{bearing\_A} = \frac{R_A}{3 \times A_{bA}}$$

$\sigma_{bearing\_A}$ = 8.8 MPa

5.4.4.4 Discussion and conclusion

All the stress values are below the 50MPa value measured during the pilot study.

A peak stress of 38.8 MPa is predicted to occur as a result of the bearing load caused by F_{MAX} at point P where the ball joint is secured to the veneer/Biome component. This stress is within the predicted limits of the material, this represents the most likely cause of failure within the wishbone assembly.

A study by Khashaba et al (2006) observed that in bolted composite joints, an additional preload applied through an 18 mm washer, can reduce bearing stress by as much as 15%. Khashaba et al (2006) advises a washer producing a large contact pressure to increase the performance of bolted joints. To reduce the risk of failure a 22 mm diameter washer is used to reduce the bearing stress at point P. If required, this bearing stress can be investigated further.

Analysis of the stress shows that the wishbone should perform under maximum predicted loading conditions. Manufacture of a prototype component for the Aston EcoCar allows for further evaluation.

5.4.5 Mould manufacture

The male and female moulds were modelled in the Solidworks CAD package using the model of the wishbone. The female mould is illustrated in figure 5.55a and the male mould in figure 5.55b.

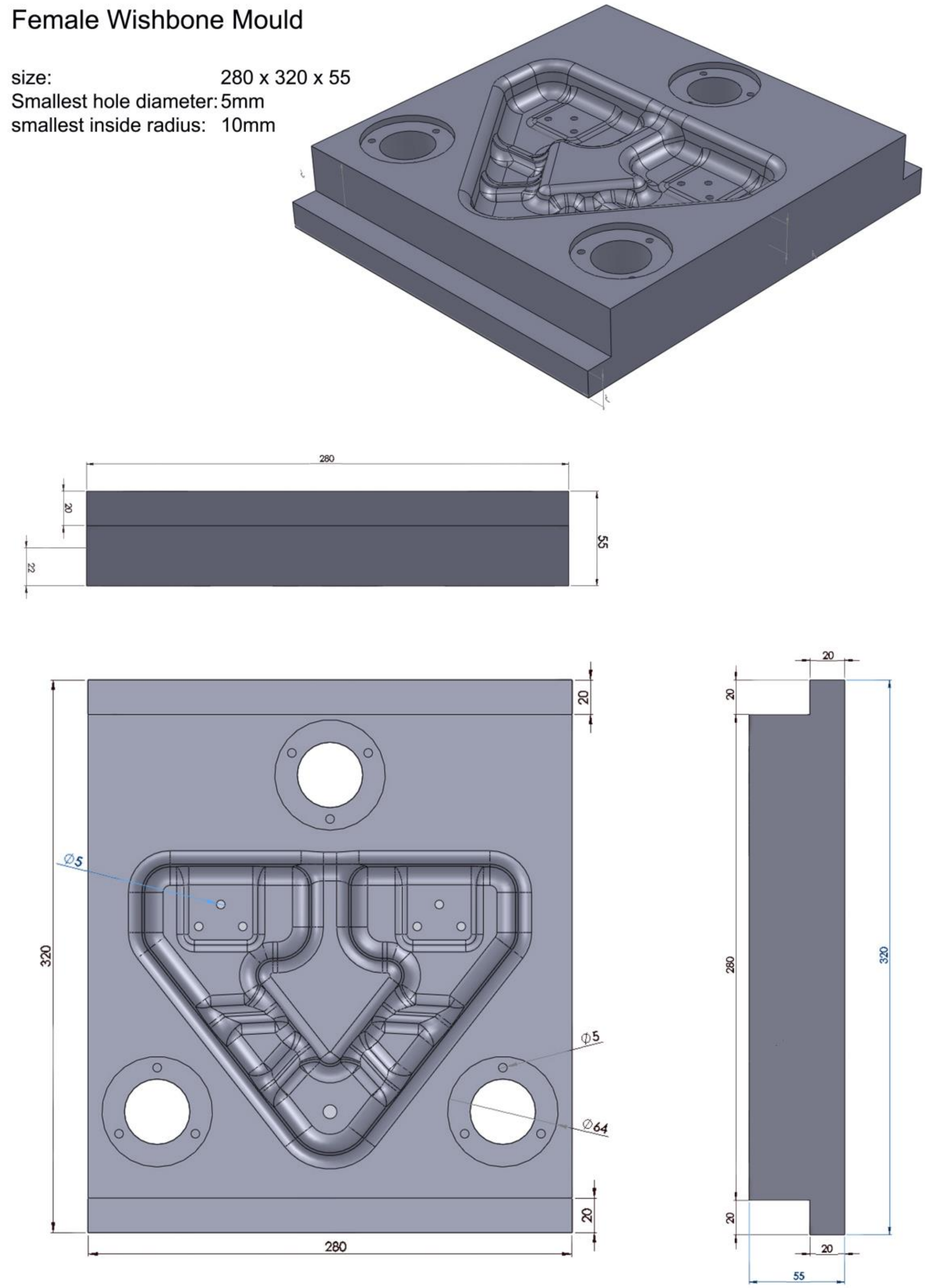


Figure 5.55a, CAD image of the female mould

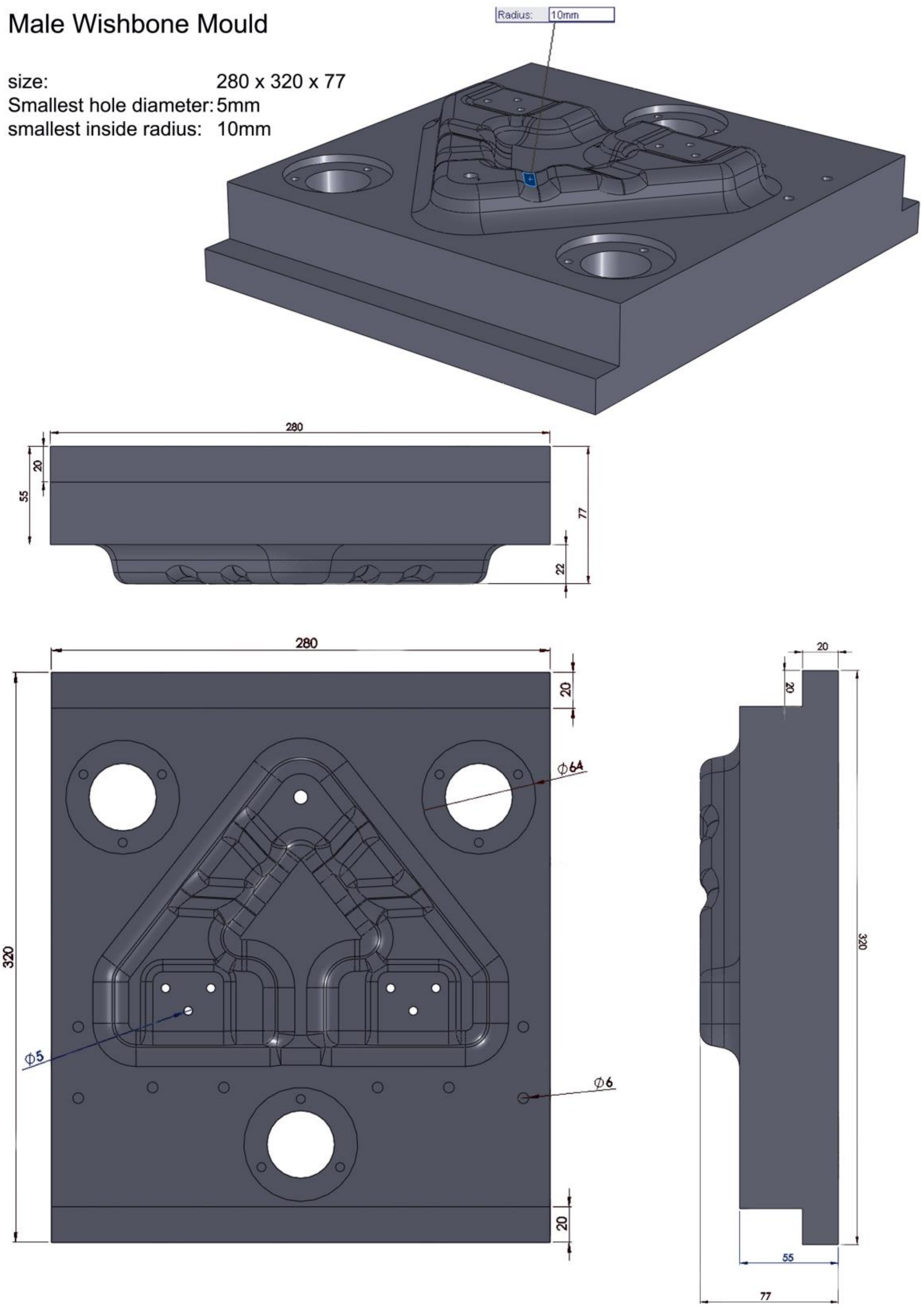


Figure 5.55b, CAD image of the male mould

The moulds displayed in figures 5.55a and 5.55b consist of the wishbone feature set onto a 55mm thick aluminium base. This thickness is required so that the mould does not deform under the pressure during processing.

5.4.5.1 Mould features

Machined into the mould are the following features:

1. Guides and bushes - 3 Guide pillars, spaced evenly but away from the wishbone feature, will align the male and female moulds during pressing. These pillars are set into die set bushes (see parts list). These bushes are held in place with collars recessed into the mould bed.
2. Locations of fixtures - The locations of the fittings need to be identified in the moulded part. These include the pivots that are to be held in place by 6 M6 bolts and the ball joint which requires an 8.2mm hole. To achieve this, dowel pins inserted into holes at locations for of the fittings will show as indented features in the moulded part.
3. Guides - a series of guides incorporated into the mould allow the pivots to be placed in the correct place. These guides are located with dowel pins and bolted to the base of the mould.
4. Ejector pins - The dowels will provide assistance when breaking out the part.
5. Edge for clamping - The mould needs securing to the heated platens. The edges of the moulds have a 20mm shelf feature, these shelves are spaced 260mm apart to allow the mould to be clamped to the platens of the lab press.
6. Surface finish - The wishbone feature requires a smooth surface finish in order for the parts to be ejected from the mould, this finish is achieved using the CNC machining (no polishing is required) and is specified in the technical drawings.

As the mould is to be machined from aluminium and is also unlikely to be a highly polished finish, a large draft angle of 12° will ensure that the part is removed in one piece. Failure to break open the mould will not only ruin a moulding but also stop production.

These CAD models of the mould can then be sent for CNC milling. The precision offered by this equipment was critical in ensuring a tight tolerance on the cavity thickness (3mm) and alignment when the two moulds close.

5.4.5.2 Parts list

Table 5.24 contains component parts required to assemble the mould. These parts are sourced from RS components.

Component description	RS stock no.	Quantity
24mm Plain Steel Parallel Dowel Pin, 6mm Diameter	270-647	2 (bags of 15)
24mm Plain Steel Parallel Dowel Pin, 8mm Diameter	270-675	1 (bag of 15)
Hex Socket Countersunk Stainless Steel Socket Screw, M6 x 16mm	171-893	1 (box of 50)

Table 5.25, Mould components.

A number of parts require machining, full technical drawings of these parts can be found in appendix B. The CAD models for drawings SEM2016_JB_DTL_001_v02 and SEM2016_JB_DTL_002_v01 were sent for manufacture by CNC milling machine.

The machined and assembled aluminium mould is displayed in figure 5.56.

Figure 5.56, Aluminium male mould for the wishbone part, Bottom: Detail of the pivot positioning bar and mould surface.

5.4.6 Wishbone component manufacture

5.4.6.1 Proposed manufacturing process

The 2016 Aston EcoCar requires 2 wishbones. The design is symmetrical therefore, the front left and front right wishbones can be pressed using one mould. To create the parts required, 4 mouldings need to be pressed.

Moulding the wishbone part will lead to a number of findings about the material and the manufacturing process:

1. Proof of principle - prove that the process followed would generate the required product by fabricating a component that can be tested.
2. Manufacturing process - discover whether the multistage stage process discussed in chapter 4 is feasible.
3. Material - it needs to be tested whether the wood fibres will break when being formed into a 3D shape. This can only be tested by moulding complex curves.
4. M/D/M Process - The wishbone will demonstrate to what extent the holistic materials, design and manufacture process has worked.

A 6 stage process has been designed using information learned during the Materials Investigation and the Pilot Study. A diagram of this method is displayed in figure 5.57:

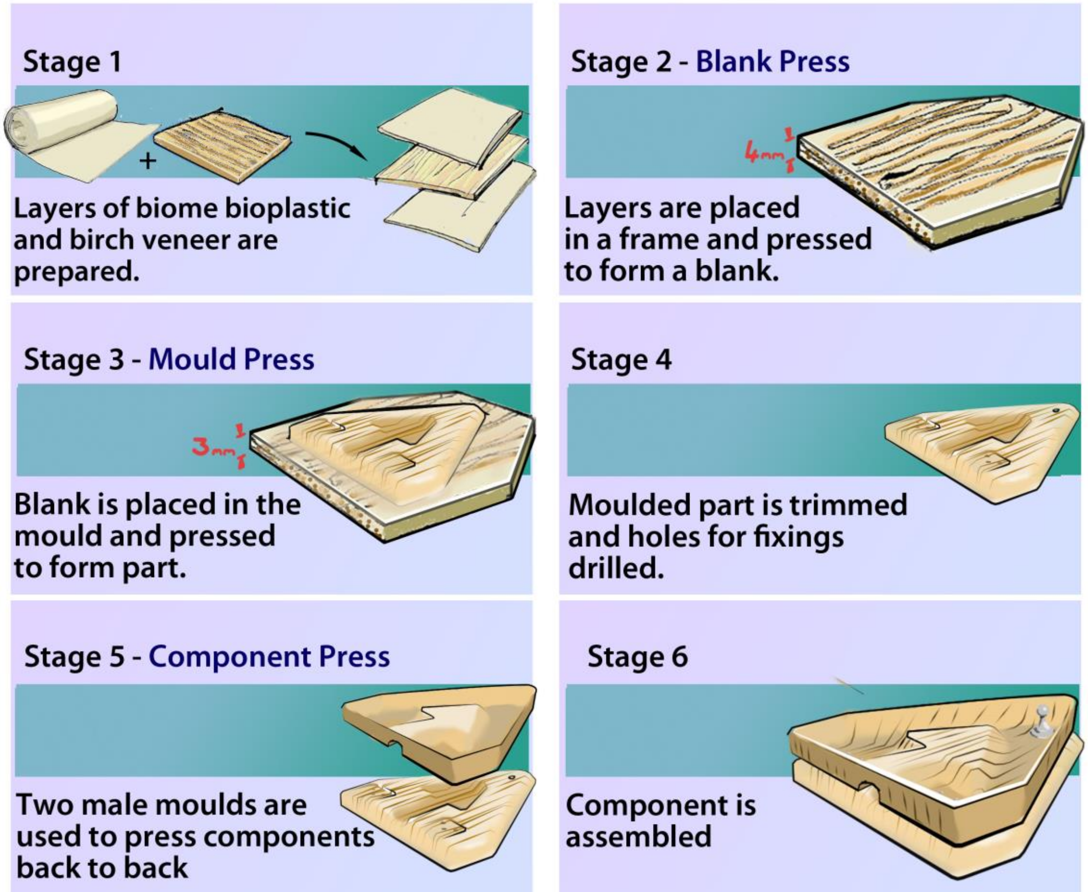


Figure 5.57, veneer/Biome 6 Stage manufacturing process.

As this is a new combination of materials, the compression moulding process has been tailored to suit the material. It is expected that modification may be needed to refine the process and achieve the best result possible. The moulding will be completed using the lab press equipment following the 6 stage process, the pressing of the parts is detailed below.

5.4.6.2 Wishbone manufacture stage 1 - layer preparation

The first stage of wishbone manufacture is to prepare the layers of Biome and birch veneers. For strength and rigidity, the wood fibres will run the length and then width of the moulding in alternate layers (much like a plywood panel). The composite will be strongest in the direction the fibres are orientated.

The method by which the layers are stacked will affect the way the fibres are distributed in the polymer matrix during pressing. To improve understanding of the moulding process, two separate methods were chosen for layering the material in stage 1.
These 2 methods are described in experiment 10.

5.4.6.2.1 Experiment 10

Experiment 10 uses 2 methods to prepare the Biome and veneer layers. The ability of wood fibres to be moulded into complex shapes is investigated by comparing method 1 (wishbone A) with method 2 (wishbone B).

In order to experiment with different parameters, only a single manufacturing stage could be chosen to vary conditions. Stage 1 (from the process described in figure 5.57) was chosen as it is important to know whether the separating of wood fibres when processing films is significant to the manufacturing process. It is also theorised that the early stages of the manufacturing process would have the greatest impact on the finished product.

The 2 methods are:

1. Layers of pressed veneer/Biome films.
2. Alternate layers of birch veneer and Biome bioplastic (not pressed)

Method 1 (Wishbone A) Stacking films.

Structural birch veneer (straight grain with no knots) of 0.6mm thickness is used during manufacture. Table 5.25 describes the 2 sizes of birch veneer used for wishbone A:

Layer type	Dimension	Length (mm)
Type 1, grain running across wishbone	Veneer width	40
	Veneer length	280
Type 2, grain running length of wishbone	Veneer width	50
	Veneer length	220

Table 5.26, Veneer size for film pressing

The size of film to be pressed is dependent on the achievable pressure and the size of the platens. To allow the full length of the fibres to run the width of the wishbone, veneers 280mm in length were prepared. From the materials investigation (section 5.2, experiment 8) fibre separation was expected across the resulting films.

To make the film, the veneer is sandwiched between 0.3mm thick extruded Biome sheets. The Biome sheets are cut to be oversized by 5mm around the veneer ensuring the veneer is fully covered during pressing. The three layers are then placed between the beds of the lab press and the films are fabricated under the press conditions listed in table 5.26.

parameter	value
Press temperature	180°C
Pressure applied	18 Tonnes (16 MPa)
Preheat time	10 minutes
Press time	10 minutes
cooling time	40 minutes

Table 5.27, Wishbone A film pressing conditions.

Although the timings are accurate, the temperature was measured to vary by 5°C. The greatest imprecision occurs in the pressure, as the film is pressed, the press gauge decreases by up to 1 tonne as a result of the film spreading under the conditions. This is rectified as much as possible to ensure a consistent force of 18 tonnes is applied to the press beds.

