BRAUN

TUDelft

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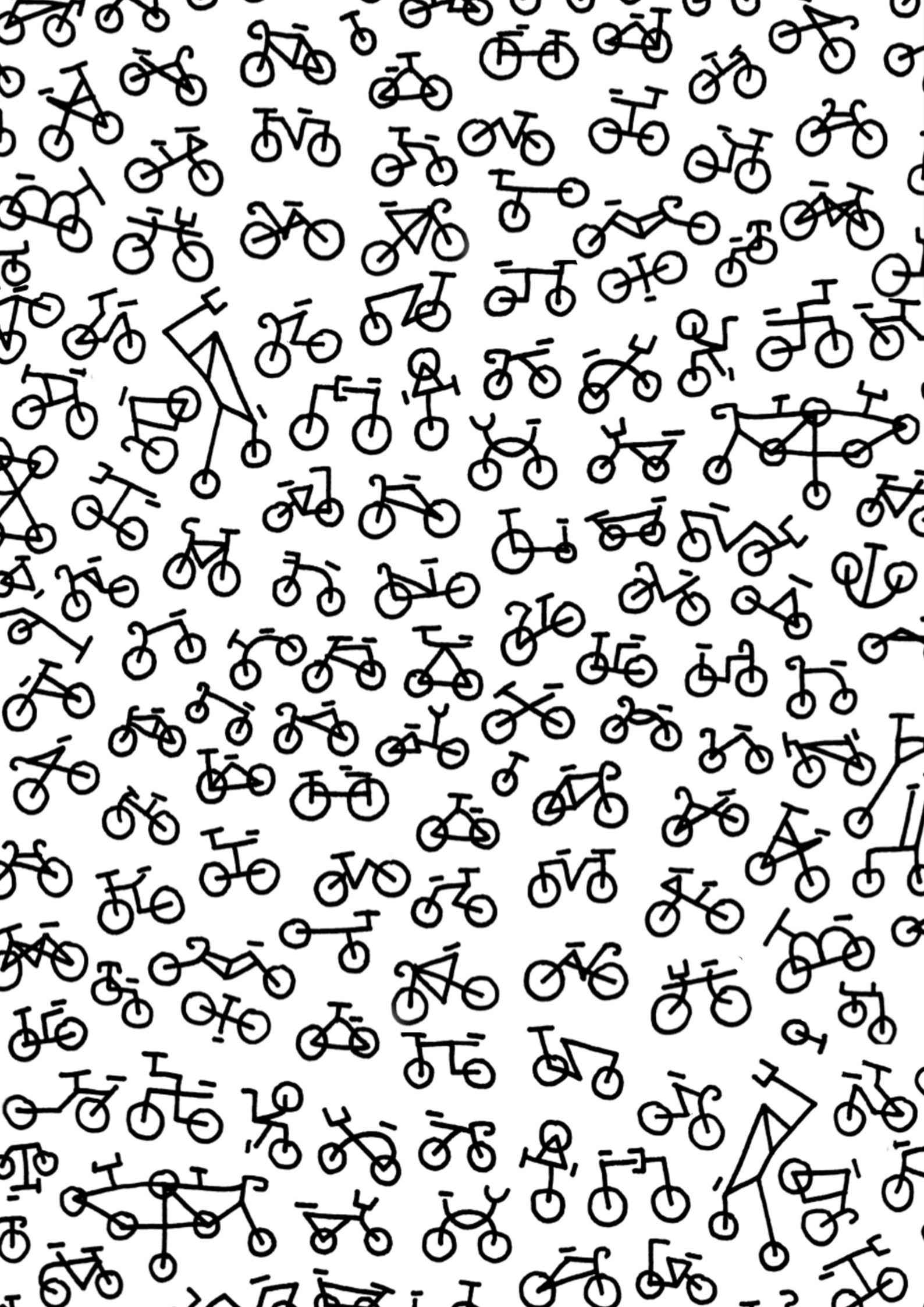

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Executive summary

Problem
The past two decades, the road race cycling industry has been changing faster than ever. Innovations in material and production methods have changed the face and performance of the road race frames drastically. Custom frames are mostly built out of metal-alloys, as this material is easier to work with than carbon material. Virtually, all metal-alloy frames are made out of tubes that are welded together to form a classical diamond frame. The classic diamond frame tube-look has been around for decades. This unchanged look makes the modern metal-alloy road race bicycle easily comparable to heavy and cheap frames from the past.

Braun-cycling has been around for over 40 years and builds custom metal-alloy road race bicycle frames. For a long time, the business has been going well. Braun was selling bicycles to a lot of amateur cyclists and even ex-professional cyclists. However, the company has seen a decrease in sales over the last couple of years, as its market slowly gets saturated. Switching to another radically different manufacturing material for the frame is not an option, as all the knowledge, and machinery is specific for the metal-alloys building process. This is why there should be opted for other solutions.

Analysis
The (non-professional) road race bicycle industry is a multi-million dollar industry, with over 679.200 active cyclists in the Netherlands alone. The consumer group can be split up into four target groups: the image-builder, the adventurer, the fanatic, and the purist. The current consumer-group of Braun-cycling consists mostly out of purist cyclists.

There is a growing interest in the cycling lifestyle. This creates a market with a more conservative way of cycling. The purist cyclist group and the cycling lifestyle group are the new focus groups of Braun-cycling. There is a lot of overlap between the existing consumer group (purist) and the new lifestyle group. To penetrate the created market of the lifestyle group whilst maintaining a grip on the old market, a new product is introduced. This product combines the classical methods and knowledge of Braun with cutting edge technology. This product has the goal to overcome biases and negative emotions associated with metal-alloy bicycle frames.

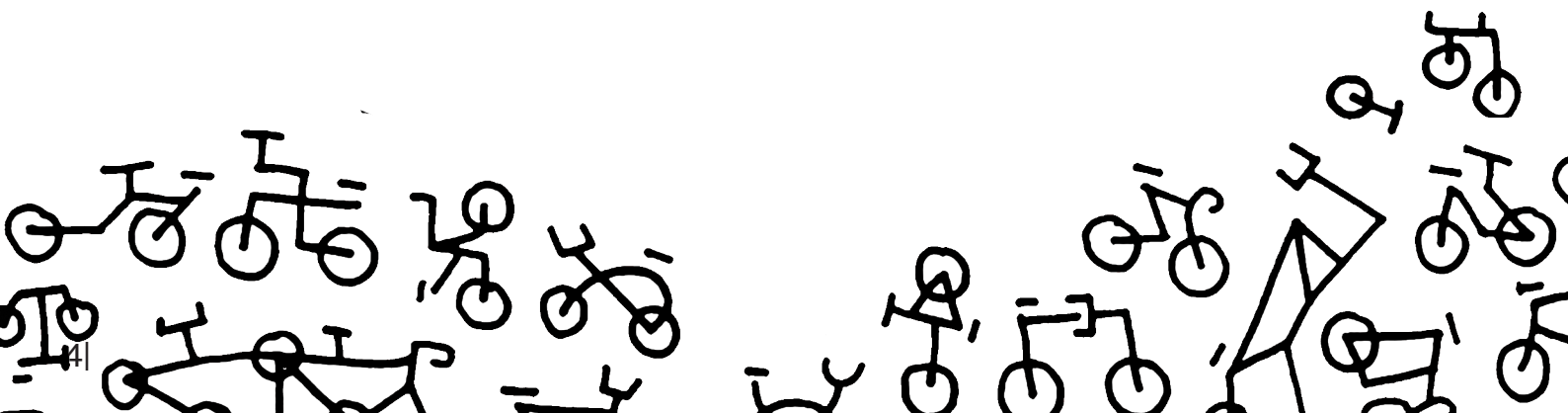


Fig1:*Herman Braun assembling a bicycle at the Braun cycling workshop*

Solution

In the competitive road race-cycling sport, having a frame that is lighter and more aerodynamic, grants a competitive advantage. If we look at the market, the lighter and more expensive bicycles are made from carbon, where as the cheaper models are made out of metal-alloys. This makes the consumer biased towards metal-alloy frames, this is mostly based on the weight of the bicycle. Concluding this, the choice is made to focus on making the product look and feel lighter, compared to a conventional (custom) frame. To make this optical and physical change in weight, the connection points (lugs) in between tubes are chosen as a platform. Using the new lugs in frames improves production speed, whilst maintaining conventional production knowledge and technologies. A new lug has the opportunity to make a frame lighter and stiffer compared to a frame without lugs made out of the same material.