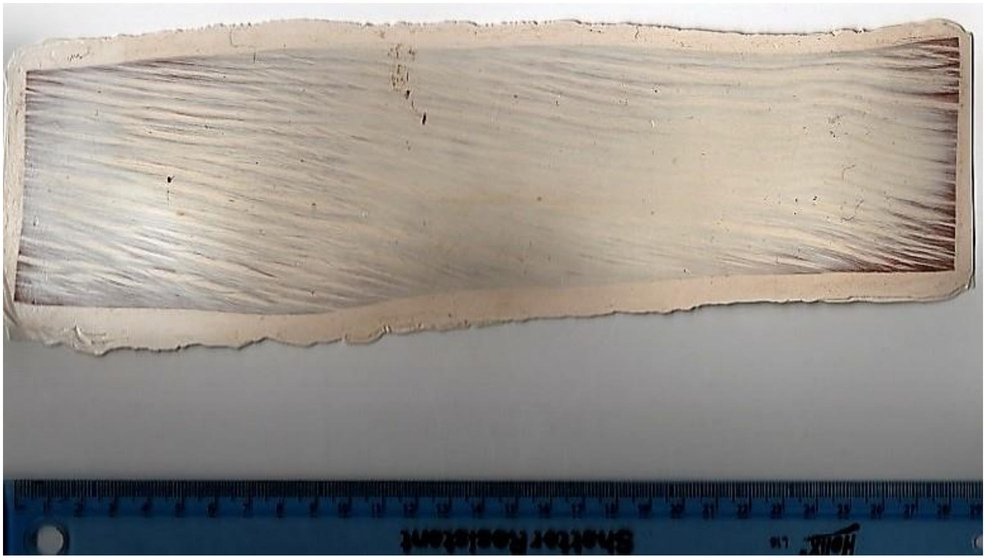


Figure 5.58, Image of a 'type 1' film.

As can be seen from the image of the 'type 1' film in figure 5.58, at 180°C the fibres are not heated excessively, but the plastic still softens to the point where it can be forced through the sample - separating the layers. The width of the film then increases by approximately 90% to between 75mm and 80mm. As the sample has a thickness of 0.8mm this is not below the original thickness of veneer and so it is thought that the wood fibres are not compressed to the point of destruction. Although the processing conditions are maintained at the same levels, the patternation of the fibres within the films vary, in part due to natural variation of the veneers.

The films are then cut to shape, and stacked in the frame, as shown in figure 5.59.

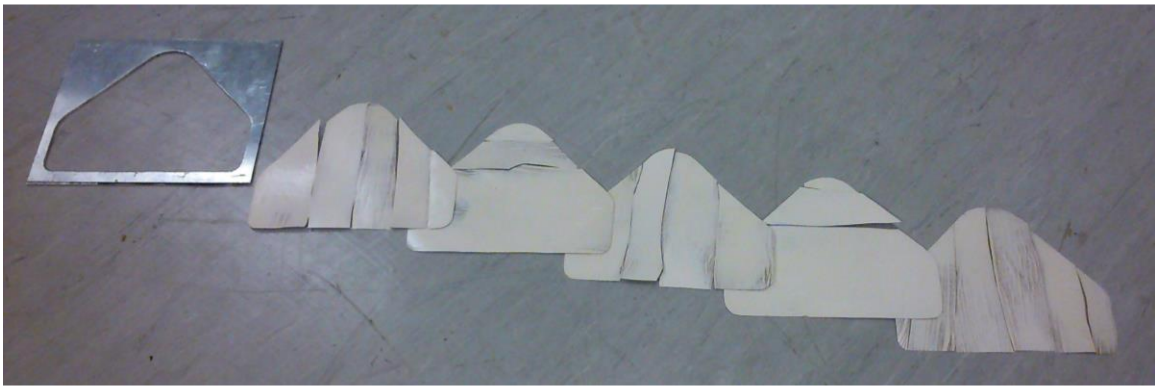


Figure 5.59, 5 layers of films with alternating grain direction, top left - frame for creating blanks

<u>Method 2 (wishbone B) Stacking un-pressed veneer and Biome layers</u>

Method 2 uses a much simpler process of stacking the birch veneers and extruded Biome sheet. Alternate layers of 0.6mm thick birch veneer and 0.3mm thick extruded Biome sheet are stacked in the frame.

To increase the overall thickness of the stack (to prevent cavities forming in the blank) an extra layer of Biome sheet is placed on the top and bottom of the stack. The wood fibres and plastic used in method 2 does not undergo a pressing cycle at this stage of manufacture. This may cause less damage to the fibres and plastic than method 1, however the bonds between the fibres and polymer matrix may suffer due to less water being driven out.

The results of experiment 10 are discussed in chapter 6.

5.4.6.2.2 Completion of stage 1 - layer preparation

Both methods contain 5 layers of birch veneer. The grain of the wood alternates between each layer. The grain in the outer layers runs from the edge where the pivots are located to the ball joint. Layering in this way provides the wishbone with the optimal strength and stiffness. In order to minimise the gaps between layers when pressing the blank in stage 2, the stack of layers is approximately 5mm thickness (to be stacked into the 4mm deep frame).

It is important for the understanding of the material to know what the effects of pre-pressing films in this stage has on the moulded product. It is predicted that pressing layers of films containing separated fibres will allow corners with tighter radii to be moulded. All subsequent processing parameters are kept constant during the manufacture of the wishbones.

5.4.6.3 Wishbone manufacture stage 2 - Pressing the blank

The layers of veneer and Biome (from stage 1) were stacked in a frame. This frame has a depth of 4mm. The final part has a 3mm thickness. The 'blank' is created with an extra 1mm thickness to ensure no cavities form when pressing the component in stage 3. The blank is also oversized (220mm x 280mm) to ensure that a complete moulded part was made. Table 5.27 contains the conditions used to press the blanks using the lab press.

Parameter	Value
Press temperature	185°C
Pressure applied	18 tonnes (2 MPa)
preheat time	20 minutes
Press time	10 minutes
cooling time	40 minutes

Table 5.28, manufacturing stage 2 'blank' pressing conditions

Figure 5.60, Pressed 'wishbone A' blanks

Displayed in figure 5.60 are the blanks for wishbone A produced during manufacturing stage 2. Production of these blanks allows manageable pressing of the material in the mould as the layers will not slide out of position.

5.4.6.4 Wishbone manufacture stage 3 - Moulding the component

The moulding process consists of a number of steps. It is important these are followed to ensure the press is not broken, the mould does not become seized and a fully formed wishbone component is removed.

<u>Set up</u> - The moulding surface and moving parts need to be prepared before preheating the mould:

1. A coating of PTFE mould release agent (rated for temperatures up to 270 °C) was sprayed onto the moulding surface.
2. To prevent the pillars seizing in the bushes, graphite lubricant (Loctite LB 8009) was applied to the pillars and bushes.

The male and female moulds along with the pillars and dowels are assembled in the closed position. Using toolmakers clamps, the mould block was then secured in place between the platens of the lab press. This allows the heated assembly to be winched up and down freely.

Mould pre-heat - The heated platens were set to a temperature of **215°C.** once up to temperature, the mould was pre-heated for a period **1hr 30mins**. Expected heat loss from the aluminium mould meant that the temperature at the moulding surface was between 170°C to 195°C (measured by infrared thermometer on opening the mould). Because the mould differs in thickness, the temperature at moulding surface varies. This temperature variance is not ideal, and is a limitation of the equipment.

Blank insertion - The upper heated platen (clamped to the male mould) is winched up, opening the mould. The blank from stage 2 is inserted between the male and female moulds. The blank is oversized to allow material to be pulled into the mould.

Pre-heat - The top platen and male mould are winched back down until the mould surface makes contact with the blank. The region where the mould first makes contact with the blank is at the thickest part of the mould (with the furthest distance to the heat source), the temperature of this region is measured using the infrared thermometer. The ideal temperature is 170°C. During pre-heat, regions of the blank are not in contact with the mould surface. The material is initially left under the weight of the top platen and male mould – shown in figure 5.61 - to gain temperature for **15mins.**

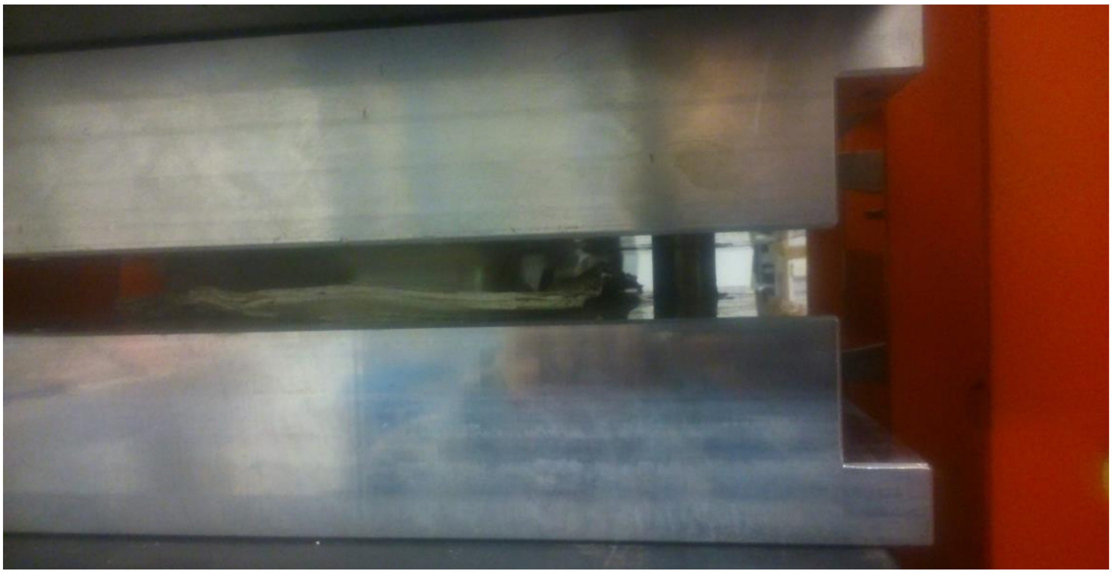


Figure 5.61, Pre-heating the veneer/Biome blank in the mould

Spacers - At this point 3mm thick steel strips are placed between the moulds - at the corners as illustrated in figure 5.62. The thickness of the strips control the thickness of the moulded part.

Figure 5.62, 3mm spacer strip between male and female moulds

Mould closed - The mould is slowly closed by gradually increasing the force applied by the hydraulic rams. The pillars guide the mould to the correct position. The mould is closed over a period of **20mins,** this is performed gradually to allow heat to transfer from the mould to the material which occurs where the two are in contact. The plastic needs to be molten to allow the fibres to 'flow' in the material and not break. A force of approximately 15 tonnes is needed before the male mould touches the 3mm thick steel strips as the 4mm thickness of the blank is compressed to 3mm. At the point the mould is closed and the pressing force is increased to **18 tonnes**.

Heating phase - The mould is heated under pressure for **10mins** to allow gasses and excess material to escape. It is for this reason that the sides of the mould are left open. The dowel pins are placed in a position where gases that would otherwise build up (creating cavities) can escape, this prevents voids forming in the moulded part. Care needs to be taken to ensure there is not too much excess material in the mould as this can cause problems with overflowing.

Cooling under pressure - The heating elements in the platens is turned off. The mould is left to cool under full pressure for **4hrs.** There is a large volume of aluminium to cool to a temperature of approximately **90°C.**

Eject part - The mould is unclamped from the platens and removed. The guide pillars are knocked through. The dowel pins are now tapped with a hammer to eject the part from the mould.

Figure 5.63, Wishbone moulding with flashing and risers.

In figure 5.63 the flashing, and evidence where the plastic has displaced the dowel pin demonstrates that the Biome bioplastic was at a sufficient temperature where it could flow adequately.

5.4.6.5 Wishbone manufacture stage 4 - Trim flash and drill holes for fixings

The excess material is trimmed using a tenon saw. The edges are then sanded. The plastic pillars seen in the figure 5.63 (where the pressed plastic has displaced the dowel pins) show where the ball joint and M6 bolts will be located, these are drilled out creating the finished half wishbone component shown in figure 5.64.

Figure 5.64, Trimmed half wishbone moulding

As can be seen in figure 5.64, tearing occurred when drilling out the holes, this could be remedied by improving the moulding of the hole feature.

Two mouldings per wishbone are required, therefore stages 1 through 4 were repeated before moving on to stages 5 and 6.

5.4.6.6 Wishbone manufacture stage 5 - press components back to back

After considering the benefits of fusing the two moulded components together, Stage 5 was not performed for two reasons:

1. After observing the stiffness of the two components bolted together, further pressing to fuse the two mouldings together has been deemed unnecessary.
2. It was realised that in order to heat up the surfaces that were to be fused, the entire component would need heating. This heating process would blister the surface and deform the shape of the wishbone.

As there was little to be gained from proceeding with stage 5, this step was ignored.

5.4.6.7 Wishbone manufacture stage 6 - Assembly.

Through careful planning, the bought in components (the flag hinges and axial ball joint) fitted the moulded shape. The integration achieved is a key benefit of this process and demonstrated that there is little shrinkage or deformation of the moulded material.

The total 39 components have been laid out in figure 5.65.

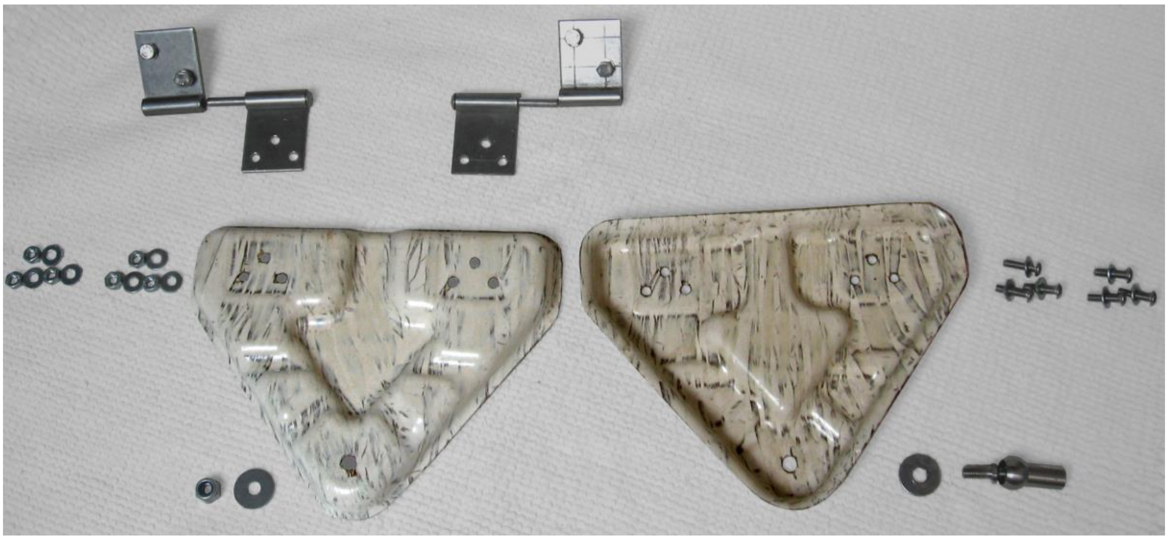


Figure 5.65, 39 wishbone components.

The pivot brackets (flag hinges) are delivered without holes for mounting. The positions of the 6.1mm holes were marked and drilled enabling the wishbone to be assembled displayed in figure 5.66.

Figure 5.66, Assembled wishbone.

5.5 Conclusion

Two completed wishbones were delivered to the Aston SEM 2016 team (final year design and engineering undergraduates) to fit the components to the 2016 Aston EcoCar vehicle.

Chapter 6: Results and Discussion

This section will evaluate the performance of the wishbone component itself, followed by an assessment of the M/D/M process used.

6.1 Wishbone performance.

Two veneer/Biome wishbones were manufactured. In order to evaluate the wishbone design, manufacture and materials, the two wishbones were fitted to the 2016 Aston EcoCar, displayed in figure 6.1.

Figure 6.1, 2016 Aston EcoCar at the 2016 Shell Eco Marathon in London.

As designed, the wishbone was attached to the chassis using the pivot plates and attached to the front uprights by the axial ball joint. Figure 6.2 shows the 2016 Aston EcoCar front upright assembly.

Figure 6.2, Veneer/Biome wishbone attached to the 2016 Aston EcoCar front assembly.

The wishbone conformed to the system boundaries defined in the design brief (section 5.3.3). The installed wishbone matched the design for the front upright geometry and the chassis construction. This arrangement allowed for an adequate range of suspension movement - as designed. The pivots and ball joint provided free movement without interfering with the brake disc or chassis. In this regard, the wishbone was successfully integrated with the rest of the suspension system.

The wishbone component was tested on the 2016 Aston EcoCar at the Shell Ecomarathon 2016 (SEM 2016) in London. This testing comprised of a rigorous technical inspection by the SEM 2016 officials. The wishbone was required to meet the following conditions:

- Support the vehicle when fully loaded with the driver.
- Withstand the forces exerted during the brake test.
- Pass the vehicle design inspection - checking that the chassis and components are robust and firmly secured.

Aside from the fuel cell inspection, the 2016 Aston EcoCar passed the technical inspection at SEM 2016.

The wishbone performed as designed. Although further dynamic testing on the vehicle is desirable, the wishbone and the material has been successfully applied to a structural component of the Aston EcoCar.

6.2 Design goal

To meet the sustainable design goal stated in section 3.3.1 the following approach has been used during development of the 2016 wishbone:

- <u>Closed loop materials flows</u> – ‘waste equals food’ is considered during the material and design stages of the study. This includes design for disassembly.
- <u>Energy efficiency</u> – materials with high embodied energy - Aluminium, epoxy resins and synthetic fibres (Ashby, 2011) have been avoided. Ideally renewable energy could be used during the products lifecycle, in line with cradle to cradle principles (stated in section 3.3.1).

<u>Product lifecycle</u>

The product life cycle is discussed with regard to the materials source, the manufacturing process, the product lifetime and the EoL scenario of the wishbone.