The new lugged bicycle frame is made out of Titanium. Braun-cycling has already worked with titanium in one of their previous models. This titanium model served as the geometrical blueprint for the new lugged bicycle. The geometry of the titanium bicycle is the classic diamond shape Braun-cycling geometry. The frame is made out of multiple titanium alloys, grade nine for the tubes, grade five for the lugs. The lugs are created using selective laser melting, one of the production methods used in metal additive manufacturing. Grade five titanium is, at the moment, the only commercially available titanium alloy that is printable. Titanium grades nine and five are very comparable and weldable, thus making them suited for the production of the new bicycle.

The frame lugs have been made with a topology optimisation method. Topology optimisation software is a new design tool that can calculate the minimal amount of mass of a product whilst maintaining maximal strength. Besides having a performance enhancing effect, the topology optimisation could also help in giving the metal-alloy a new unique shape. The extreme shapes of the topology optimisation have been translated into a more approachable and safe product for the final frame.

Fig2: *Render of the assembly of the custom made titanium Hone bicycle frame. The lugs of the frame are made with topology optimisation technology.*

Method

The Delft innovation model (Buijs, 2012) (Fig 3.) depicts a methodology that is applicable to most 'normal' design processes. This model uses the three pillars of industrial design (technology, human interaction and business) to offer a solid structure for a project. Despite being the correct structure, the Delft innovation model is not totally applicable to this assignment, because, after the analysis phase the choice was made to work and design using topology optimisaition (TO) software. The resulting design structure can bee seen in Fig 5.

Topology software needs to have a lot of input before it can be used. This requires early decisions in the design process. The choices that need to be made can be seen as setting boundaries for the topology software to operate within. Now if we describe the TO input as boundaries, we can suddenly see the comparison to the Material driven design method of Elvin Karana (2015) (Fig 4.). This method first lets the designer play with the materials, researching what the properties of the material are. After this, a suited set of boundaries is formulated to design a new product.

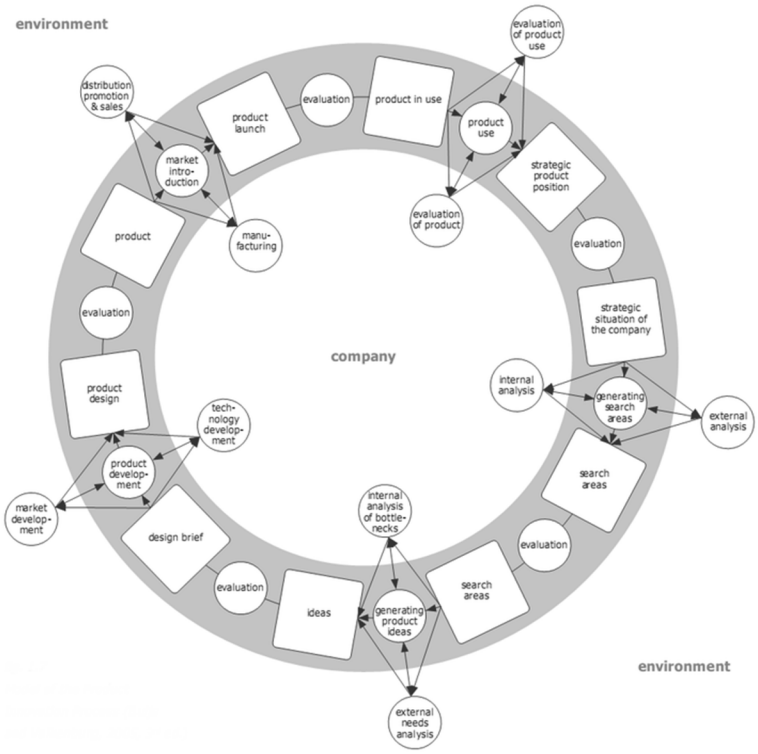
The software that was used was new to me. So I needed to play with the software, figuring out what the restrictions of it were, and what or what not to do when designing a bicycle. This is a new way of designing a product.

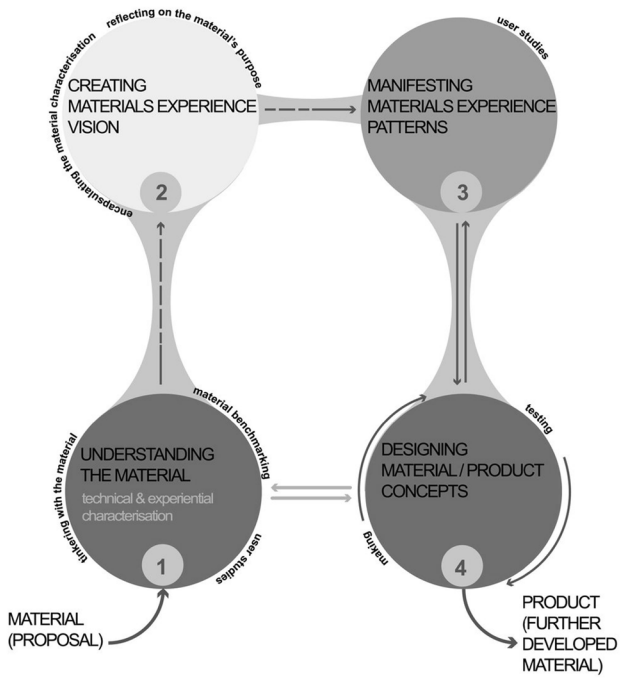
The designer as a bridge between the human who has the knowledge and the computer who creates.

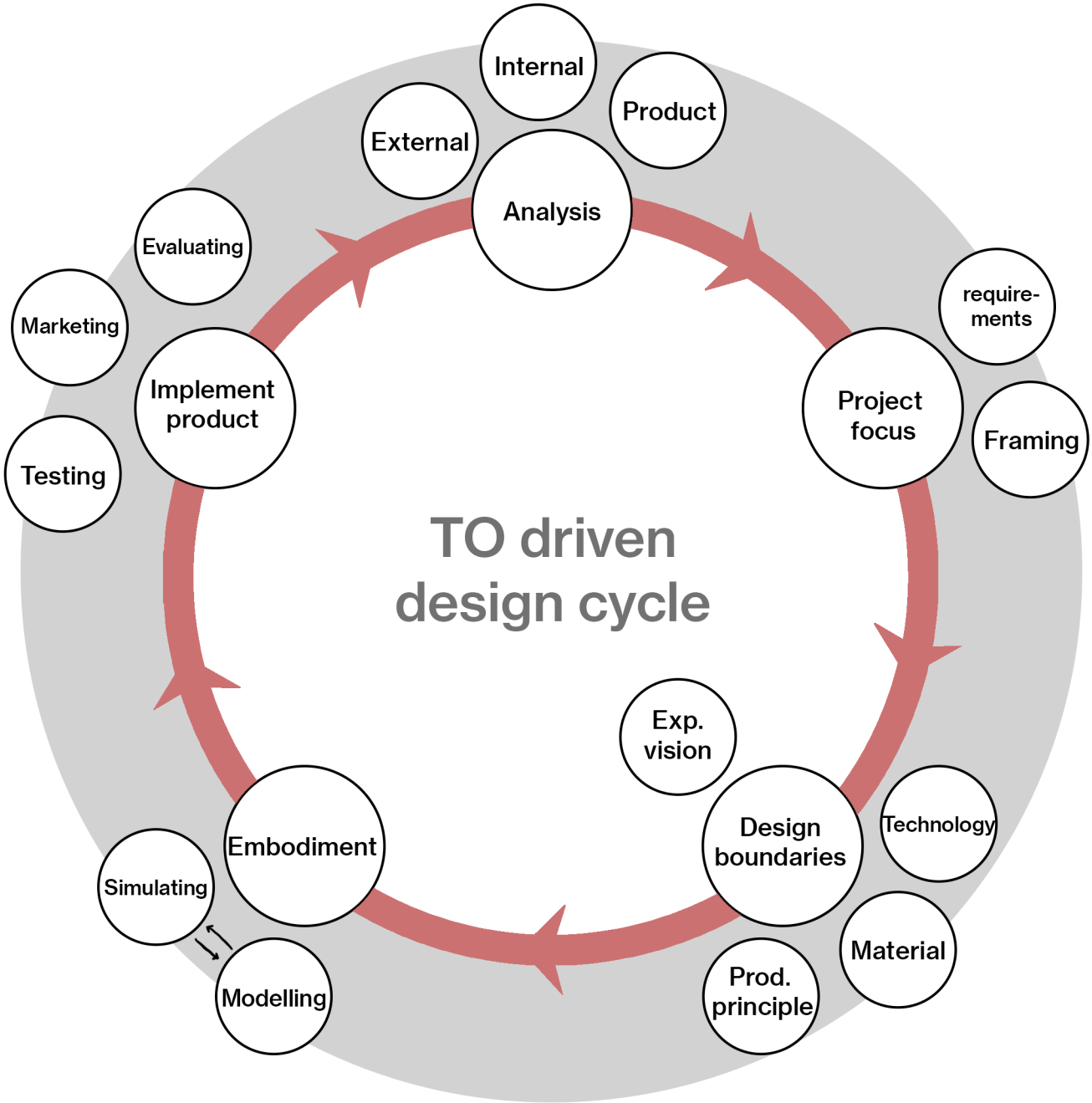
The analysis was done to figure out what the requirements of the company and the user were. The project scope was limited to reduce the quantity of outcomes. Limitations needed to include the needs and wishes of the consumer and company and in addition, were subject to the limitations of the software used. The design boundaries were determined by the requirements and the limitations of the project scope. These boundaries were then used as a starting condition for the topology optimization process. The steps of modelling and simulating give a short feedback loop, which makes creating product iterations at a high pace possible.

When the requirements were met and the generated topology shapes were satisfactory, the step was made to move further into the design cycle. The final design steps are again based on the Delft Innovation Method. Marketing strategy, final testing and production have been included in this project.

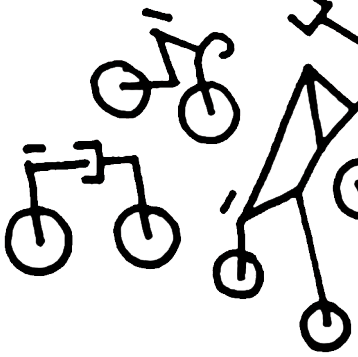
Fig3: *(Top left) Delft innovation model of Jan Buijs (2012)*
Fig4: *(Top right) Material driven design method Elvin Karana (2015)*
Fig5: *(Bottom) TO driven design cycle the method created and used for the design of the Hone bicycle. This method is a combination and alteration of the methods of Buijs and Karana.*


environment
company
evaluation of product use
distribution promotion & sales
product launch
evaluation
product in use
product use
market intro-duction
strategic product position
evaluation of product
manu-facturing
product
evaluation
evaluation
strategic situation of the company
product design
internal analysis
generating search areas
external analysis
tech-nology develop-ment
product develop-ment
search areas
market develop-ment
design brief
internal analysis of bottle-necks
evaluation
evaluation
ideas
generating product ideas
search areas
external needs analysis
environment


reflecting on the material's purpose
user studies
CREATING MATERIALS EXPERIENCE VISION
MANIFESTING MATERIALS EXPERIENCE PATTERNS
encapsulating the material characterisation
2
3
material benchmarking
testing
UNDERSTANDING THE MATERIAL
technical & experiential characterisation
DESIGNING MATERIAL / PRODUCT CONCEPTS
interacting with the material
user studies
making
1
4
MATERIAL (PROPOSAL)
PRODUCT (FURTHER DEVELOPED MATERIAL)


Internal
Product
External
Analysis
Evaluating
Marketing
Implement product
Testing
require-ments
Project focus
Framing
TO driven design cycle
Exp. vision
Design boundaries
Technology
Material
Prod. principle
Embodiment
Simulating
Modelling

1. Analysis



What drives people to cycle for over 100 kilometres without a destination? What makes people spend thousands of euros on bicycles and equipment? Why are some many people in the Netherlands enthusiastic about road race cycling? To design a good product the designer must truly understand the emotions and drive of the consumer. To do so an analysis is done to get a better view of the assignment for Braun-cycling and the industry of road race cycling, see Fig 7. This analysis was done by researching the company, the context, user groups, trends and other stakeholders that have anything to do with the road race cycling sector. The information that is gathered from the analysis is used as a basis for the design of the new bicycle for Braun-cycling.

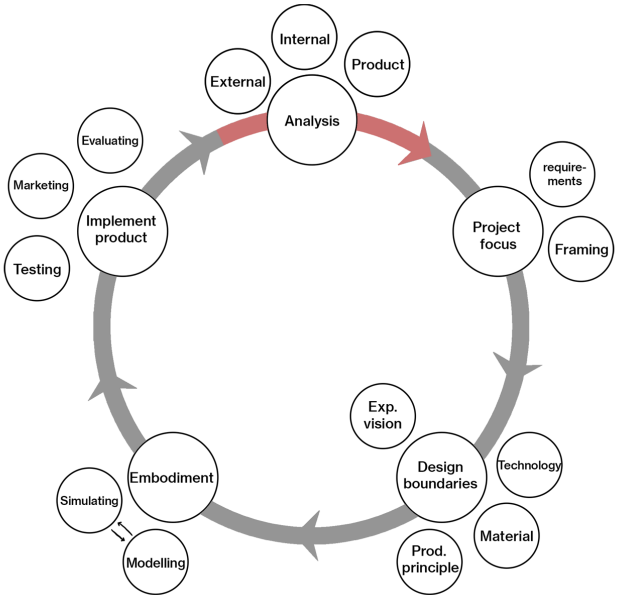


Fig6: *(left) A professional cyclist in agony after a long race.*
Fig7: *(right) The focus of chapter one based on the TO driven design cycle.*

1.1 Braun-cycling

Braun cycling is a company that builds tailor-made, custom bicycles. The small brand is family owned and run by Herman Braun and his son Dave Braun. Located in the province of Zuid-Holland, the company is a well-known brand within this region. Herman and Dave believe that a road race bicycle should not only be fast, but also comfortable and made to last. These principles are reflected in the classical diamond shaped frames made out of the traditional bicycle material: steel.

Herman Braun

Herman is the founder of Braun cycling. Most of the time, he takes care of the bicycle assembly and customer services. During his years of working as a mechanic, Herman gathered an unimaginable amount of knowledge on bicycles. The mix of the feedback from professionals, the hours of tweaking the frame geometry and the vast amount of bicycles he built, gave Herman an almost instinct driven building method. 'Knowledge by vast amounts of experience' is a phrase that fits Herman Braun best.