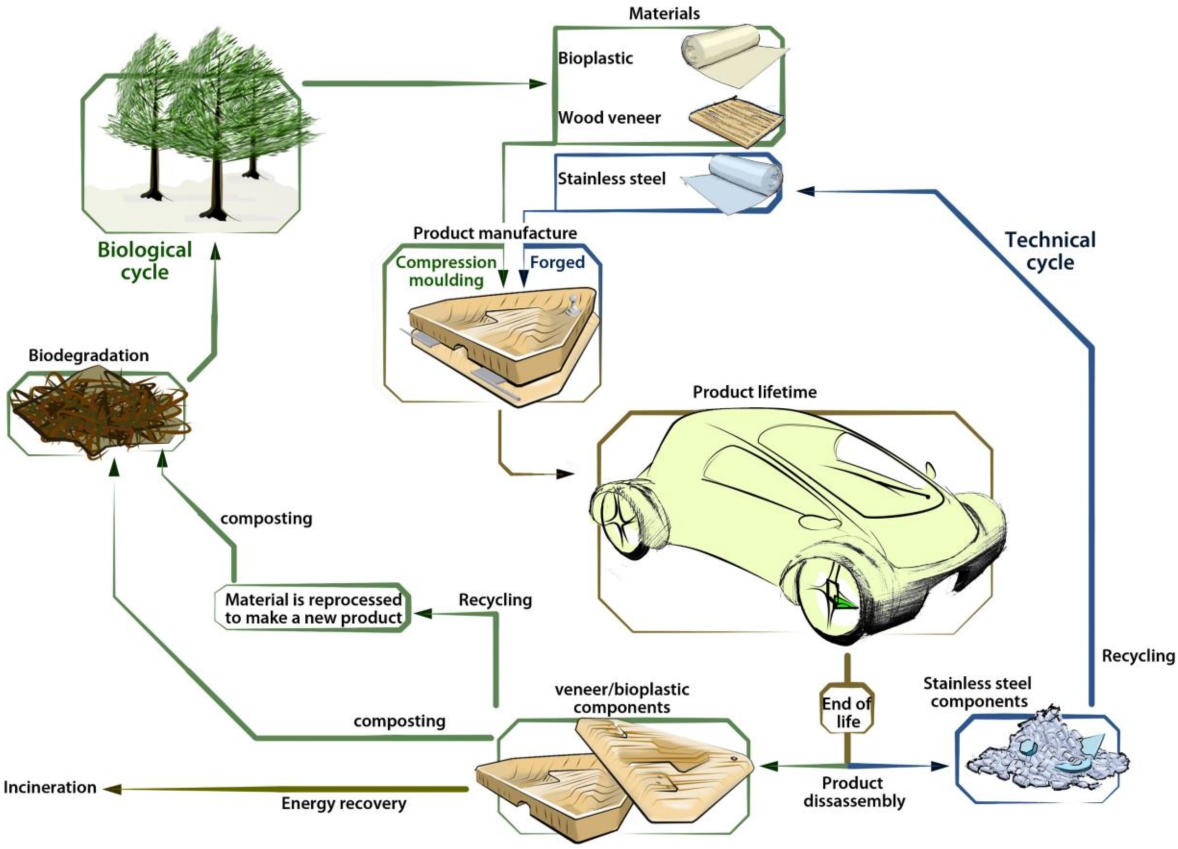


Figure 6.3, Proposed product lifecycle.

As suggested by Vilaplana, Strömberg & Karlsson (2010) "the main challenge lies in the design of products that are structurally and functionally stable during their application, using benign synthesis and modification processes, together with appropriate waste management procedures (recycling, incineration, or composting) that complete the return of the material and/or energetic value to the environment." This research project has attempted to achieve this closed loop product lifecycle model described in figure 6.3.

6.2.1 Materials source

Birch veneer

Wood veneers in the composite have been sourced from Forest Stewardship Council approved timber, this ensures environmentally responsible management of the material. An advantage of using timber is the lower water consumption compared to crops such as cotton (Chico, Aldaya & Garrido, 2013), however a drawback may be the slow renewal rate of trees due to slow growth.

Biome

Biome is a cellulose based bioplastic derived from plant material in “biomass refineries” (Biome bioplastics, 2014). Biome bioplastics originate from “GM-free and non-food derived source” (Biome bioplastics, n.d.). As discussed in section 2.6.5, cellulose based bioplastics are renewable and abundant (Huber et al., 2011).

Stainless steel

A high proportion of stainless steel comes from recycled feed stocks (Johnson et al, 2008). Stainless steel contains chromium which is described by Braungart and McDonough (2009) as “problematic” (p.174). However, the use of stainless steel is considered necessary to resolve the linkages in the moving parts. The use of stainless steel (instead of alternative aluminium or steel components) ensures the linkage components are not the limiting factor with regards to the technical properties or the lifespan of the wishbones.

6.2.2 Manufacture phase

Compression moulding used during the wishbone manufacture requires energy to heat and press the veneer/Biome composite. Use of this manufacturing process increases the embodied energy of the wishbone. To conduct further research, the energy usage during manufacture could be measured for use in an LCA.

6.2.2.1 Materials inventory

The materials inventory displayed in figure 6.4 demonstrates the mass reduction in the 2016 wishbone compared to the 2014, 2015 and Alfa Romeo benchmarks.

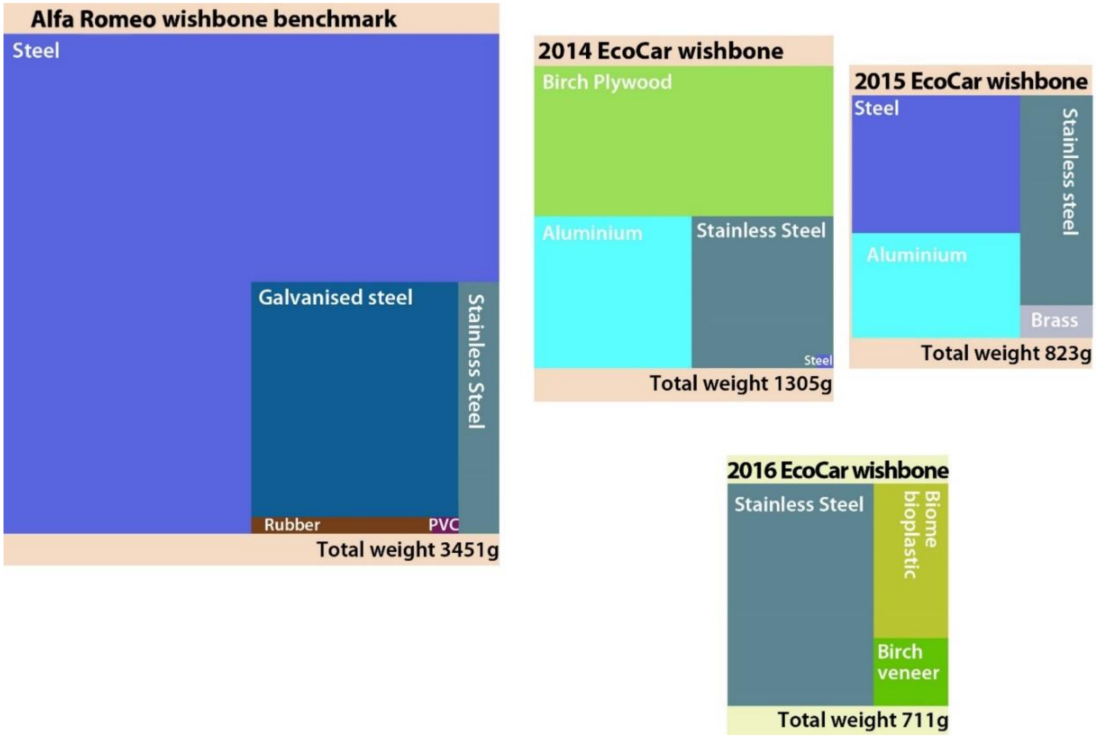


Figure 6.4, Comparison of 2016 wishbone to benchmark wishbones by material weight.

The 2016 veneer/Biome wishbone weighs 45% less than the 2014 model, and 14% less than the 2015 model. Compared to the benchmarks displayed in figure 6.4, the use of stainless steel components simplifies disassembly. Avoiding contamination during recycling would mean the properties of the stainless steel may be better preserved.

6.2.2.2 Embodied energy

The embodied energy for the material in the 2016 and benchmark wishbones in table 6.1 has been estimated from available data from Ashby (2011: p.516).

	Embodied energy			
Product	Material	Embodied energy of material (MJ/kg)	Weight (kg)	Embodied energy (MJ)
Alfa Romeo wishbone	Steel	35	2.056	71.96
	Galvanised steel*	35	0.216	7.56
	Stainless steel	85	0.246	20.91
	Rubber	120	0.032	3.84
	PVC	95	0.005	0.475
			Total embodied energy	**105 MJ**
2014 EcoCar wishbone	Birch plywood*	8	0.644	5.152
	Aluminium	220	0.347	76.34
	Stainless steel	85	0.306	26.01
	steel	35	0.008	0.28
			Total embodied energy	**108 MJ**
2015 EcoCar wishbone	Steel	35	0.329	11.515
	Aluminium	220	0.246	54.12
	Stainless steel	85	0.216	18.36
	Brass*	74	0.032	2.368
			Total embodied energy	**86 MJ**
2016 EcoCar wishbone	Stainless steel	85	0.469	39.865
	Birch veneer*	8	0.075	0.6
	Biome bioplastic*	118	0.167	19.706
	Total embodied energy			**60 MJ**

Table 6.1, Embodied energy for 2016, and benchmark wishbones.

*Representative data from similar materials has been substituted as follows; steel for galvanised steel, copper alloy for brass, cellulose plastic for Biome bioplastic, and wood for birch plywood and veneer.

From analysis of the materials used for the wishbones in table 6.1 it can be shown that 2016 wishbone has less embodied energy compared to the benchmarks. The use of aluminium is a predominant factor in the 2014 and 2015 wishbones energy consumption, this material has been avoided for the 2016 wishbone.

66% of the energy embodied in the 2016 wishbone relates to the stainless steel components, some of this invested energy may be retained at EoL through recycling.

6.2.3 Product lifetime

The performance of the component is discussed in section 6.1 and is further considered in sections 6.4 and 6.5. Mass reduction (as discussed in section 2.3.4) of the 2016 wishbone as displayed in figure 6.4, represents an energy saving over the lifetime of the vehicle.

A limitation of this research is the full lifespan of the wishbone has not been examined, as a prototype product the Aston EcoCar has a limited life because it is built for a single event. It is proposed that the lifespan of the wishbone could be increased by applying a protective coating as a barrier to microbial and fungal attack. As a prototype, the wishbone tested on the 2016 Aston EcoCar can only partially meet the sustainable design goal. An analysis of the durability of the wishbone and veneer/Biome material is a limitation of this study, however similar materials are discussed in the review of the literature (section 2.5.7).

6.2.4 Wishbone EoL

The 2016 wishbone is designed for disassembly, this allows the materials to be separated at the end of the useful life of the product. These materials can then be fed back into materials flows.

6.2.4.1 Biological nutrients

According to the manufacturer Biome is “100% biodegradable and compostable according to EN 13432, ASTM D6400 and Vinçotte OK compost standards" (Biome Bioplastics, 2014). The birch wood fibres are inherently biodegradable. A fully biodegradable system provides a closed loop materials cycle and reduces “the problems related to the everyday production of solid, plastic-derived waste” (La Mantia & Morreale, 2011).

As the veneer/Biome wishbone component has a thickness of 3mm the time required to biodegrade is not clear without testing, this may take longer than certified by the Vinçotte OK compost standards. Vinçotte has rated Biome as industrially compostable to a maximum thickness of 0.124mm (Vinçotte, 2017). To ensure the veneer/Biome component is compostable, it is proposed the component could be mechanically separated (chipped or shredded) prior to composting at EoL. Factors affecting biodegradation discussed in 2.6.7 (such as exposed area and moisture levels within the composite) have not been explored in this study. Further evaluation is required before the wishbone may be described as a ‘biological nutrient’.

6.2.4.2 Technical nutrients

To conserve the embodied energy invested during refining and processing the raw material, the veneer/Biome wishbone could potentially be recycled - dependent on the level of biodegradation at EoL. The composite could be chipped into pellets and remanufactured into less technical products - downcycled into non-load bearing applications, “the mechanical recycling of a bioplastic leads always to an overall reduction of the environmental impact associated to the production and disposal of the bioplastic” (Piemonte 2011). The wood fibres may still provide stiffness within the material and could be blended with virgin Biome feedstocks for production of stiffer plastics.

Stainless steel can be produced using 100% recycled feedstocks (Johnson et at, 2008), allowing a ‘closed loop’ materials flow. The stainless steel may therefore be considered a technical nutrient.

6.2.4.3 Energy recovery

Some embodied energy contained in the wishbone through processing materials and manufacture may be recovered at EoL:

- The energy embodied in veneer/Biome components may be recovered through incineration. Along with recovering energy Dufolou (2012) reports incineration of biocomposites produces similar levels of greenhouse gas emissions to composting.
- Recycling of the stainless steel components preserves the energy invested in the material. Compared to virgin materials 100% recycled stainless steel uses 67% less energy and creates 70% less CO_2 emissions (Johnson et al, 2008).

6.2.5 Limitations of the study

The lifecycle of the wishbone requires further investigation before it can be described as fulfilling the cradle to cradle system in figure 6.3.

<u>Biodegradability</u> – The effect the thickness of the veneer/Biome composite has on the materials biodegradation requires further tests to validate the material as being a biological nutrient. “An important concern for biodegradation is whether the process itself or its products exhibit ecotoxicity” (Duflou et al, 2012). Although the manufacturer state

that Biome is ‘biodegradable’, information regarding exact chemical constituents of the material are not available.

Life cycle assessment – it is recognised that an LCA study such as the study conducted by La Rosa et al (2013) would demonstrate the impact of the wishbone on the environment and this would allow the sustainability of the wishbone to be better evaluated. Data sets for materials (specifically the Biome bioplastic) are not available. As the wishbone is a prototype, a complete lifecycle can not be accurately obtained. The incomplete data and scope provided by this study would make an LCA inaccurate.

6.3 Manufacturing results

For the manufacturing stage of the wishbone project, two wishbones were produced for the 2016 Aston EcoCar, as described in section 5.4.

The processing parameters of the final pressing in the mould were kept consistent. The first stage - forming the blanks - was conducted as a controlled experiment (experiment 10).

6.3.1 Experiment 10 results

2 separate methods were used to layer the veneer and Biome bioplastic for each wishbone:

Wishbone A - Pre-pressed Veneer/Biome films were stacked into a frame.

Wishbone B - Alternate layers of Biome sheet and veneer were stacked into a frame.

The results of the process are detailed in table 6.2

Metric	**Wishbone A** (using method 1)	**Wishbone B** (using method 2)
Number of pressings per blank	14	1
Number of veneer layers per blank	5	5
Time taken to create blank (hours)	15.30	2.10
weight of moulded component	121 grams	113 grams

Table 6.2, Differences between wishbones A and B.

6.3.1.1 Polymer to fibre ratio

From the weight of the component, the amount of wood by weight can be calculated:
From the CAD model of the wishbone moulding, the volume of the pressed wishbone part is 105.2cm^3.
Density of Birch veneer 0.76 g/cm^3
Density of Biome 1.3 g/cm^3 [from data sheet, see appendix A].
A 100% birch wood veneer wishbone would weigh approximately 80 grams.
A 100% Biome bioplastic wishbone would weigh approximately 140 grams.
From these figures, the amount of wood fibres (by weight) in the manufactured veneer/Biome mouldings can be estimated using the weight of the moulded components as displayed in figure 6.5.

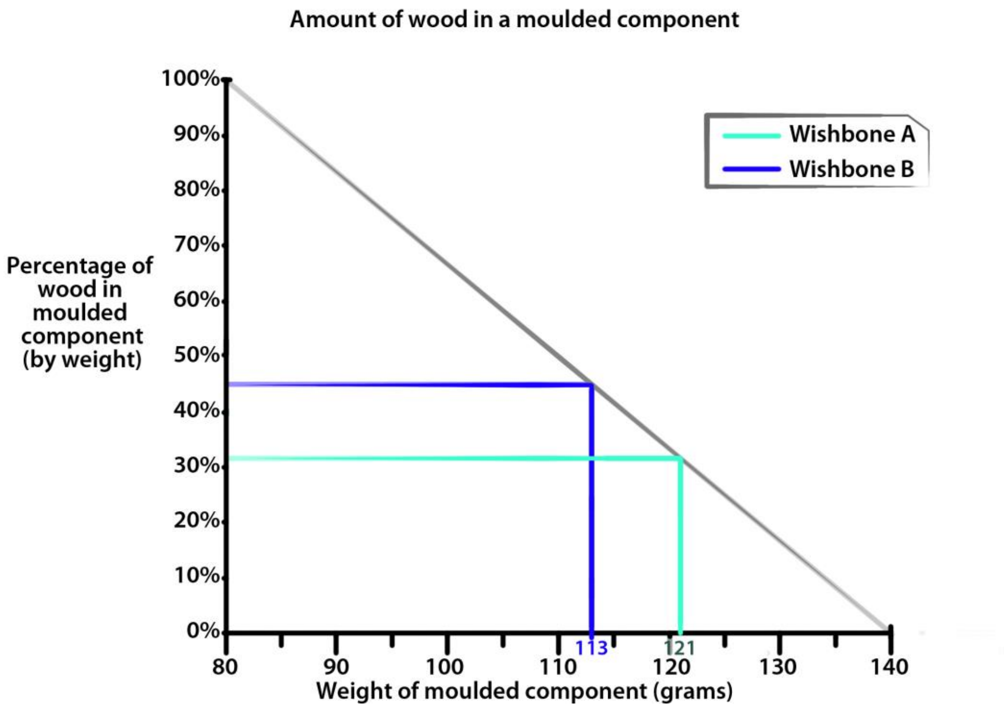


Figure 6.5, Graph showing the amount of wood in each moulding.

The method for deducing this assumes that there are no cavities in the mouldings. The weights of components are consistent across the samples (2 for each type A and B) and are also consistent with the amount of each material laid into the blanks.

Wishbone B contains 15% more wood fibres than wishbone A. This indicates that the fibres are significantly less separated in wishbone B.

6.3.1.2 Product comparison

A major advantage of using method 2 is that it is 80% quicker to manufacture the blank. There are however significant differences between the resulting mouldings, figure 6.6 details the differences between wishbone mouldings A and B.