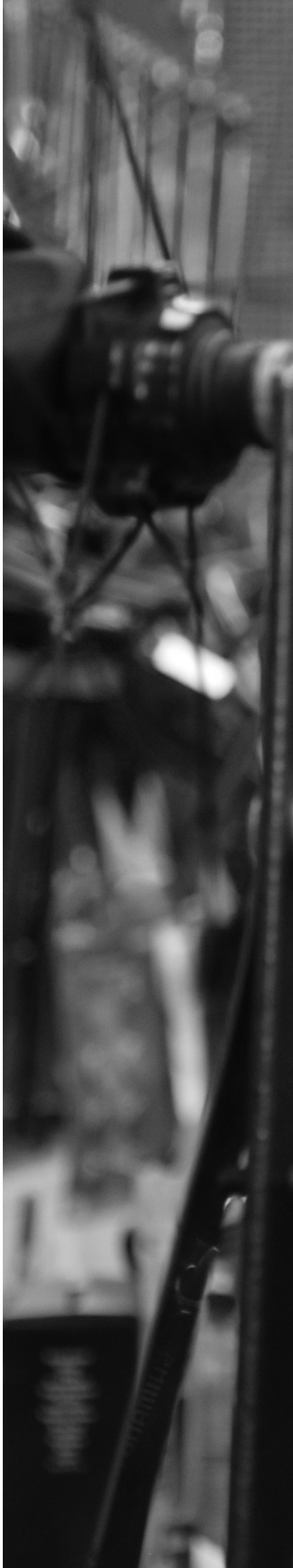


Fig8: *Herman Braun placing and checking the exact position and alignment of the spokes in a wheel*

Dave Braun

In 2010, the son of Herman, Dave Braun, entered the company. Being educated as a welder, it seemed a logical fit that Dave became the builder of the frames at the Braun company. Dave strives for perfection in his work and does so in a very tidy and orderly fashion. Every step in the building process of a frame is carefully written down in multiple books by Dave. Normally, manual labour has its freedoms that give room for creativity but, more importantly, room for mistakes. However, the workflow of Dave, following his workbooks, guarantees that everything that is done by hand is made to perfection.

Fig9: *Dave Braun milling a bicycle tube to the exact length for a custom steel bicycle frame*

Working with metals

Steel and other metal-alloy road race bicycle frames are surrounded by prejudice and seemingly disadvantages (heavy, slow, cheap, flimsy). Still, the Braun-cycling company makes custom metal-alloy frames that are in no way old-fashioned or second-grade.

Someone unfamiliar with road race cycling and the Braun-cycling company might ask why Braun cycling does not change its bicycle frame material, mainly due to all of the developments that have been made in carbon. If we look at other tailor-made road race bicycle frame companies, we can see that a lot of them are working with metal alloys, but why? Milling tubes of steel and welding them together to make a frame is much faster than layering carbon-fibre sheets, putting them in an oven, etc. This makes the production of a metal-alloy frame less costly than a carbon frame. The stacking of the carbon layers is a precise and critical job. Doing it wrong will lead to a faulty material structure and could cause frames to break very easily. This makes creating metal-alloy frames much more suitable for a small market in which every order is in a different size. That is why many custom frame builders still work with metal-alloys.

The knowledge of Braun-cycling behind the bicycle as it is right now is something that has been evolving over countless custom frame productions. Up to the point that there is 40 years worth of knowledge invested in perfecting the geometry. All of the knowledge and production methods of Braun are based and perfected on building with metal-alloys. Many ex-professional cyclists ride the custom frames of Braun. There are even stories of Braun frames that are badged over with competitor logos, which are then used in pro-competitions and championships.

If Braun-cycling would change the frame material, a whole new production technique needs to be created and optimised. To create such a technique would be time-consuming and costly. The strength and uniqueness of the Braun-cycling company are its 40 years of knowledge and experience, the strength of the company will go unused when switching to new materials. Next to the unused company strength, we could also note something else. There is a potential demand for metal-alloy road race bicycles. The metal-alloy bicycle makes for a very versatile bicycle as, the material is less fragile and delicate than carbon. Looking at big bicycle retailers like Mantel.com, it could be concluded that carbon bicycles are often built with one goal: either climbing, time trial or long distance riding. This is shown by the separate categories of time-trail, tour and climbing bicycles. A bicycle that is optimised for one goal is very suitable for professional ‘sponsored’ cyclists as they need to perform at the highest level and do not pay for the bicycle themselves. As more people around the world focus on becoming more sustainable, it is relatively easy to create a platform for a more multifunctional bicycle. This development could create a bigger market for a metal-alloy bicycle.

Fig10: *Herman Braun, mitering the chain-stays of a custom steel bicycle to make an precise before welding the chainstay to the bottom bracket*

Conclusion 1.1

Braun-cyclings' strength lies in making custom metal-alloy frames. The frames are made with a time-tested and optimised classic geometry that is seen as a signature of Braun-cycling. With metal-alloy production as its core strength and the whole company revolving around metal-alloys, it could easily be concluded that switching to carbon is not a viable option. A switch to carbon would lead to increased production costs and times and could even lead to overall product quality drops, as the material is very prone to building errors. The latter, as the product quality is one of the focal points of Braun-cycling, would be devastating. This is why no big changes can or should be made to the bicycle. The new product will be designed so it can be made within the existing knowledge and methods of the Braun-cycling company.

Fig11: *(left) The head tube, down tube and top tube mitered and placed into the frame jig, ready to be welded. Braun-cycling always ensures the tubes fit exactly together before they are welded together, this to ensure an as strong as possible weld.*
Fig12: *(right) A figurative example of Braun cycling selling their metal-alloy frames to the consumer.*

1.2The Road-race cycling industry

With the company being analysed, it is time to look further into the cycling industry and its context. This part, widening the scope of the research, is called the context analysis. The context analysis is split up into two parts. The user analysis, done by interviews, literature research and trend analysis, and the stakeholder analysis, done by literature research and interviews done at different bicycle companies in Italy.

The road-race cyclist market in numbers

The Netherlands counts 679.200 active road race cyclists. That is more than the total amount of inhabitants of Rotterdam (614.000). This incredibly large number of cyclists makes up for a staggering 4.9% of the 18+ population of the Netherlands. 80% of this group of cyclists is male, but it must be acknowledged that the female road race cycling group has steadily been steadily growing over the last years. The average age of the road cycling enthusiast is 49 (2017). Back in 2014, the average age was 43 years, and 45 and 46 years in 2015 and 2016 respectively. These results were obtained from the research of the NTFU in 2016,2016 and 2017.

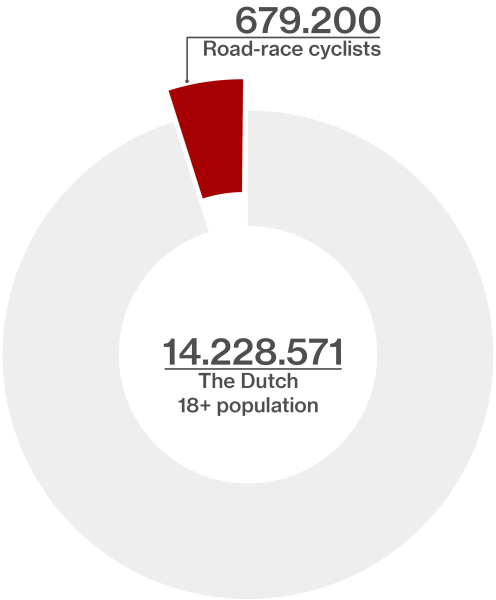


Fig13: *A graph of the Dutch population and the ammount of road-racing cyclists.*

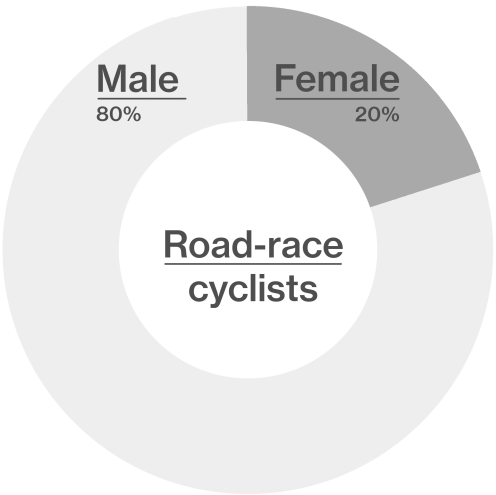


Fig14: *A graph of the division of men and women in the Dutch road-race cycling industry.*

Market segmentation

To get a better view of the consumer market of the road race cyclist, field research and a literature study was conducted. The field research was done via open interviews on location at 'Fausto bike & coffee' in Schoonhoven and over the telephone. The information gathered from the conversations with Janluc Coenen (owner of Fausto) and twelve other bicycle enthusiast was clustered and further processed to form groups.