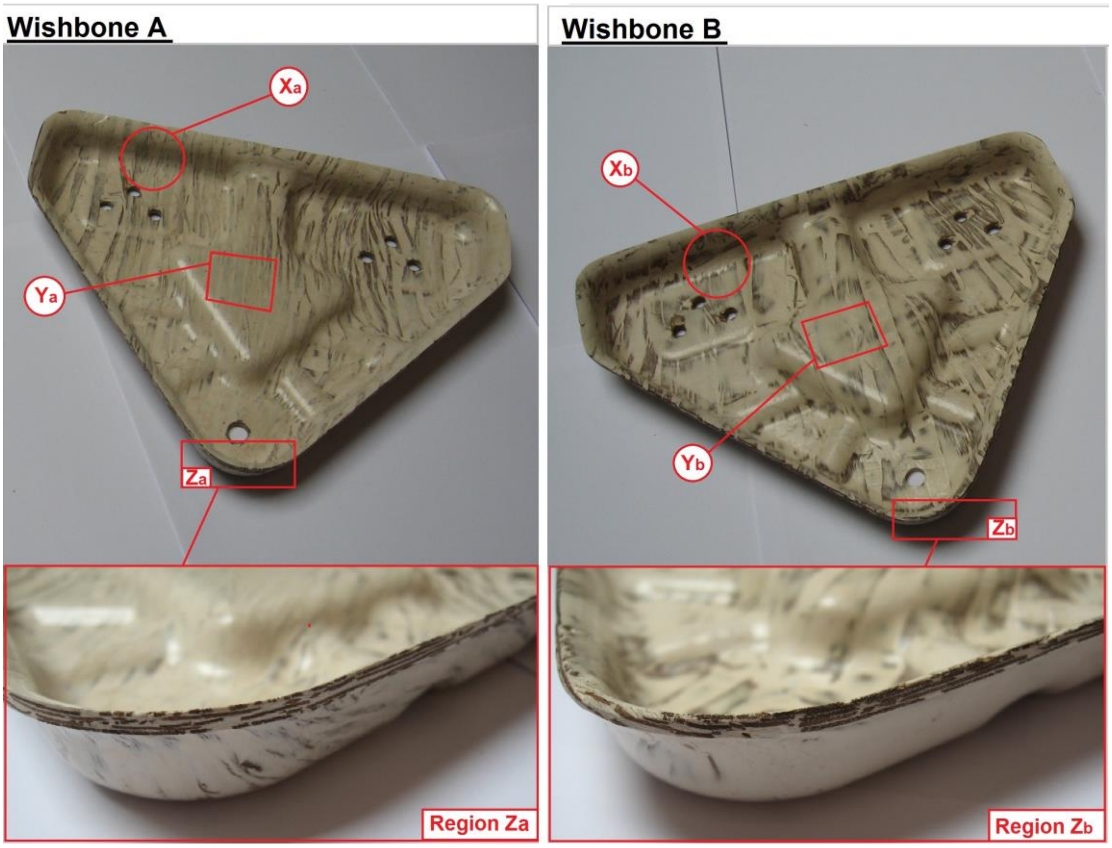


Figure 6.6, Image of wishbones B and A, displaying major differences in regions X,Y & Z

From a visual inspection of the wishbones A and B the following conclusions are drawn:

1. Corner breakages - It can be seen in region X in figure 6.6 that the fibres have moulded around the contours. In wishbone A the wood fibres are moulded into the radius of the corners, this provides the structure with the strength required at these potential weak points. In wishbone B, there are no fibres in the internal or external radii of the moulding. The wood fibres breaking in this way, weaken the structure and prove a major failing of this method of layering.
2. Lateral splits – It can be observed in region Y in figure 6.6 how the fibres separate. In wishbone A there are numerous and even separation of the fibres across the moulding (an average of 3 splits per cm). Wishbone B contains fewer splits (an average of 0.5 splits per cm measured in the surface layer).

3. Matrix control - For wishbone A, by separating the fibres before forming the blank, an even lattice can be constructed. The extent of the polymer/fibre matrix in wishbone B is not known. The trimmed edges of the mouldings displayed in region Z in figure 6.6 suggest the Biome and wood fibres are less intermingled in wishbone B.
4. Processing cycles - The wood fibres in wishbone B undergo less cycles of heating and compression. The repeated heating and pressing of the fibres in wishbone A probably caused more damage.

Although manufacturing blanks using method 2 are quicker and the wood fibres may be less damaged, method 1 is more predictable and controllable.

Due to the equipment, the temperature at the moulding surface was variable. This may have led to fibres being heated to temperatures higher than were stated in the Recommended Processing Variables table 5.9 (section 5.2)

The 3mm wall thickness and the quality of the moulding were deemed sufficient so that both wishbones could be installed on the vehicle.

6.3.1.3 Quality control

Cavities - Due to the repeated pressing of the material, there is little off-gassing as a result few cavities formed on the moulded part.
Surface finish - The cooling under pressure resulted in a superb surface finish.
Repeatability - The similarities between parts produced using the mould was excellent, proving that the process is predictable.
Minimum radius - A tighter radius may be achievable using the layering system of wishbone A,
Productivity - Producing parts from the mould was extremely time consuming using the layering method 1. A mould with increased minimum radii should improve the quality of moulding produced using method 2.

The manufacture of Wishbone A was time-consuming - preparing and pressing the films was laborious. The final outcome was as envisaged - evenly separated fibres distributed evenly in the polymer matrix.

The manufacture of wishbone B was far more effective in terms of time, however, the broken and un-separated fibres demonstrate that the processing of the blank using method 2 is inferior to method 1. With further development, the stacking of films used in method 1 displays the most promise.

6.3.2 Manufacturing Conclusion

The manufacturing process used was successful. The moulding tool produced parts with a superb finish and the final mouldings worked as designed. It is recognised that due the equipment used, the temperature of the mould was difficult to control, as a result high temperatures may have damaged the fibres – reducing the strength of the material. The off the shelf components fitted the parts as designed. From these results, it is recommended that layering method 1 (stacking pre-pressed veneer/Biome films) is used for manufacturing the wishbones. Figure 6.7 displays a recommended manufacturing process for this material.

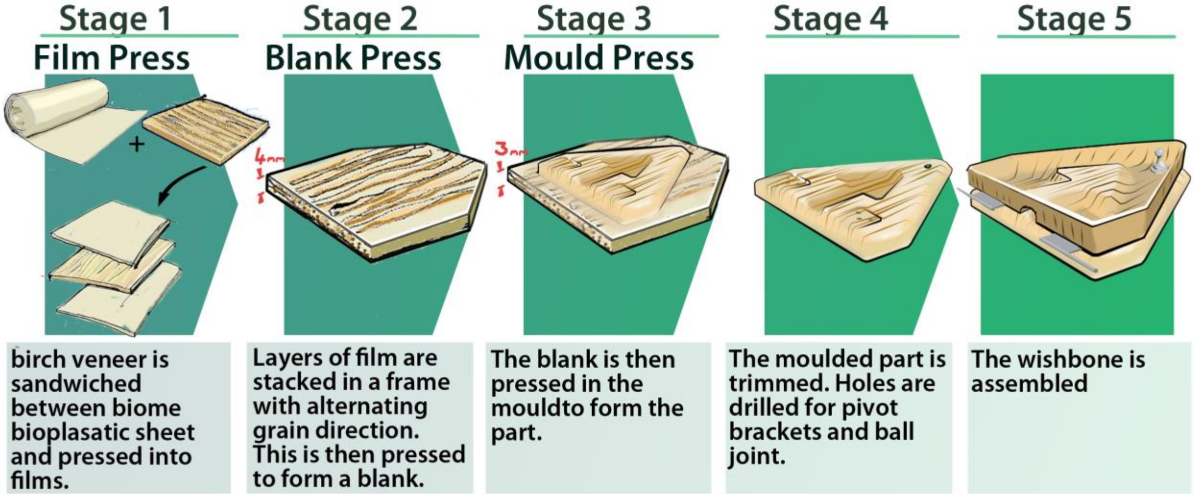


Figure 6.7, Recommended manufacturing process.

No conclusions can be drawn regarding scalability, however, the process is repeatable.

6.4 Design results

The success of the wishbone design is determined by:

1. Compliance with the performance characteristics set out in the target specification.
2. Comparison to the 2014 and 2015 Aston EcoCar wishbone designs, benchmarked in Chapter 5.
3. Environmental impact of the wishbone (discussed in section 6.2).

6.4.1 Performance against the target specification

The target specification of the wishbone (as detailed in section 5.3.7) is set out in table 6.3. In the right hand column, a score (weighted by importance) has been given for the performance of the 2016 wishbone.

Sustainable Design					
No.	Metric	imp.	unit	ideal value	score
1	Use of veneer/Biome material	5	-	70% - 100%	3
2	Impressive representation of material	1	-	yes	1
3	less environment impact than original	4	-	80%	4
4	Designed for disassembly	1	Sec	<300	1
5	Follow Materials Design methodology	4	-	yes	4
					14/15
Material and Manufacture					
No.	Metric	imp.	unit	ideal value	score
6	Process on 'hot press' in lab	2	MPa	<2	2
7	Max size of component	2	mm	<300 x 300	2
8	Minimum radius size for moulding	5	mm	>10	4
9	Depth of mould	4	mm	<10	3
10	Thickness of material	3	mm	2 - 5	3
11	Number of components	1	-	<31	0
12	Accuracy of the mould	5	mm	+/- 0.25	5
					19/23
Performance					
No.	Metric	imp.	unit	ideal value	score
13	Attach to M8 post on upright	2	-	yes	2
14	Withstand lateral force under braking	5	N	>2000	5
15	Vertical travel at 'wheel upright' end	4	mm	> 20	4
16	Distance from pivot to 'wheel upright'	4	mm	>150	4
17	Keeping the wheel vertical	5			5
18	Distribute force into chassis	3			3
19	Not deflect, holding wheel in position	5	mm	<2	5
20	Weigh less than 2015 wishbone	4	g	<600	2
21	Meet Shell competition regulations.	5	-	pass	5
22	Not interfere with clearance or wheel	4	-	yes	4
					39/41

Table 6.3, The 2016 wishbone design scored against the target specification

In table 6.3 17 of the 22 criteria the wishbone design has met the specified performance target. Areas where the finished wishbone product has failed to meet the specification are:

- No. 1, The percentage of veneer/Biome by volume was calculated as 64%, just shy of the 70% target. The percentage of veneer/Biome by weight is 44%. The remainder of material is stainless steel - mainly consisting of nuts, bolts and washers.
- No.8, A decision was made to reduce the 10mm minimum radius to 7mm, at a minimum radius of 10mm little room was left for modelling the features.
- No. 9, A mould depth less than 10mm was not possible as a radius was required along the rim of the wishbone feature. Some fibres broke during the moulding which indicates that 22mm is the maximum depth for this mould size. The number of broken fibres was not significant.
- No.11, The number of nuts, bolts and washers push the total number of parts up to 48. This in turn increases the amount of stainless steel in the component.
- No.20, In total the 2016 wishbone weighed 711.5g (including the 4 bolts attaching the wishbone to the chassis), considerably over the 600g target weight but less than the 2014 (1305g) and 2015 (823g) benchmarks. The target was not met due to the amount of stainless steel components and the thickness of the flag hinge pivot components.

6.4.2 Performance against the 2014 and 2015 benchmarks

To aid the design process, the 2014 and 2015 benchmark wishbones are rated against the needs identified in chapter 5. The scores for each need is weighted by importance. Using the same criteria, the 2016 veneer/Biome wishbone is scored and compared with these benchmarks in table 6.4 - this establishes whether improvements have been achieved.

Need	Imp.	2014	2015	2016
Sustainable design				
Has a low impact on the environment.	_/5	3	1	3
Simple to disassemble.	_/1	1	0	1
Consistent in style to automotive parts.	_/1	0	1	1
Constructed to complement the material.	_/4	1	3	4
Material and manufacture				
Is moulded using Veneer/Biome.	high	-	-	✓
Can be manufactured using hot press process.	high	-	-	✓
Standard parts are used for fixings and linkages.	_/2	2	1	2
Be manufactured in time for SEM competition.	_/10	10	8	10
Performance				
Attaches to vehicle chassis and wheel upright.	_/8	6	6	8
Secures the wheel upright in the correct position.	_/8	6	7	8
Allows the wheel upright to move vertically.	_/8	6	5	7
Does not interfere with other parts of the vehicle.	_/5	5	5	5
Performs at the Shell EcoMarathon competition.	_/10	10	8	10
Survives under loading.	_/5	3	4	5
Does not lose integrity before end of life.	_/3	3	3	3
Can be installed using team equipment.	_/5	5	5	5
Contributes as little possible weight.	_/5	0	1	3
	Total	61	58	75/80

Table 6.4, Performance comparison of 2016 wishbone against the 2014 and 2015 benchmarks.

In each of the design, manufacture and performance criteria the 2016 wishbone outperformed the benchmark models as scored in table 6.4. The final wishbone also outscores the initial 20 design concepts which indicates that the design was improved through the development. Although subjective, this framework provides a balanced approach to evaluating how successfully the wishbone has met the needs for the product.

A key problem with both the 2014 and 2015 Aston EcoCars was the weight, the weight reduction of the 2016 wishbone contributes to the overall weight reduction of the 2016 EcoCar. The brackets for mounting both the 2014 and 2015 EcoCar wishbones were also poorly considered. The pivot mount for the 2016 EcoCar wishbone was located closer to the chassis allowing a longer span between the upright joint and the chassis, while also improving the attachment to the chassis.

The 2016 wishbone is lighter and suited to the goals of the Aston EcoCar, this represents an improvement on the 2014 and 2015 wishbone designs.

6.4.3 Design conclusion

The 2016 wishbone performed better than the 2014 and 2015 wishbone parts. The 2016 design performed well, scoring a total of 75/80 against the specification (in table 6.4). The wishbone could be improved by reducing the number of bolts, washers and nuts. Overall the 2016 wishbone complies with the majority of the design specification and partially meets the Cradle to Cradle design goals - discussed in section 6.2.

6.5 Materials results

Due to the materials investigation, it was possible to successfully forecast the conditions for pressing the films produced for the wishbone manufacture. The birch fibres separated in the manner predicted, allowing for successful layering. The open mould design and corner radii used, allowed a wishbone to be successfully manufactured.

The results of Experiment 10 demonstrate that the fibres require separation before a component is formed in a mould. Pre-separation of fibres (method 1 in manufacture of wishbone A) enhances the processing properties. This separation stage allows tighter corners to be moulded, therefore increasing the intricacy of the products able to be made. The veneer/Biome can then be used in a range of applications, increasing the potential of the material.

6.5.1 Tensile test results

For a full evaluation of the material, a tensile test was performed. Samples were taken from the excess material from the manufacture of the wishbones. The samples for testing were prepared by machining the samples to the ISO527-2 1B standard shape. The samples were from the areas shown in figure 6.8.

Figure 6.8, Source of tensile samples.

Tensile tests were conducted on two samples displayed in figure 6.8. During testing the samples withstood maximum loads of 482N and 496N before failure occurred. The samples both failed as a result of sudden brittle failure, it is recognised that the material or process may need improving as it is suspected that high processing temperatures damaged the wood fibres, the results of the test are as follows:

Tensile strength	16.3 MPa
Tensile modulus	25.6
Flexural strength	No data
Flexural modulus	No data
Density	1.15g/cm^3

These results can be compared to the benchmark materials in table 6.6

Material	Tensile strength (MPa)	Tensile Modulus (MPa)	Flexural strength (MPa)	Flexural modulus (MPa)	Density (g/cm^3)
Biome HT90 (Appendix A)	70.4	1564	Not available	4260	1.3
6.5mm thickness birch plywood	42.2	9844	50.9	12737	0.63
E-Glass/Epoxy (GFRP)	241	Not available	455	18000	1.82
Biotex (flax/pla)	110	14000	123	7100	1.33

Table 6.5, benchmark materials.

16.3MPa is a low tensile strength value for a material used in a structural application and is less than the material measured during the pilot study (50MPa) (in section 4.3). The reduction in the veneer/Biome performance is thought to be due to thermal degradation during pressing as indicated by darkened fibres. Further experimentation should focus on the manufacturing stage of the process to improve the materials performance.

If the 2016 Aston EcoCar cornered at speed, the component may fail. Under maximum loading conditions a predicted bearing stress of 38.8MPa at the veneer/Biome and ball joint interface is the likely mode of failure. On track testing of the 2016 EcoCar at the SEM 2016 competition would have provided further evaluation of dynamic loading.

The materials investigation led to the creation of a suitable process where the separation of fibres was exploited to create a composite. The low strength of the material in the wishbone prototype is a concern, accurate processing equipment would improve prototype manufacture and the use of lower processing temperatures should result in a stronger wishbone prototype.

6.6 M/D/M methodology evaluation

The M/D/M methodology displayed in figure 1.2 can be judged on:

1. The wishbone performance.
2. Achieving the Cradle to Cradle design goal.

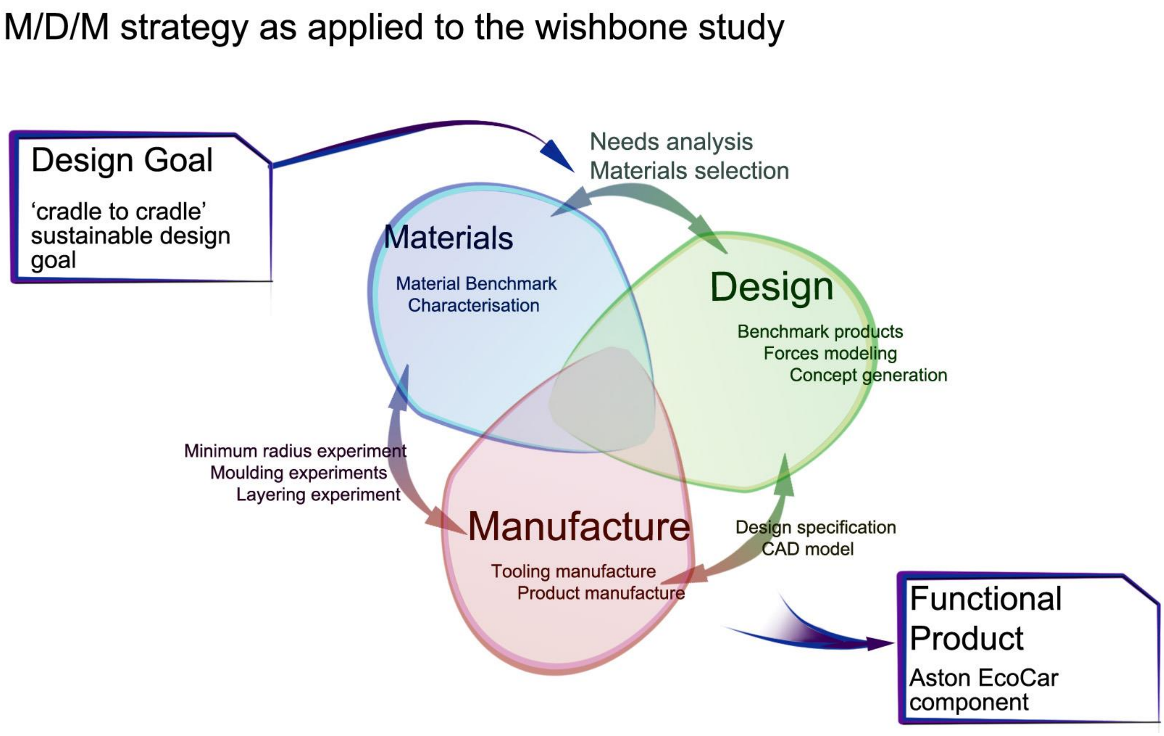


Figure 1.2, Layout of wishbone study structure

6.6.1 Wishbone performance and design goal.

Using the M/D/M strategy, a successful environmental design has been produced. This is displayed in the results of the wishbones performance on the 2016 Aston EcoCar and the results of the sustainability analysis.

<u>Performance</u>

The wishbone performed on the 2016 Aston EcoCar as designed. Unfortunately the vehicle was not able to be tested on track, however the component passed the required safety and technical inspections.

<u>Design goal</u>

A large part of the wishbone is constructed using biodegradable wood and bioplastic materials. All the other materials are stainless steel - which can be considered 'technical nutrients'. The wishbone is designed for straightforward disassembly.

In this regard the wishbones partially meet the sustainable Cradle to Cradle goal. A limitation of this study is that a full life cycle analysis has not been conducted (due to lack of available data) this would provide more clarity regarding the sustainable outcome of the project.

In future iterations, stainless steel could be eliminated. It is recognised that producing the steel and processing the plastic multiple times uses a lot of energy. The sustainable design goal could be modified to take wider environmental impacts into consideration.

6.6.2 Approach

The key to the M/D/M process is in how each piece of the process informs the others. For an understanding of the success of the methodology, the interactions between materials, design and manufacture can be analysed.

<u>Materials/Design</u>

Through careful selection of the materials and conducting a needs analysis, a component has been designed using the knowledge gained from the materials investigation. Understanding the capabilities of the material have been key to the design of wishbone. The design has been shown to be within the limits of the material (in section 5.4.4).

<u>Design/manufacture</u>

The feasibility of the proposed design was informed by the materials characterisation experiments and the pilot study. The design specification and CAD modelling have allowed the proposed design to be prepared for manufacture.

<u>Manufacture/Materials</u>

The capabilities of the material and equipment informed the minimum radius able to be moulded and the maximum size of the component. This allowed the design to be successfully manufactured using the veneer/Biome material.

One failing of the process was that the lab press did not allow for fine temperature controls. Combined with the sensitivity of the material to temperature, the resulting material has reduced strength compared with the pilot study sample. Processing temperatures need to be investigated further to produce a successful prototype.

6.6.3 Conclusion

The method has been a success. Where failings have occurred, they can be identified within the process. This feedback allows improvements to be made and can be considered a benefit of using the method.

The structure of the M/D/M strategy lacks definition, however, this is necessary as each process is iterative. It is advisable a number of design tools and processes are considered at each stage with a focus on the outcome - a functional product.

The method has been successful for the production of a sustainable and functional wishbone for the Aston EcoCar.

Chapter 7: Conclusion

7.1 Key findings

In terms of raw materials, production, use and disposal, more can and could be done to improve cars' impact on the environment. Through studying the VW Golf it has been shown that the manufacture of cars has not changed significantly in the last 40 years. Through studying how the automotive industry makes their decisions, it is speculated that much of their sustainability efforts may be 'greenwashing'. Generally, the automotive industry may not be concerned with environmental sustainability.

A new holistic approach to car design may be required. The Aston EcoCar offers an alternative approach to the design of a car by considering the whole lifecycle of the vehicle. The 2015 EcoCar contained 41% biodegradable materials, and weighs only a 1/7 of a standard car. A small sustainable 'urban concept' passenger vehicle such as the EcoCar could replace standard cars in an urban environment. An improved methodology was developed to further improve the sustainability of the EcoCar. This is however a prototype, and it is yet to be proven whether the processes developed within this study can be upscaled.

Materials research centres around details of properties rather than a useful end product. A new methodology has been formulated - M/D/M. This strategy can be applied to the field of design as a method to formulate materials in sympathy with the design and manufacture of products. The main wishbone study proved the use of the M/D/M methodology in principle.

Following the 'Cradle to cradle' design goal, a structural and biodegradable composite was formulated and a design was manufactured. Testing the component on the Aston EcoCar vehicle has demonstrated that while successful, improvements to reduce the amount of 'technical nutrients' (stainless steel) and the weight can be reduced further (compared to the benchmarks products).

After considering a range of biodegradable materials for composite, a new material has been successfully formulated by combining birch veneers with bioplastic. Through heat and pressure it has been discovered that the fibres can be separated. This allows a material of intermingled plastic and long fibres to be made. This material can be moulded to a radius of 7mm and for an intricate moulded part to be formed.

The design phase of the M/D/M strategy also established - through benchmarking - that an improvement can be achieved on the established materials and designs - the 2016 wishbone component is lighter than the steel and plywood benchmarks, while also containing a significant proportion of biodegradable material.

Many of the stated goals were achieved and the components performed on the car at SEM 2016. It is acknowledged that further improvements could be made in future iterations.

7.2 Contribution to knowledge

Changing the way cars are manufactured has been established through comparing the VW Golf and the Aston EcoCar. This has been achieved through comparing the materials used for the respective vehicles. This has led to a possible route forward in sustainable automotive development.

A new method has been developed to consider the role of materials development in the design process (described in chapter 3).

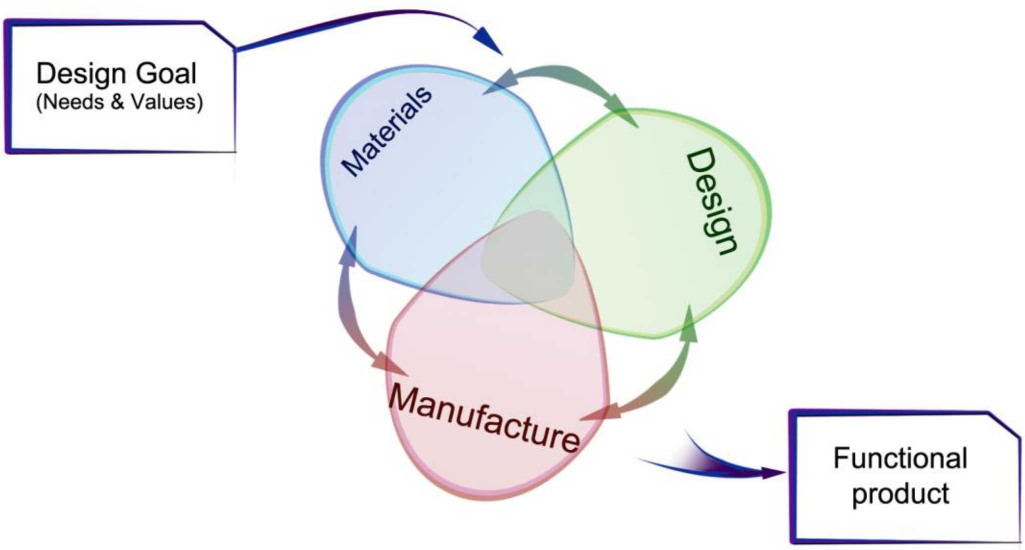


Figure 3.4, Materials/Design/Manufacture (M/D/D) strategy

The structure of the method illustrated in figure 3.4 relies on the use of design tools and materials investigation to inform the manufacture of a product. The use of this method to manufacture a wishbone is proof of principle and establishes the importance of considering the materials and manufacture as part of the design process.

A new material has been formulated using a novel process whereby wood veneer is sandwiched between thermoplastic sheets. When processed using heat and pressure it has been discovered that the plastic forces its way between the wood fibres in the veneer. These fibres then become suspended in the molten plastic and are able to splay apart under the pressure. On cooling, the combination of long, aligned fibres encased in mouldable plastic provides a material useful in the creation of structural components. This material may have potential for other applications in the automotive industry.

The proof of the methodology and material was demonstrated on the 2016 Aston EcoCar. In doing so, this aids the development of environmentally sustainable vehicles.

7.3 Limitations of the research

This research is generally sound in that the production of a useable component was achieved. However the research is limited to:

- A study of sustainability in the automotive industry - the component was developed for use on cars; the study does not explore other possible applications for use of veneer/Biome in structural uses elsewhere.
- The development of a sustainable design and manufacturing methodology - less consideration has been given to efficiency or costing.
- The development of a novel sustainable composite material - while the material was fully developed and utilised, it would be beneficial to further explore and optimise the material properties including strength, stiffness and microscopic properties. There are also a number of potential fibres and plastics which were not explored which could have had different results.
- Finally, to interrogate the methodology automotive design application - a full vehicle designed and developed using the M/D/M method would develop the strategy further, as well as having the potential to be more sustainable.

The work was conducted in isolation. Were the project conducted by a larger team with expertise in materials and engineering, then more would have been achieved

The initial training of the author is in product design rather than engineering and materials science knowledge and it is recognised that expertise in this area would have been beneficial to the project. However, it is also important to note that the design focus of the study was a key characteristic.

The author also has a lack of professional experience of the automotive industry. However, the Aston EcoCar is produced by undergraduate students in an academic setting, and it is envisaged that the product could be put to broader applications. Research funded by the automotive industry would imply a real effort to improve the sustainability of car production.

The biodegradable composite material developed shows promise, though there is further experimentation to develop further, this research project has shown that a material can be formulated and used for design and manufacture of a successful product.

The result of the project was generally positive, and there are advantages to developing a product using the holistic M/D/M method:

<u>Advantages</u>

- As the system is holistic, experimentation can be targeted towards the information required for the end product.
- Bespoke products can be created for specific purposes.

<u>Disadvantages</u>

- Evaluating the sustainability of the component did not reach expected standards due to lack of data.
- Suitable methods and tools need to be chosen in order to be relevant.
- The focused nature of the investigations make the results specific to this project. Other projects may produce alternative outcomes; for instance, a bioplastic with a lower resistance to temperature may be more suitable for an indoor product.

Reflecting on the methods used, there were no serious flaws in the process, and its use can be recommended when attempting to design a product where a step change is needed in terms of lifecycle philosophy. Improvements can be made and these modifications to the process would include:

- A more detailed structure - the pilot study could be extended and include defined gateways.
- Expertise from both materials science and engineering to the design process to further justify the design concept chosen.
- An interdisciplinary team to create the most successful component using the materials available.

7.4 Importance of the research

Based on this research, it is recommended that automotive companies change their practices and devote time and resources into developing a more sustainable approach to the design, manufacture, use and disposal of cars. Rather than piecemeal improvement, this research advocates a holistic strategy - following a Cradle to Cradle philosophy.

From the study of the automotive industry in chapter 2, it is unlikely that a sustainable approach to design and manufacture will be adopted by the major car manufacturers. Although the automotive industry may not currently focus on sustainability, it is important that alternative practices - such as the methods used in this study - are experimented with, as sustainable practices are likely to become increasingly important.

The research in this study demonstrates a strategy by which poor practice (in terms of sustainability) can be replaced with a new method, delivering a sustainable solution.

Car manufacturers could be encouraged not only to reduce CO_2 emissions, but also do less damage to the environment during the manufacturing process. This research presents a considered 'Cradle to Cradle' approach to achieving this.

This strategy is unlikely be adopted by the automotive industry on a large scale - there has been too much investment in current infrastructure over the past 40 years. The process itself is in need of further development as the use of veneer/Biome and the 'wooden car ethos' in general is somewhat in its infancy. Automotive industry has an alternative focus in developing new vehicles, a reason for which could be a lack of consumer pressure. Sustainability may become a more important factor for product development more widely, consumer attitudes may also reflect this.

7.5 Further research

With increased funding and resources, the findings of this research could be taken further. Now that the method and results of the study have been proved in principle, they may be of interest to a small car maker who could focus on sustainability in their marketing - like Morgan or Bristol. At some point in the future, larger automotive manufacturers will become interested in the sustainability of vehicle manufacture. To further the work of this research project, there are a number of possible courses of action:

1. Conduct a more ambitious M/D/M study - veneer/Biome feasibility study, refining the processing conditions, design and manufacture a more ambitious component using a larger press and tool.
2. Materials study - conducting a materials focused investigation, optimising the veneer/Biome material.
3. Design study - apply the veneer/Biome to other suitable products (or further areas of the Aston EcoCar vehicle) - towards a goal of a fully biodegradable vehicle.
4. Manufacturing study - explore the scalability of the process for higher volume pressing.
5. Apply the same methodology to a new subject - creating a new material, design and manufacturing process.

Full life cycle assessment study

Aside from future projects, it would also further the understanding from research in this study if a full LCA were to be carried out comparing information gathered in lifecycle inventories of the EcoCar and wishbone. Although materials have been selected (through analysis of materials used) based on the Cradle to Cradle approach and design philosophy their impact has not been quantified.

Resources (data sets used in LCA software) have not been available to conduct the proper analysis of the environmental impact the EcoCar has in comparison with a motor car. Performing this would validate the environmental approach and highlight areas for improvement.

- Time 6 months.
- Cost approx. £5,000.
- Requirements datasets.
- Resources LCA software.

Sustainable automotive design

Based on the research carried out in this project, a recommendation can be made with regard to further development of the materials and methods produced in this study.

Continuing the research regarding the sustainable design and manufacture of cars, a larger cycle of the M/D/M method could be used to produce a sustainable car. A fully sustainable 'Cradle to Cradle' car is feasible. To build on the research in this project it is assumed that the sustainable design goal would remain the same, but the scope of the project would be larger than the creation of a wishbone - perhaps a chassis. Future development would require increased resources and may be carried out as follows.

Stage 1, the scope of the project would need reviewing, followed by a materials selection process to define the materials and design specifications. This process is estimated to need:

- Time 2 months.
- Cost negligible.
- Requirements A project to apply the process to.
- Resources few.

Stage 2, Understanding of the materials capabilities is a key part of the M/D/M process, the previous pilot study, materials investigation and wishbone study will inform the choice of parameters for the further study. To understand the technical capabilities of the veneer/Biome material a more measured approach (than that taken in chapter 4) is needed. A materials investigation would need to take place. If the veneer/Biome composite is to be explored further then a rigorous materials investigation is needed. This would be achieved by running a series of controlled experiments producing samples according to ASTM D638, with the results measured using an Instron machine; producing three samples of each variation of material reduces the possibility of anomalous results.

It is proposed that materials experiments would use taguchi methods (Phadke, 1989) for a robust experimental design. Using Taguchi experimental design 15 processing variables can be investigated at 2 levels using an L16 array. This is the minimum number of experiments needed to conduct a full investigation of the process described at the end section 5.2. - pressing of Biome and veneer films, stacking layers and moulding to shape. It would be recommended that tensile, flexural and impact tests are carried out to measure the quality characteristics desired. Through testing the samples to destruction, the failure modes can be analysed using an electron microscope. This would lead to a better understanding of the fibre polymer bonds and the properties of the composite can then be improved.

The results of further materials testing will provide the processing conditions to improve manufacture and better exploit the material - generating improved product design.

- Time 6 months.
- Cost approx. £5,000.
- Requirements A project to apply the process to.
- Resources Accurate Hot press, bio-plastic supply.

Stage 3, Design process, depending on the application of the design, a similar process to the one used in this study could be used. different design challenges may require the used of different methods - for example, prototypes may need to be made.

- Time 6 months.
- Cost approx. £2,000.
- Requirements A project to apply the process to.
- Resources Accurate Hot press, bio-plastic supply.

Stage 4, The design and materials would then need to be brought together to manufacture a component. Assuming a future project would be a more ambitious one, then a larger press is needed than can be found at the university. It would also be desirable (for control of the processing parameters) to have a mould where the heating elements and thermostat are imbedded into the mould close to the moulding surface.

This equipment and tooling is expensive and the project would need either a partner or funding. Because of this, the manufacture would require:

- Time 12 months.
- Cost approx. £20,000.
- Requirements An industry partner; a project to apply the process.
- Resources Large hot press (estimated 100T, 2m x 1m bed), bio-plastic supply, large format veneers, heated mould.

Large scale production

The equipment used for the wishbone manufacture in the main study is not suitable for producing more than a handful of pressed components. For a full study of how to introduce a full manufacture process of veneer/Biome products, the veneer/Biome films would need to be manufactured as a pre-impregnated sheet. This could be developed using a heated drum pressing layers of veneer and plastic as they are fed through. A full feasibility study would need to be undertaken. This would enable the production of saleable products, as such the design of a component. Tooling would also be needed.

- Time 30 months.
- Cost approx. £60,000+.
- Requirements A manufacturing partner, A product to manufacture.
- Resources A production line, CAD package, Materials supply.

Alternative product

There are many applications, other than automotive, that the M/D/M methodology could be applied to in a meaningful way. By using the method to a different product design application - such as furniture or packaging - the M/D/M approach is examined further. This would test how robust the M/D/M approach is while also consider a different problem - presenting a new challenge. Depending on the nature of the application this could require:

- Time 30 months.
- Cost approx. £10,000.
- Requirements A project to apply the process to.
- Resources Accurate Hot press, CAD package, Materials supply.

7.6 Closing statement

It has been found through studying one typical example of a family car, the Volkswagen Golf, that car manufacture, use and disposal is very detrimental to the environment. The automotive industry as a whole is doing little to address this. A new holistic method based on materials, design and manufacture (M/D/M) of sustainable car components has been developed, trialled and found to be successful in implementation on the Aston EcoCar. While current pressures mean that this is unlikely to be adopted by the automotive industry at large, this proof of principle study indicates that the production of cars can and should be more environmentally friendly. When the need for environmental sustainability becomes more paramount, this holistic approach is one option for further development.

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Appendices

Appendix A - Biome Datasheet

biome bioplastics

320 m.c HT90

Technical Information Sheet: Biome HT Resins

Overview

A limitation of bio-resins is that they commonly show poor mechanical properties at higher temperatures. BiomeHT resins are a range of bio-materials developed to offer improved temperature resistance combined with good processing and end use characteristics. The resins are designed to be suitable for injection moulding, sheet extrusion/thermoforming.