The first thing that stood out from the start was the clear divide between the progressive and conservative cyclist. The progressive cyclist tends to have a big (almost obsession like) interest for the newest gear, having marginal gains in weight and performance of products and are always up-to-date on the newest trends and product developments. The conservative cyclist is either really slow or even non-adaptive to new technology and trusts the time-tested technologies that have been available for many years.

The second divide that can be made within the road race cyclist group is one of the intrinsic motivation of the cyclist. There are two extremes within this division, the experience cyclist and the performance cyclist. The experience cyclist rides his bicycle purely for the personal experience of cycling; being outside, the struggle against the elements (wind and rain) and the rewarding feeling after a long day of cycling. The performance cyclist is focussed on the race; improving time, being faster than peers and showing to the world how fit he/she is.

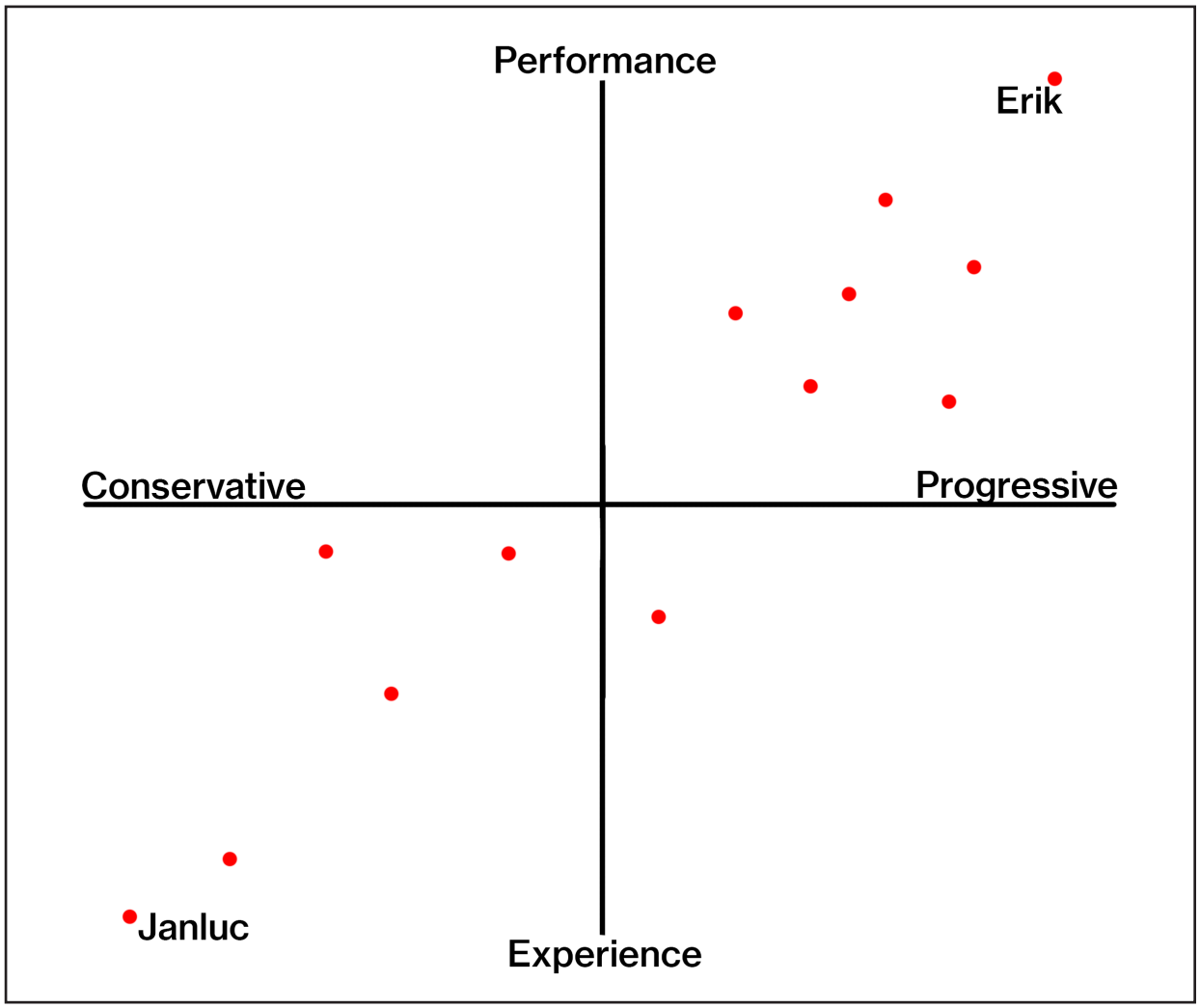
Fig15: *Fausto bike and coffee in the small village of Schoonhoven. This is a gathering spot for a lot of cyclists to talk about bicycles and the cycling life. This was the location of a lot of interviews of this study.*

Market segmentation graphs

If these divisions are placed on an axis, a chart can be made. In this chart, the interviewed cyclists are placed, based on their behaviour, attitude towards innovation and their intrinsic motivations of cycling. Figure 16 shows the chart with the interviewed cyclists shown as red dots.
Two things can be quickly noticed when looking at the chart. The first being the two most extreme cyclist, Janluc the owner of Fausto and Erik, a regular customer at Fausto. Janluc solely cycles for the pleasure of cycling itself, the struggle against the elements or the 'heroism' of cycling, as he would say himself. Janluc cycles on a fairly low-cost, standard, perfectly maintained, steel confection bicycle. Erik cycles for the high speed and performance, together with a group, or challenging virtual friends on Strava (online bicycle platform). Erik has the highest price segment, aerodynamically optimised, carbon, BMC Timemachine bicycle.

The second thing that can be noticed is the lack of red dots at the top-left and bottom-right of the chart. The lack of dots can be explained due to the fact that road race cycling is by definition a competitive sport. From this, we can conclude that innovations that enter the market are almost always (directly or indirectly) based on improving cycling performance.

Fig16: *Graph containing the interviewees and their stance towards cycling performance and the adoptability of new products. A clear correlation can be seen in being progressive and more performance minded compared to being more conservative and experience minded.*



The NTFU (Nederlandse Toer Fiets Unie) performs a yearly road race cyclist survey with 59.000 participants. This survey states that the consumer group of the road race cyclist can be divided into four different groups. The four groups; the adventurer, the fanatic, the free-cyclist and the purist, have been created by clustering the cyclists based on their buying behaviour, cycling motivation and habits. The fanatic is the most performance driven and buys the newest technology to get the best results. The adventurer participates in more types of (cycling) sports (mountain biking, running) and likes new technology, but uses it to broaden his horizon by doing and experiencing new things and places. The free cyclist cycles to stay fit and active and does not set high goals. The purist cycles for the experience and buys high-quality products that last a long time. For more information about the groups, their background and more definitions look at app.H (NTFU, 2017).

The groups from the survey of the NTFU are placed on the same axis as the interviewed cyclists, this graph is shown in Fig.17. The same pattern as shown in Fig.16. is formed. From this pattern, it is easily concluded that the information obtained from the interviews has given enough insight to get a complete overview of the market segmentation.

Fig17: *The same graph as Fig 16. This graph contains the four groups of the study of NTFU. This graph confirms the correlation that has been found by the interviews of fig 16.*

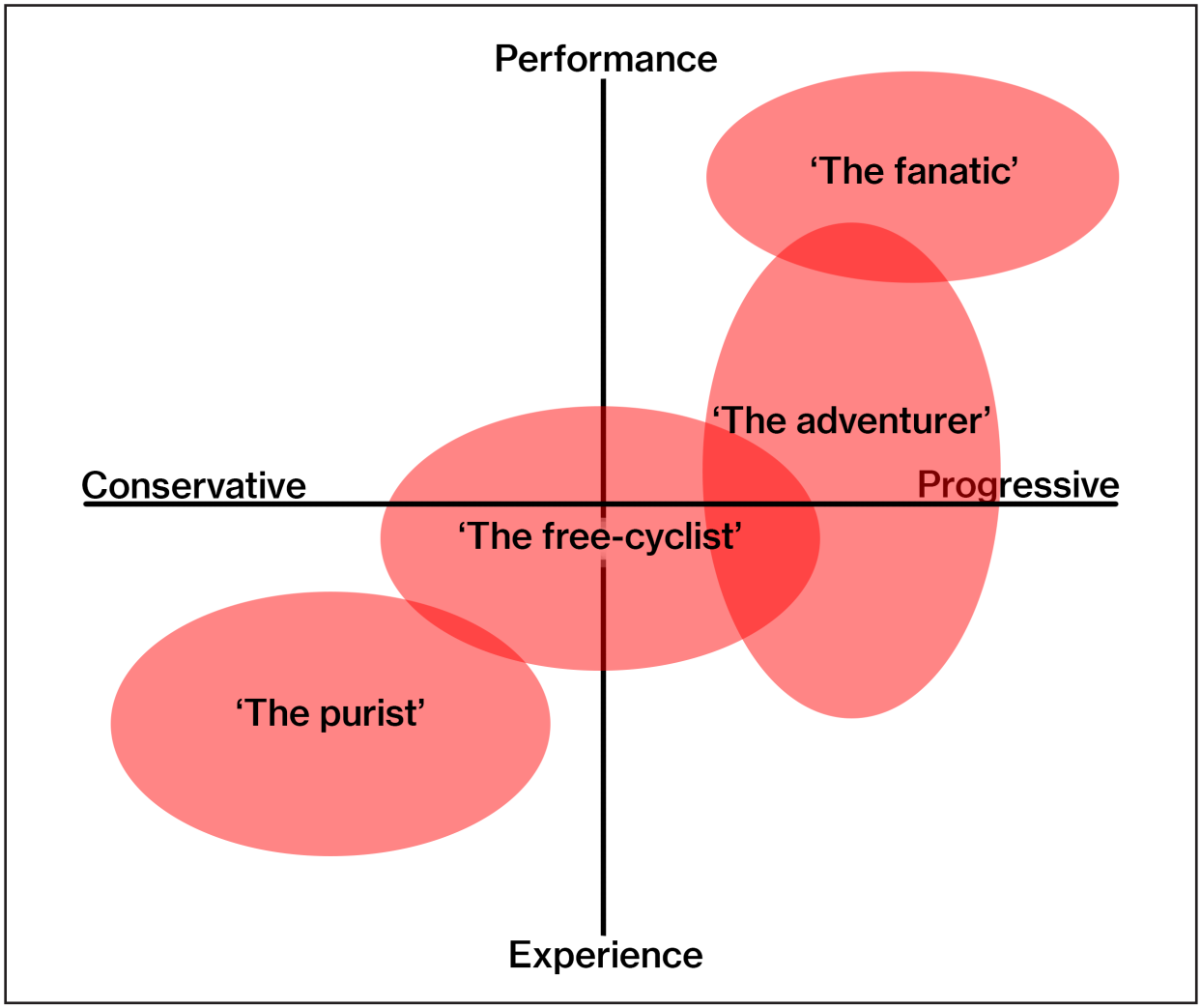


Fig18: *The proud owner of a custom made Braun bicycle.*

The Braun cyclist

Current situation
The consumer that currently rides Braun bicycles is mostly categorised in the purist group. This can be concluded by the overlap created from the interviewed braun cyclists and the purist group. This is shown in the chart in Fig.19. The bicycles of Braun are custom made and thus higher priced than the conventional convection bicycle. The Braun cyclist buys a bicycle with the expectation that it lasts a long time. The material and geometry are conservative for a modern bicycle. This is why the product is very appealing to the purist, as it matches their needs and wishes. Besides these product characteristics, Braun also offers a social experience. Most of Braun's consumers visit the shop often for small maintenance or just a cup of coffee. During these visits, Herman tells stories about old race-days, pro cyclists, their personal problems or other mesmerizing stories. This often makes Braun cyclists life long customers.