Three resins are currently offered. BiomeHT70/126, BiomeHT80/100 and BiomeHT90/102 offer food contact suitability, subject to component thickness. BiomeHT70/126 and BiomeHT80/100 have better flow characteristics but a somewhat lower temperature performance than BiomeHT90/102.

1. Properties

Product form: Pellet

Parameter	Guide Value	Unit	Test Method
Particle size	1.5 – 2.5	mm	Calliper gauge
Density	1.3	g/cm³	EN ISO 1183 -1/A
Bulk Density	~750	Kg/m³	EN ISO 60
MFI (230C/5kg)	10-32	g/10 min.	EN ISO 1133
Water Content	~0.2	Weight - %	In-house test
MFI (230C/5kg)	**HT70**	**HT80**	**HT90**
	28-32	18-22	10-14

Biome HT resins are GMO free,

2. Processing

BiomeHT resins are designed primarily for injection moulding and sheet extrusion. The resins require melt processing temperatures in the range 200-230°C. Excessive temperatures can lead to material degradation and yellowing, and should be avoided. For processing information please refer to our separate data sheets.
During purging of the machine some fuming may occur due to slight plasticizer loss. Where available remove any fumes by forced extraction. Alternatively, a well ventilated plant area may be adequate for dissipating any fumes. These fumes are non toxic or harmful.

3. **Typical Room Temperature Properties of BiomeHT materials**

The properties below are typical, but do not represent a product specification.

Parameter	Test Method	HT70/126	HT80/100	HT90/102
Flexural modulus (Mpa/Nmm^{-2})	EN ISO 527 – 1	3194	3604	4260
Tensile modulus (Mpa/Nmm^{-2})	EN ISO 527 – 1	1391	1465	1564
Tensile Strength (Mpa)	EN ISO 527 – 1	53.9	61.6	70.4
Strain at break (%)	EN ISO 527 – 1	9.1	6.7	6.1
Vicat A softening point (°C)	EN ISO 306-2004	90.5	104.2	114
Notched Izod (Kj/m2)	EN ISO 180-2000	6.94	6.07	5.36

4. **Product attributes:**

Products made from BiomeHT products

- have improved temperature performance over typical bio-resins
- show good room temperature mechanical properties
- are biodegradable and (depending on thickness, compostable)
- has a high renewable carbon content
- offer food contact suitability (depending on component thickness
- can be coloured with masterbatch

5. **General Applications**

- short-life/disposable biodegradable products (e.g cutlery, coffee-cup lids)
- thermoformed products
- injection moulded products
- tubes
- products where transport conditions might lead to exposure temperature ~80C+

6. Packaging

BiomeHT resins are delivered in 25kg aluminium foil sacks or octabins with liner bags, on CP3 pallets. Labelling includes product designation and lot numbers to ensure traceability.

7. Storage and Handling

BiomeHT resins can absorb small amounts of water if exposed to moist conditions, which can cause problems with outgassing during melt processing. The water uptake depends on the temperature and relative humidity. Ideally the resin should be stored cool and dry in the delivery packaging.

8. Shelf Life

If stored correctly, the shelf life until processing is 6 months after delivery.

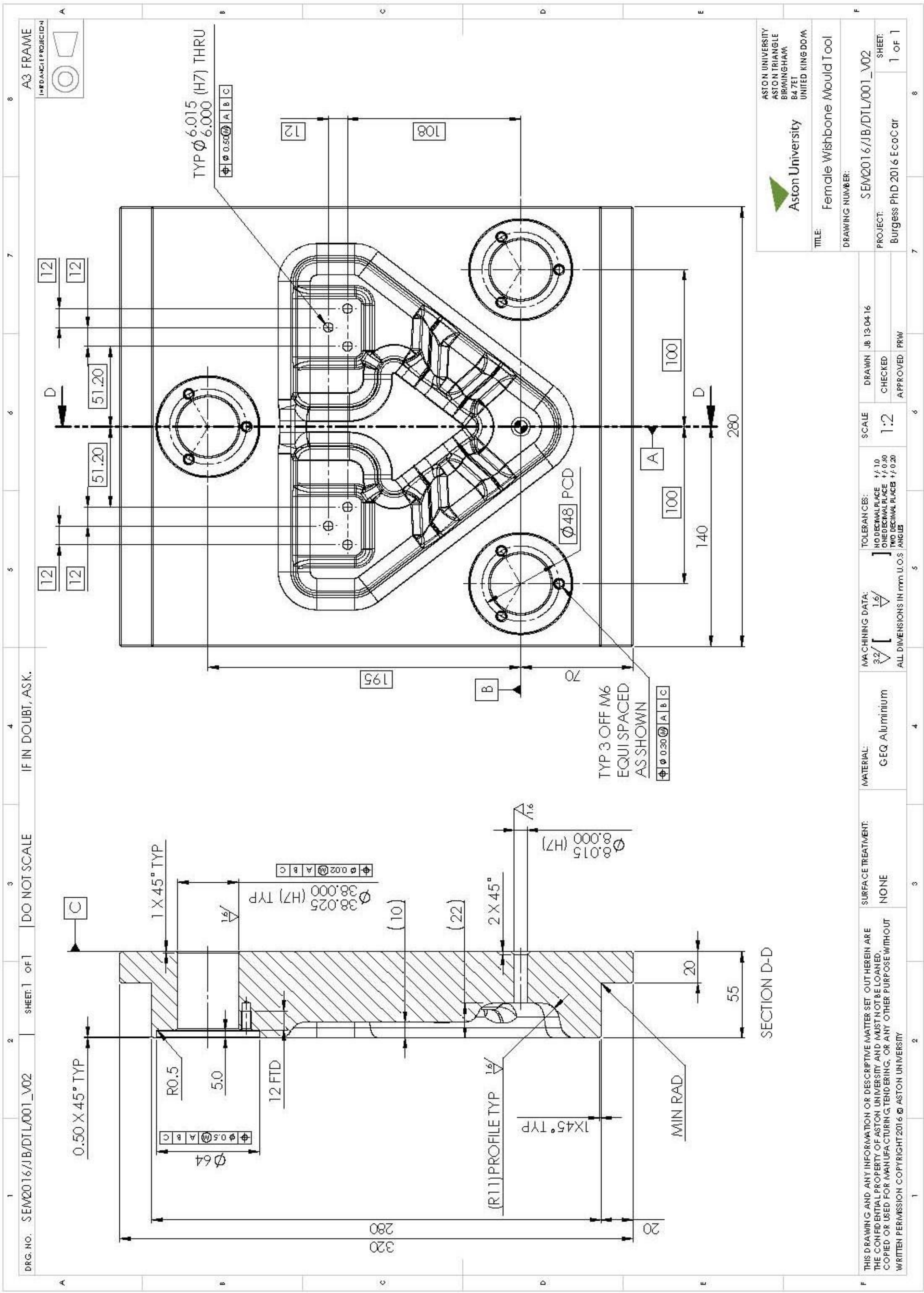
9. Safety Data

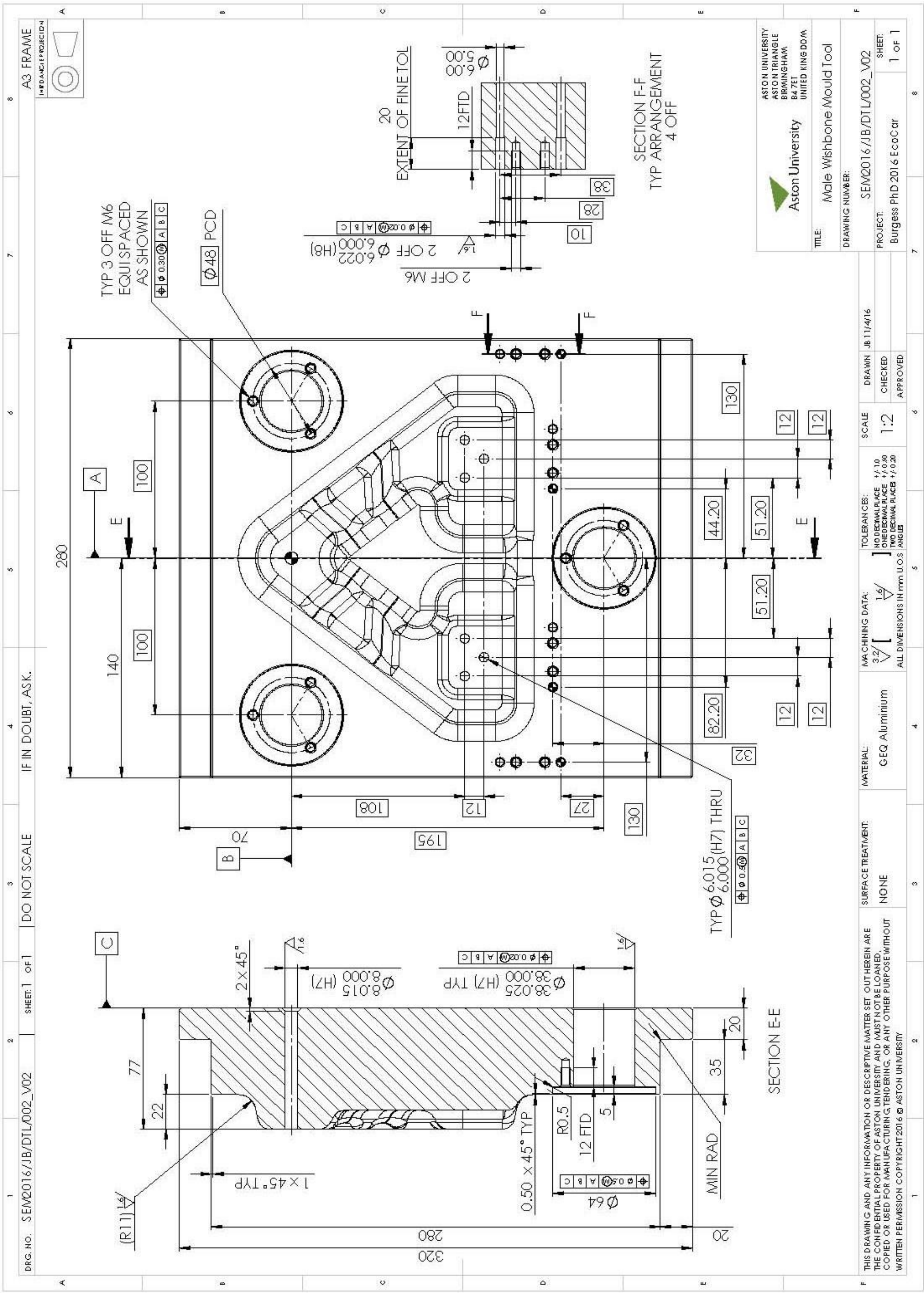
BiomeHT resins are non-hazardous according to directive 67/548/EEC and are not subject to transport regulations. The product does not decompose at room temperature. General safety, protection and hygiene procedures for the handling of the molten resin should be followed. Also, please note, that spilled granule can present a slip hazard. For further details please refer to the Material Safety Datasheet.

10. Quality Management

Quality management is a central component of Biome's business policy. The company is accredited to ISO 9001-2000 and ISO 14001: 2004.