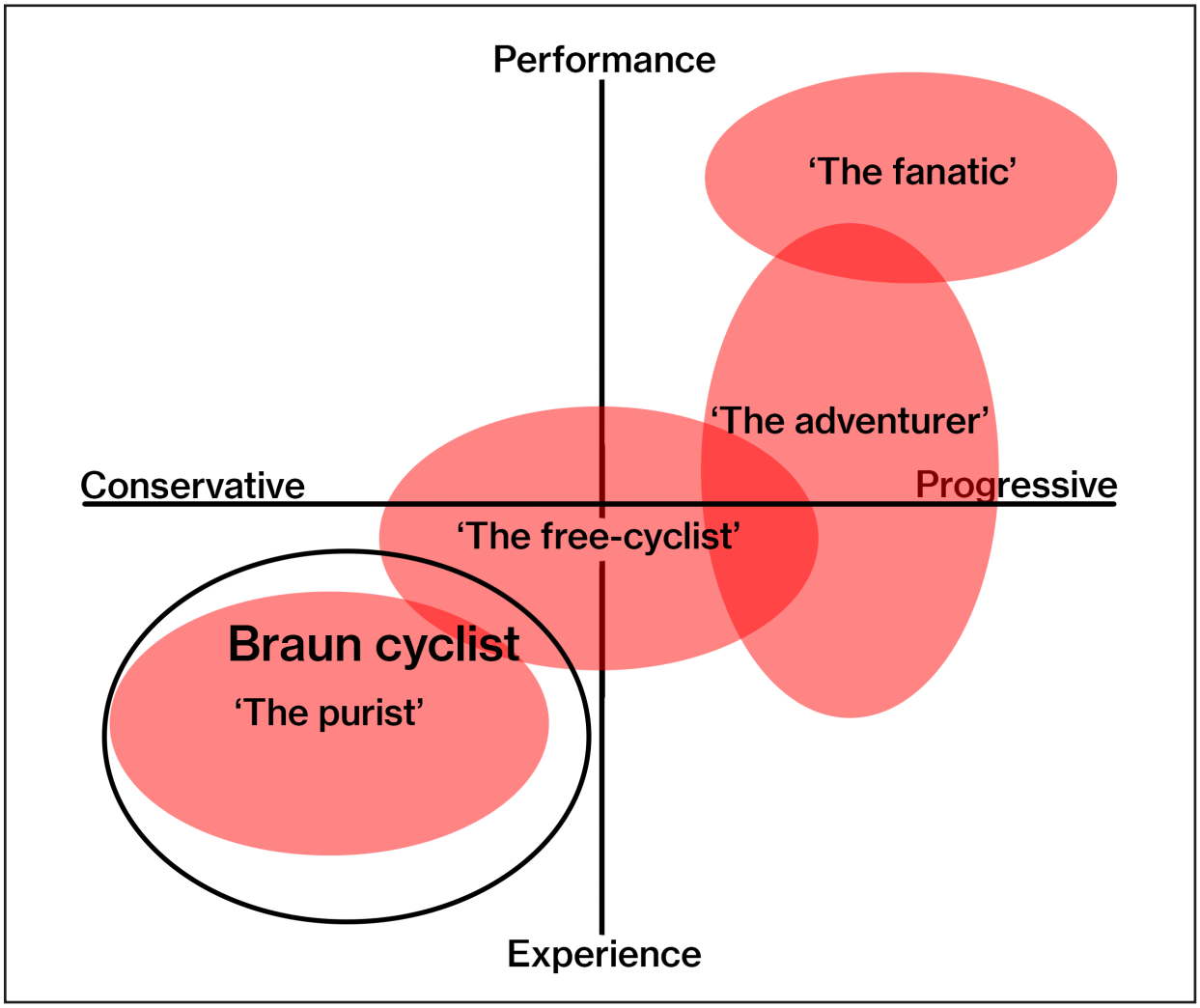


Fig19: *The location of the current Braun-cycling customer group described by a black circle. It can be seen that the current Braun-cycling group mostly consists out of the purist cycling group.*

The Braun cyclist

The Future

The current braun cyclists are getting older and the Braun-bicycles have such a long life span that the market around Braun is almost saturated. As a result, the sales of Braun cycling have slowly been dropping over the last year. Braun-cycling can have a tendency to keep looking at the past, as they have always been building for the top segment of the road race cycling industry. However, their current products are sold to the purist group. To obtain a higher sales number, a new market must be sought that could adopt the core values of the Braun-bicycle. Such a market can be found by looking at relevant trends and how the consumer market develops. To look for relevant trends a DEPEST analysis is performed for the road race bicycle industry and its context. Results of the analysis can be found in Appendix A. The two most valuable trends for the Braun-cycling company are described below.

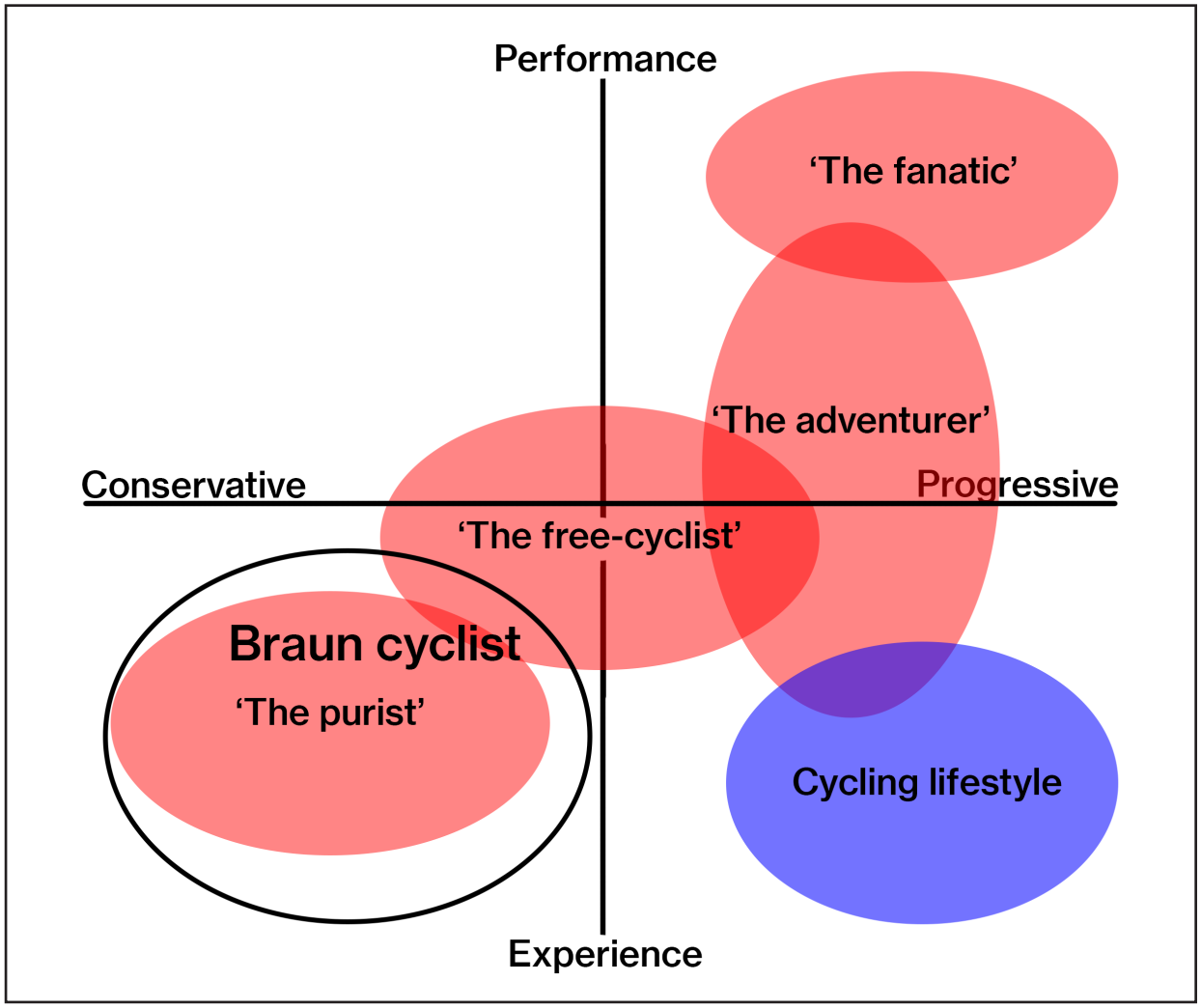
Cycling lifestyle

'The trend of nostalgia and the love for traditional products is one of the biggest trends of 2018/2019 and is here to stay' (Forbes,2019). A good example of the growth of this market is the bicycle brand Cinelli. Cinelli makes 'traditional' steel lugged bicycle frames that are painted in very flamboyant and 'trendy' colours. They have grown over the last years, not as a competitive cycling brand, but more as a fashion/design product. This brand uses the road race cycling industry not as a competitive sport but as a lifestyle. The use of nostalgic feelings works really well for the millennial consumer group. Forbes magazine says this can be exploited by letting the consumer associate the brand with positive references from the '90s, '80s and even '70s. Doing so will show the consumer that they can relate to the brand, which is something forgotten in the age of impersonal digital media (Friedman,2019). Building a social connection to the brand and product (material) through nostalgia, is an argument for Braun-cycling to stay on the route that they are.

Fig20: *(left) A woman and her vintage bicycle posing for a photo.*
Fig21: *(right) A man sitting on his vintage bicycle as a commercial for a swedish custom bicycle brand.*

If we place this movement/group in the chart that has been used for the other cycling consumer groups, something interesting happens. The lifestyle consumer movement does not cycle for the speed or performance of the sport. So, an easy conclusion that could be drawn is that the group can be placed in the lower region of the chart. If we look at the conservative/progressive chart, an interesting topic arises. The group uses nostalgia as a statement in the modern era. This does not make the group conservative, it makes it progressive. As Friedman stated 'it is a way to get back to the simpler and positive vibes of the childhood of the consumer'. This does not make the lifestyle group conservative, as they use iPhones and are following the newest trend 'nostalgia' which is very progressive. This means that the lifestyle group can be placed in the lower right region of the chart. The placement of this group is very interesting, as the lifestyle group does not follow the pattern that has been made by the other groups. This gives the road race bicycle a whole new value/meaning and is a great opportunity for Braun-cycling.