Appendix B - 2016 Aston EcoCar wishbone mould technical drawings





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SHEET 1 OF 1
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IF IN DOUBT, ASK.
TYP 3 OFF M6
EQUI SPACED
AS SHOWN
Ø48 PCD
SECTION F-F
TYP ARRANGEMENT
4 OFF
20
EXTENT OF FINE TOL
12FTD
2 OFF M6
SECTION E-E
TYP Ø6.015 6.000 (H7) THRU
MIN RAD
0.50 × 45° TYP
R0.5
12 FTD
Ø64
1 × 45° TYP
2×45°
(R11)
280
320
140
100
195
130
108
70
Aston University
ASTON UNIVERSITY
ASTON TRIANGLE
BIRMINGHAM
B4 7ET
UNITED KINGDOM
TITLE: Male Wishbone Mould Tool
DRAWING NUMBER: SEM2016/JB/DTL/002_V02
PROJECT: Burgess PhD 2016 EcoCar
SHEET: 1 of 1
SCALE 1:2
DRAWN JB 11/4/16
CHECKED
APPROVED
MATERIAL: GEQ Aluminium
SURFACE TREATMENT: NONE
ALL DIMENSIONS IN mm U.O.S
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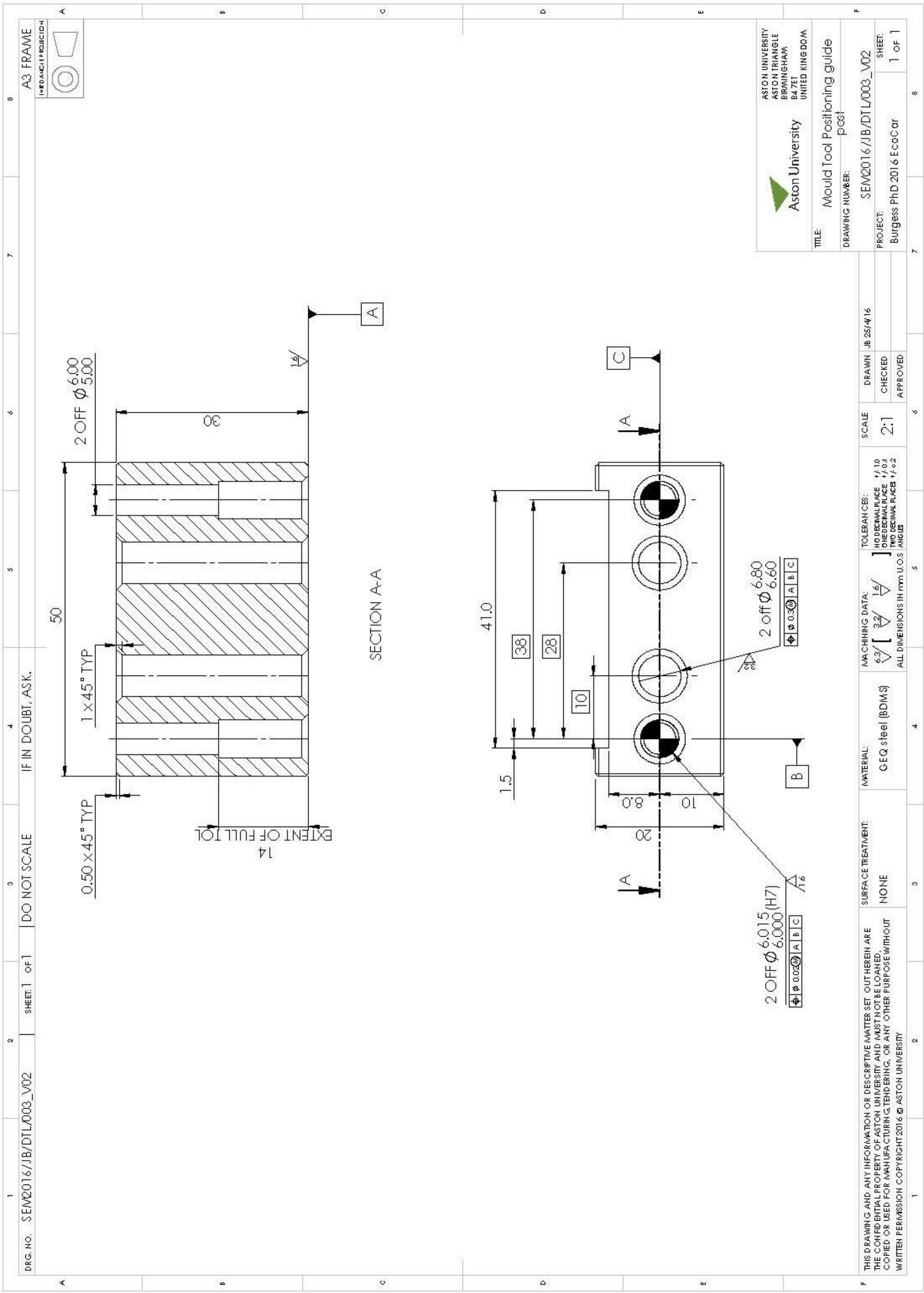
Mould Tool Positioning guide post
SEM2016/JB/DTL/003_V02
Burgess PhD 2016 EcoCar
ASTON UNIVERSITY
ASTON TRIANGLE
BIRMINGHAM
B4 7ET
UNITED KINGDOM
Aston University
SECTION A-A
A3 FRAME
DO NOT SCALE
IF IN DOUBT, ASK.
MATERIAL:
GEQ steel (BDMS)
SURFACE TREATMENT:
NONE
SCALE
2:1
DRAWN JB 25/4/16
CHECKED
APPROVED
SHEET: 1 OF 1
2 OFF Ø 6.00 5.00
2 off Ø 6.80 6.60
2 OFF Ø 6.015 6.000 (H7)
1 x 45° TYP
0.50 x 45° TYP
EXTENT OF FULL TOL
ALL DIMENSIONS IN mm U.O.S
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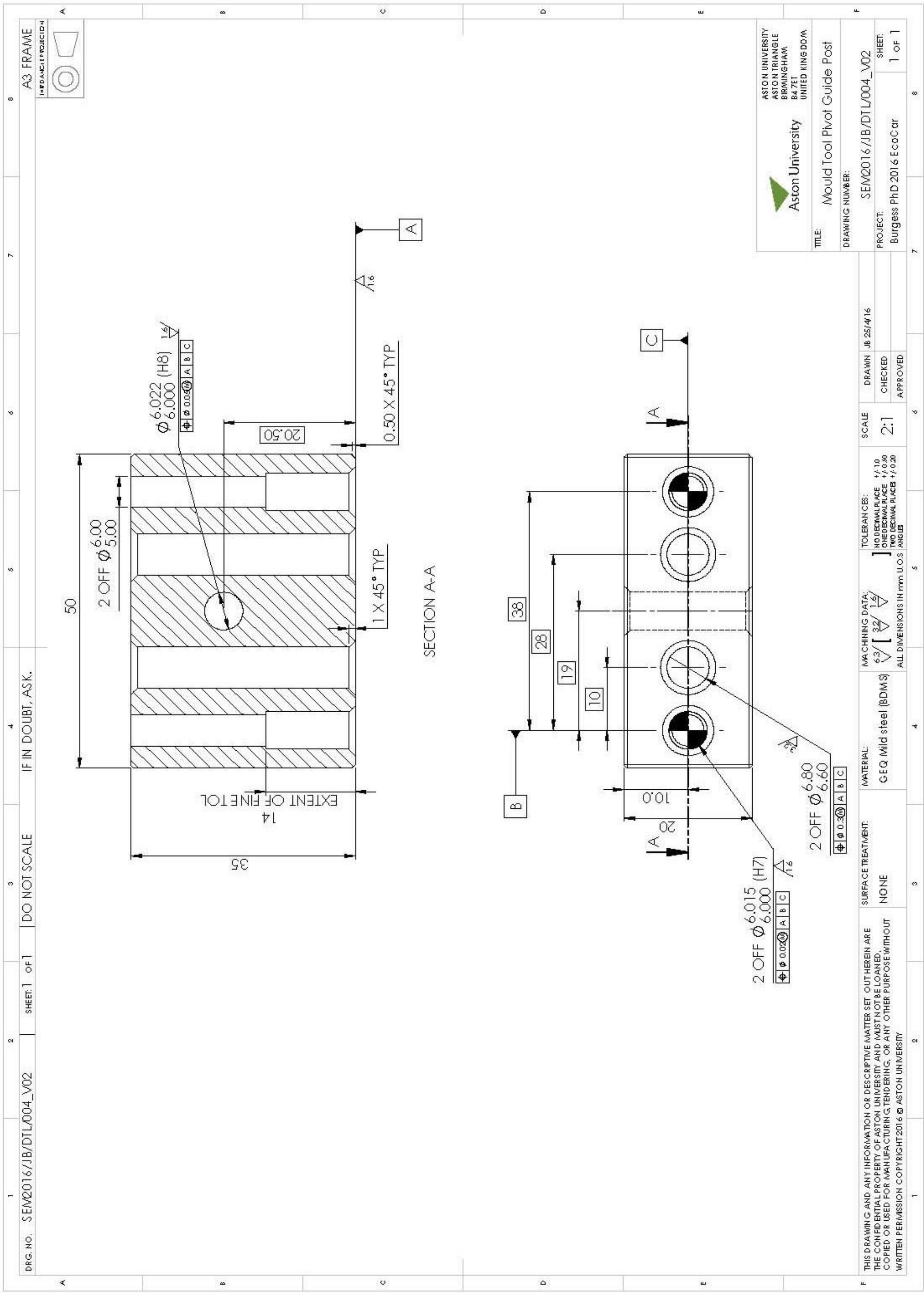
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DRG. NO. SEM2016/JB/DTL/004_V02
SHEET 1 OF 1
DO NOT SCALE
IF IN DOUBT, ASK.
SECTION A-A
EXTENT OF FINE TOL
0.50 X 45° TYP
1 X 45° TYP
2 OFF Ø6.00 5.00
Ø6.022 6.000 (H8)
2 OFF Ø6.015 6.000 (H7)
2 OFF Ø6.80 6.60
Aston University
ASTON UNIVERSITY
ASTON TRIANGLE
BIRMINGHAM
B4 7ET
UNITED KINGDOM
TITLE: Mould Tool Pivot Guide Post
DRAWING NUMBER: SEM2016/JB/DTL/004_V02
PROJECT: Burgess PhD 2016 EcoCar
SHEET: 1 of 1
SCALE 2:1
DRAWN JB 25/4/16
CHECKED
APPROVED
MATERIAL: GEQ Mild steel (BDMS)
SURFACE TREATMENT: NONE
ALL DIMENSIONS IN mm U.O.S
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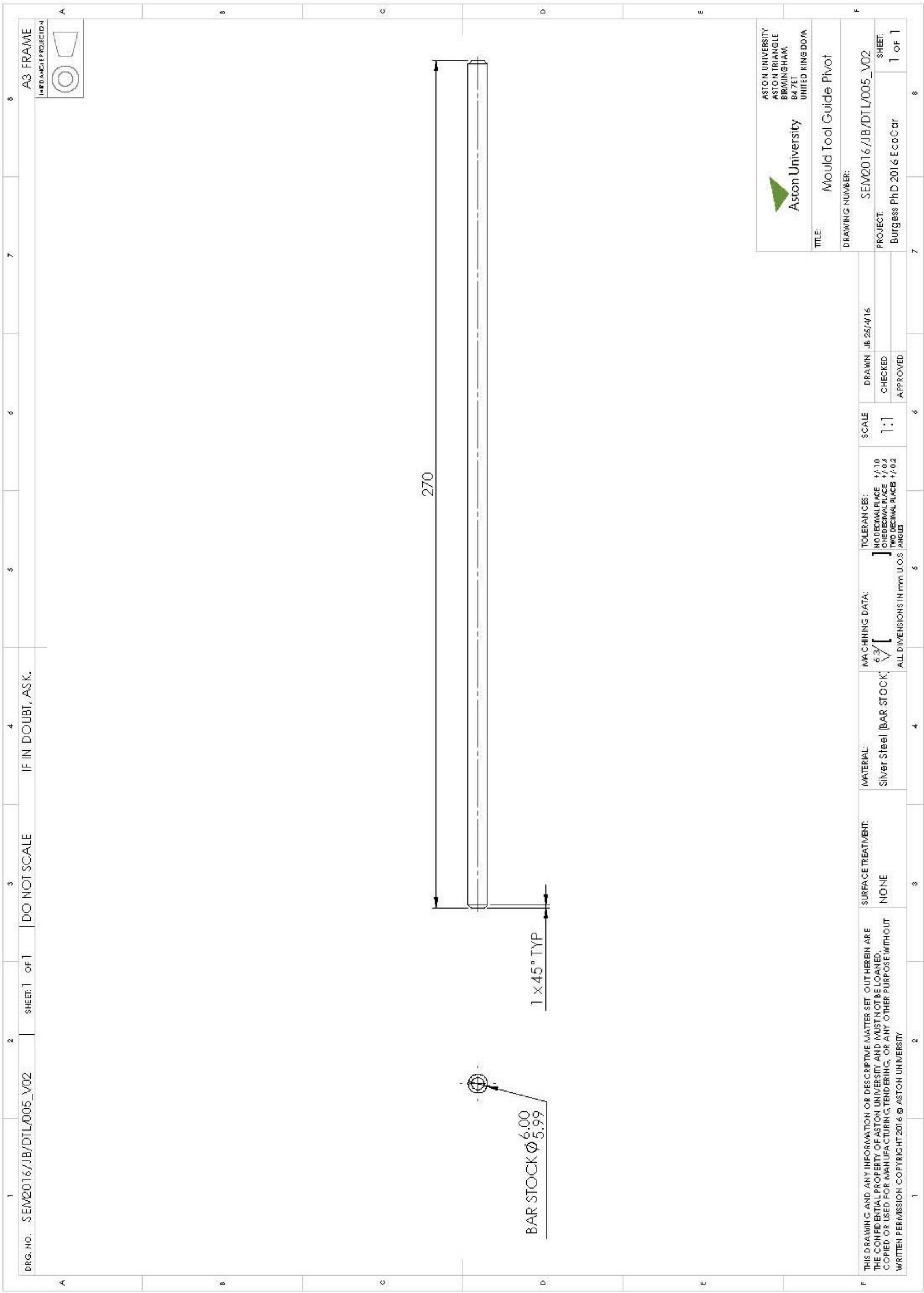
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SHEET: 1 OF 1
DO NOT SCALE
IF IN DOUBT, ASK.
270
1 X 45° TYP
BAR STOCK Ø 6.00 5.99
ASTON UNIVERSITY
ASTON TRIANGLE
BIRMINGHAM
B4 7ET
UNITED KINGDOM
Aston University
TITLE:
Mould Tool Guide Pivot
DRAWING NUMBER:
SEM2016/JB/DTL/005_V02
PROJECT:
Burgess PhD 2016 EcoCar
SHEET:
1 OF 1
DRAWN JB 25/4/16
CHECKED
APPROVED
SCALE
1:1
TOLERANCES:
MACHINING DATA:
ALL DIMENSIONS IN mm U.O.S
MATERIAL:
Silver Steel (BAR STOCK)
SURFACE TREATMENT:
NONE
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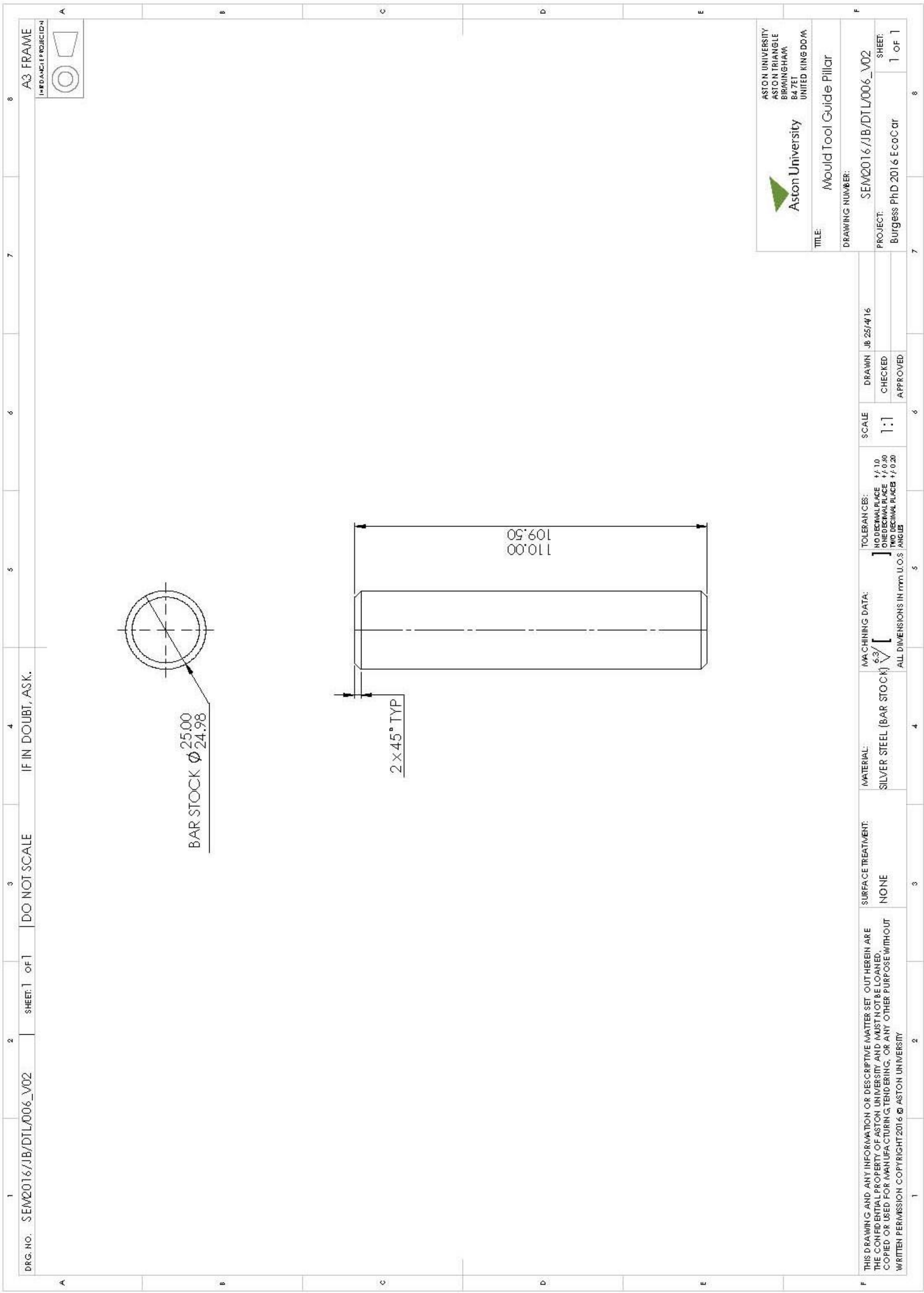
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IF IN DOUBT, ASK.
BAR STOCK Ø 25.00 24.98
2 X 45° TYP
110.00
109.50
Aston University
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ASTON TRIANGLE
BIRMINGHAM
B4 7ET
UNITED KINGDOM
TITLE:
Mould Tool Guide Pillar
DRAWING NUMBER:
SEM2016/JB/DTL/006_V02
PROJECT:
Burgess PhD 2016 EcoCar
SHEET:
1 of 1
DRAWN JB 25/4/16
CHECKED
APPROVED
SCALE
1:1
TOLERANCES:
MACHINING DATA:
ALL DIMENSIONS IN mm U.O.S
MATERIAL:
SILVER STEEL (BAR STOCK)
SURFACE TREATMENT:
NONE
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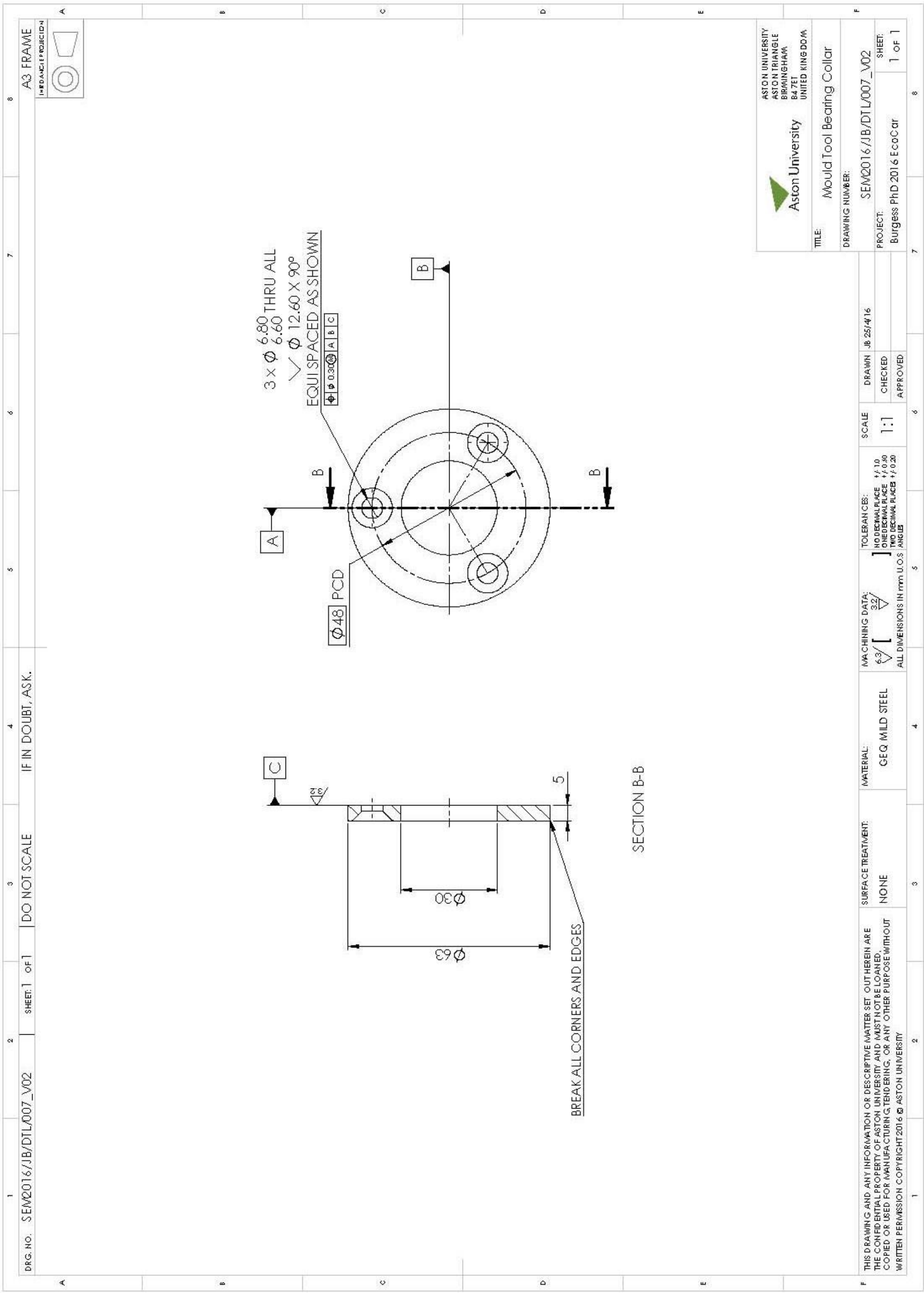
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⌵ Ø 12.60 X 90°
EQUI SPACED AS SHOWN
Ø 0.30 A B C
Ø48 PCD
A
B
B
B
C
5
Ø30
Ø63
BREAK ALL CORNERS AND EDGES
SECTION B-B
ASTON UNIVERSITY
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BIRMINGHAM
B4 7ET
UNITED KINGDOM
Aston University
TITLE:
Mould Tool Bearing Collar
DRAWING NUMBER:
SEM2016/JB/DTL/007_V02
PROJECT:
Burgess PhD 2016 EcoCar
SHEET:
1 OF 1
DRAWN JB 25/4/16
CHECKED
APPROVED
SCALE
1:1
TOLERANCES:
ANGLES
MACHINING DATA:
6.3
3.2
ALL DIMENSIONS IN mm U.O.S
MATERIAL:
GEQ MILD STEEL
SURFACE TREATMENT:
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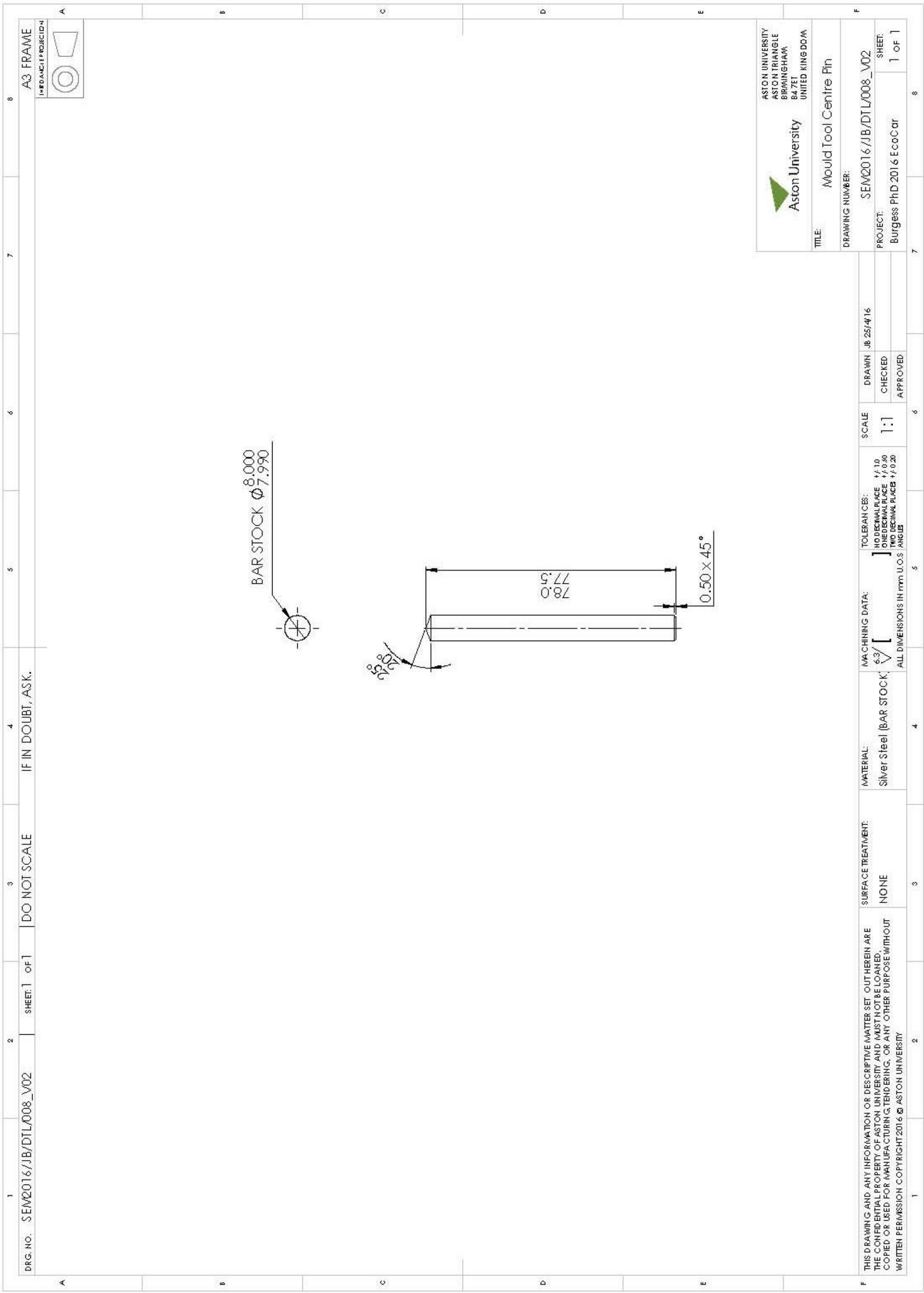
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30°
25°
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IF IN DOUBT, ASK.
Aston University
ASTON UNIVERSITY
ASTON TRIANGLE
BIRMINGHAM
B4 7ET
UNITED KINGDOM
TITLE:
Mould Tool Centre Pin
DRAWING NUMBER:
SEM2016/JB/DTL/008_V02
PROJECT:
Burgess PhD 2016 EcoCar
SHEET:
1 OF 1
SCALE
1:1
DRAWN JB 25/4/16
CHECKED
APPROVED
TOLERANCES:
NO DECIMAL PLACE +/-1.0
ONE DECIMAL PLACE +/-0.30
TWO DECIMAL PLACES +/-0.20
ANGLES
MACHINING DATA:
6.3
ALL DIMENSIONS IN mm U.O.S
MATERIAL:
Silver Steel (BAR STOCK)
SURFACE TREATMENT:
NONE
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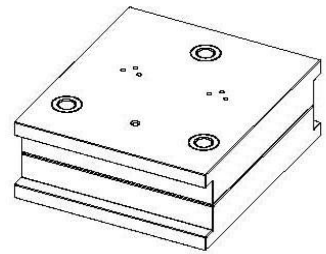
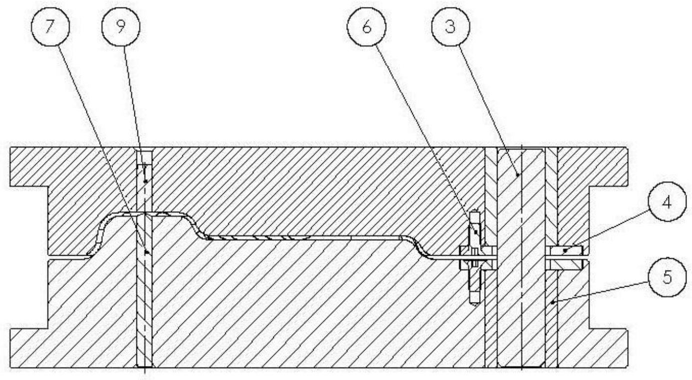
DRG. NO. 2016/JB/STAGE1/ASSEMv01 | SHEET: 1 OF 2 | DO NOT SCALE | IF IN DOUBT, ASK.

A3 FRAME

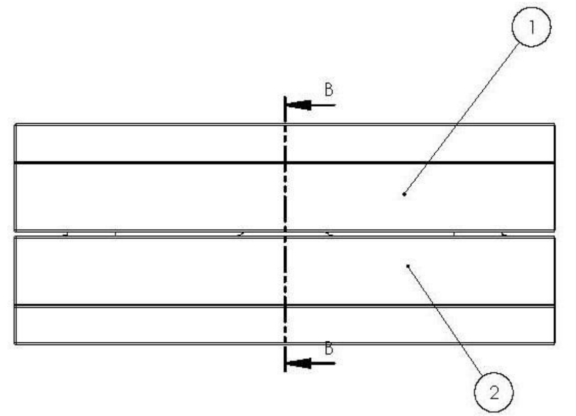
THIRD ANGLE PROJECTION

ITEM NO.	DESCRIPTION	PART NUMBER	QTY.
1	wishbone female mould	SEM2016_JB_DTL_001	1
2	wishbone male mould	SEM2016_JB_DTL_002	1
3	guide pillar	SEM2016_JB_DTL_006	3
4	guide bush collar	SEM2016_JB_DTL_007	6
5	WDS 9002-25050	WDS 9002-25050	6
6	M6 x 16mm cuontersunk screw	RS 171-893	18
7	center pin	SEM2016_JB_DTL_008	1
8	6mm dowl pin	RS 270-647	12
9	8mm dowl Pin	RS 270-675	1





SECTION B-B



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B4 7ET
UNITED KINGDOM

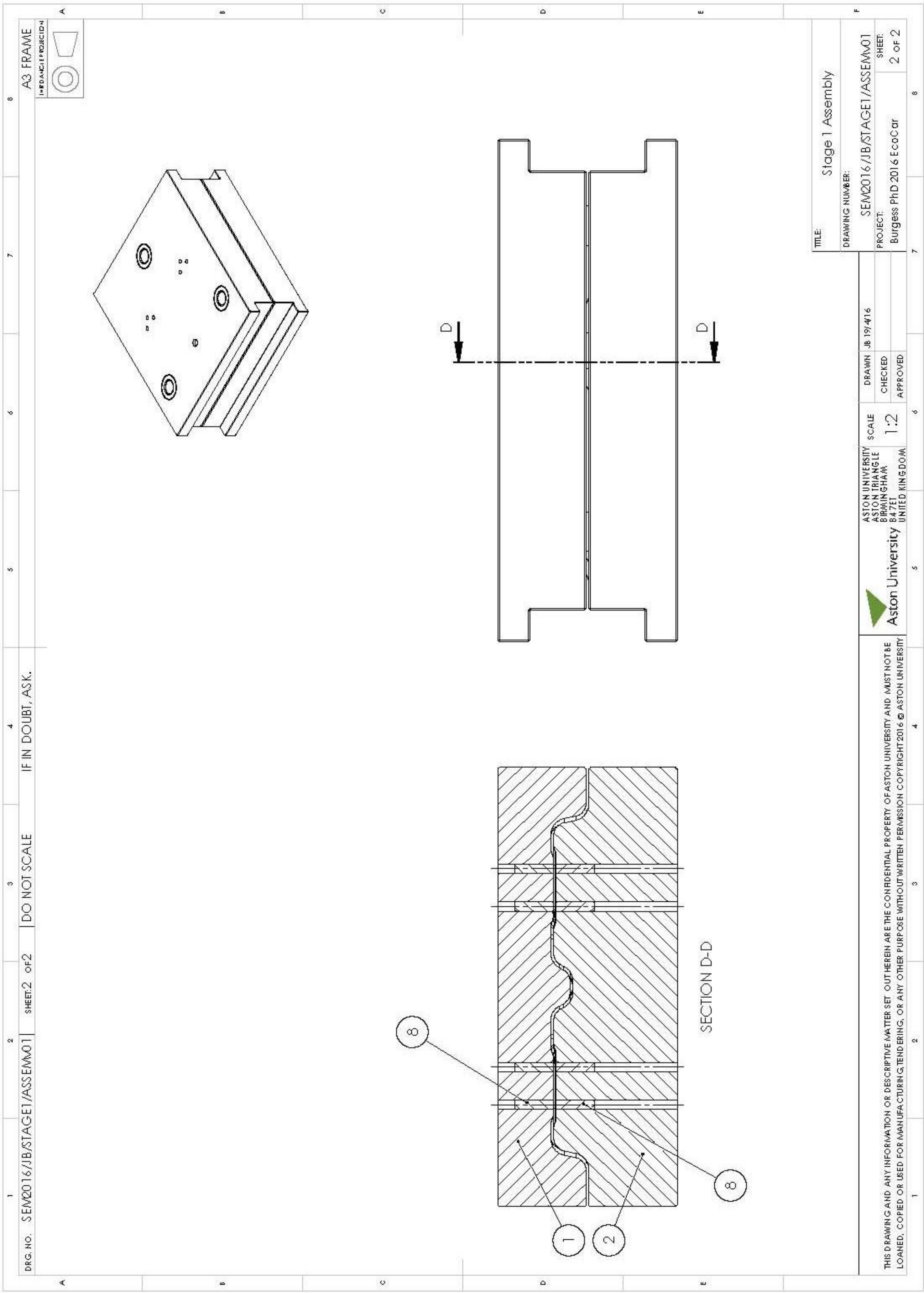
SCALE	DRAWN	JB 19/4/16
1:2	CHECKED	
	APPROVED	

TITLE: Stage 1 Assembly

DRAWING NUMBER: SEM2016/JB/STAGE1/ASSEMv01

PROJECT: Burgess PhD 2016 EcoCar

SHEET: 1 OF 2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IF IN DOUBT, ASK.
D
D
SECTION D-D
8
8
1
2
TITLE:
Stage 1 Assembly
DRAWING NUMBER:
SEM2016/JB/STAGE1/ASSEM/01
PROJECT:
Burgess PhD 2016 EcoCar
SHEET:
2 of 2
SCALE
1:2
DRAWN JB 19/4/16
CHECKED
APPROVED
Aston University
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ASTON TRIANGLE
BIRMINGHAM
B4 7ET
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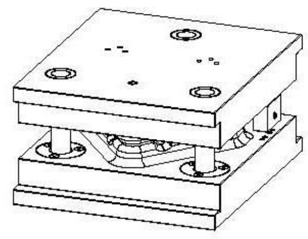
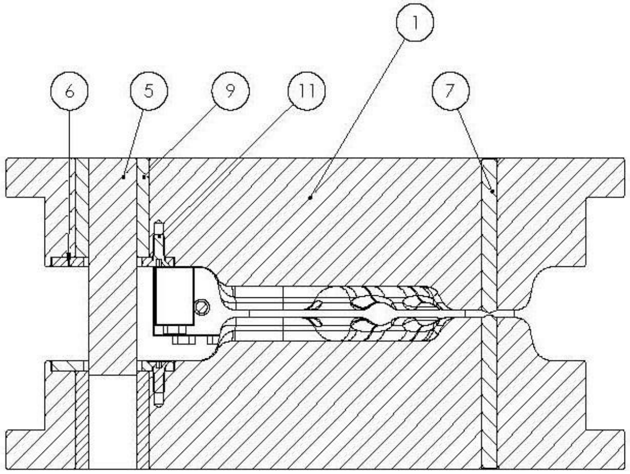
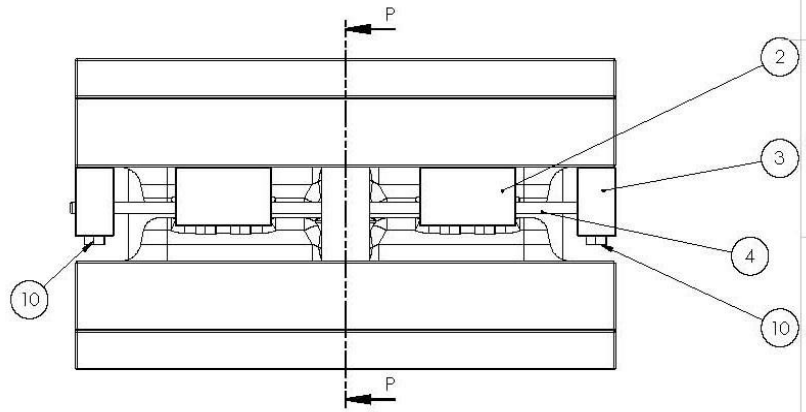
DRG. NO. SEM2016/JB/STAGE2ASSEMv01 | SHEET 1 OF 2 | DO NOT SCALE | IF IN DOUBT, ASK. | A3 FRAME

ITEM NO.	Description	Part Number	QTY.
1	wishbone male mould	SEM2016_JB_DTL_002	2
2	positioning guide post	SEM2016_JB_DTL_003	2
3	pivot guide post	SEM2016_JB_DTL_004	2
4	pivot guide	SEM2016_JB_DTL_005	1
5	guide pillar	SEM2016_JB_DTL_006	3
6	guide bush collar	SEM2016_JB_DTL_007	6
7	center pin	SEM2016_JB_DTL_008	2
8	24mm pararelel dowl pin 6mm diameter	RS 270-647	20
9	Guide Bush	WDS 9002-25050	6
10	45mm M6 hex bolt	RS 279-559	8
11	M6 x 16mm cuontersunk screw	RS 171-893	18





SECTION P-P
SCALE 1 : 2



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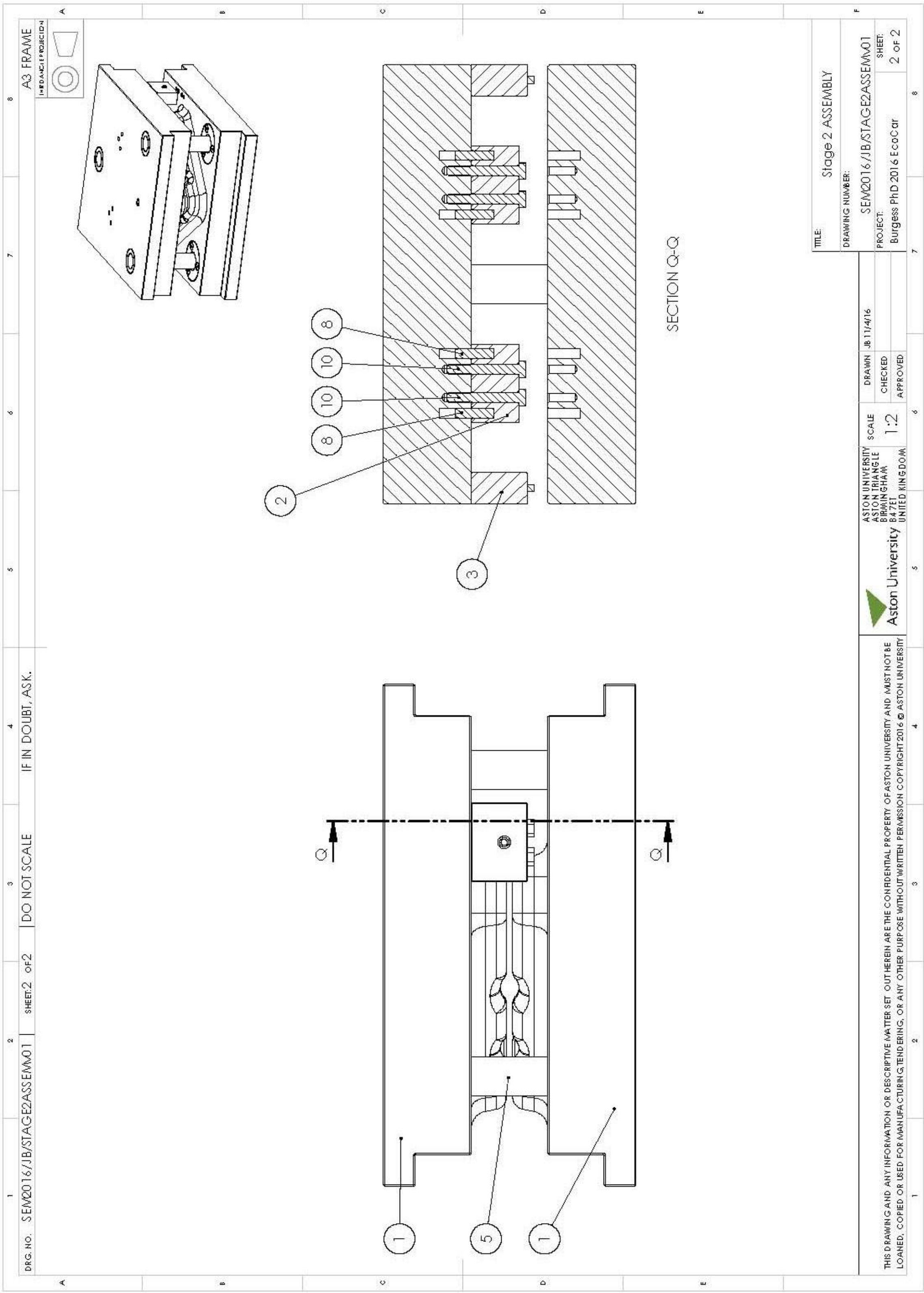
SCALE	DRAWN	JB 19/4/16
1:2	CHECKED	
	APPROVED	

TITLE: Stage 2 Assemlby

DRAWING NUMBER: SEM2016/JB/Stage2ASSEMv01

PROJECT: Burgess PhD 2016 EcoCar

SHEET: 1 OF 2



A3 FRAME
THIRD ANGLE PROJECTION
DRG. NO. SEM2016/JB/STAGE2ASSEM01
SHEET 2 OF 2
DO NOT SCALE
IF IN DOUBT, ASK.
SECTION Q-Q
Q
Q
1
5
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2
3
8
10
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8
TITLE:
Stage 2 ASSEMBLY
DRAWING NUMBER:
SEM2016/JB/STAGE2ASSEM01
PROJECT:
Burgess PhD 2016 EcoCar
SHEET:
2 OF 2
SCALE
1:2
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