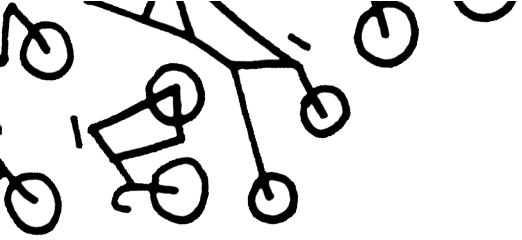
Fig22: *The new cycling lifestyle group lies outside of the 'normal' correlation of the sports minded groups. This makes for a really interesting target group for Braun-cycling.*



Unique

In the image building group, the competition to be unique and ride the 'best' and most expensive products is fierce. This trend is not only noticeable in the bicycle scene, but also in everyday life. All products come in multiple colours and sizes, an example of this would be the pod. We can also see examples of this in a large number of cyclists that let their new bicycle frames be custom painted or cyclists that look for unique coloured shoes, shirts and helmets. There lies an opportunity for Braun in this matter. Modern (carbon) bicycles have more integrated parts than the original metal-alloy bicycle. This is done to improve aerodynamics, but also to boost sales, as some frames have parts that only fit on that specific bicycle. This makes modern frames become less and less customizable. A product that exploits the unique characteristics and production techniques available for metal-alloys has the potential to be in high demand, whilst maintaining the customizability of the original frames.

Fig23: *The ass saver detachable road-race bicycle fender. These fenders are being sold in a wide variety of colours and prints making them fit to the unique style of the consumer.*



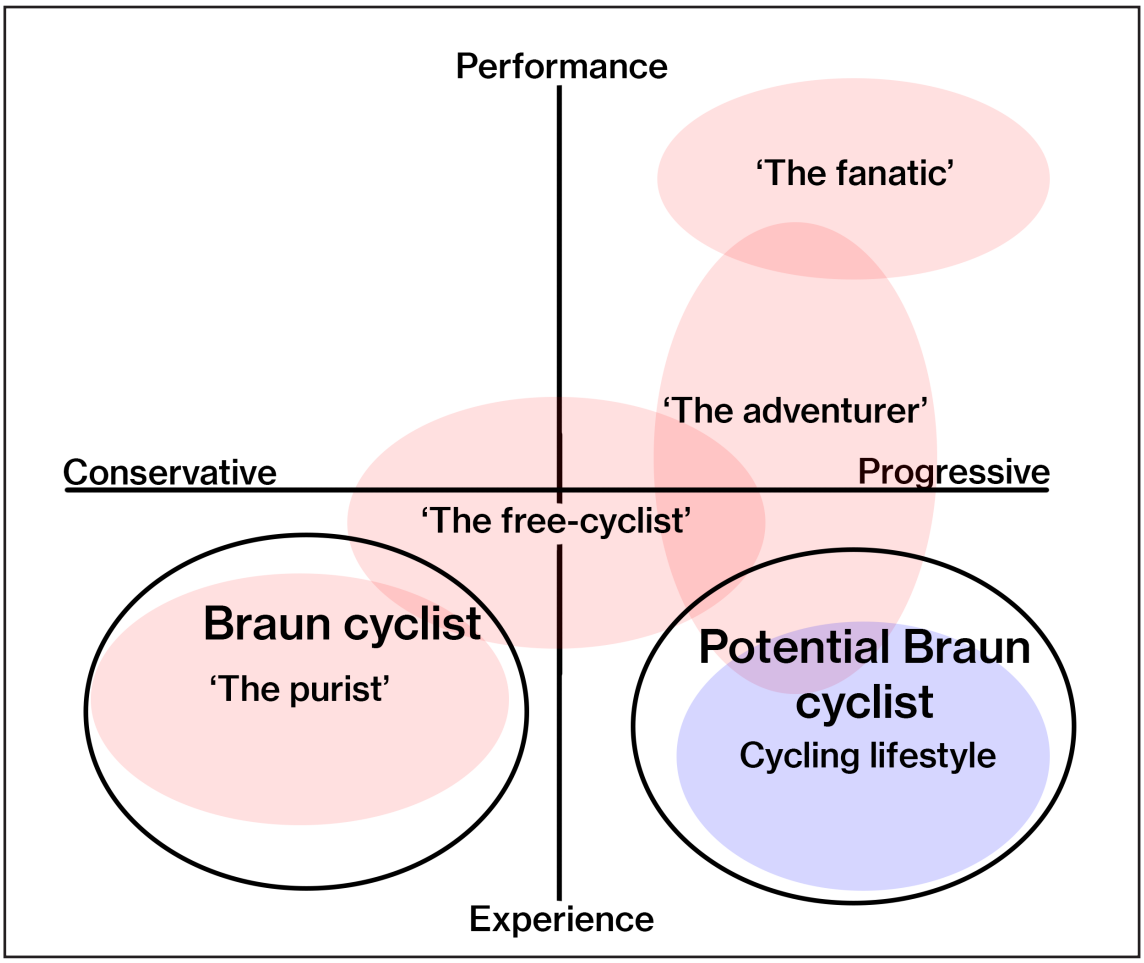
It can be said that individualisation is one of the most important selling points of this time. The world is getting smaller and smaller due to electronic devices, social media and a growing world population. This loss of space to 'be' makes a lot of people feel cramped up. This makes some consumers show their real self in drastic ways. Examples of this behaviour can be seen in Japan in their anime and rockabilly sub-group clothing-styles. The individualisation of products can be used more and better in designing products. Some even suggest adding another P to the four P's of the marketing mix. An example of this strategy can be read in the paper of Goldsmith (Goldsmith,1999).

Conclusion market segmentation

From the previous paragraphs, the conclusion could be drawn that innovations in the road race cycling market are always done to increase the performance of cycling. This explains the linear placement of the groups over the chart in Fig 24. The more performance focussed the consumer is, the more open he/she is to new innovations that are made within the bicycle market. When the consumer is less performance minded and focuses more on the experience of cycling, the interest in innovation lowers and the time-tested products that are less fragile become of higher interest. Braun-cycling its products and consumers are now focussed in the lower left region of the chart making them a brand that focuses on quality with time tested products that cater to the experience of cycling.

The lifestyle consumer group is a new trend/movement that places itself outside of the box of the 'normal' road race cycling groups. This consumer group looks at cycling as a way of expression/ a fashion statement. This group uses nostalgic/retro products and is not interested in a higher performing bicycle. The lifestyle group is very adaptive when it comes to new developments and trends. This makes the lifestyle group a very interesting target for Braun-cycling, as they combine classic looks into a new product.

Fig24: *The target groups of the new strategy of Braun-cycling. On these to target groups the new bicycle design will be based.*



Other stakeholders

Apart from Braun, and the end-user, there are other stakeholders in this design-context that should be taken into account. These consist of; confection-bicycle manufacturers, tube-manufacturers, part-producers and other custom bicycle companies. The stakeholders are analysed on behaviour within the current market.

Confection-bicycle manufacturers

There are multiple large brands in the bicycle industry. In the Dutch road race cycling community Trek, Cannondale, Specialized, Canyon and Giant are the most popular (NTFU, 2017). These companies make all sorts of bicycles; from normal city bicycles to mountain and road race bicycles. For this study, only the road race cycling segment was analysed.

Models

By offering a large range of models, the large brands try to satisfy a broad cyclists group. The models are specified on price, but also to the style of riding; from time-trial bicycles to special comfortable pebble riding road race bicycles. It is interesting to see that almost all low range road race frames are made out of aluminium, where as the high range models are made out of carbon. The low range models are the can do all bicycles, where the high priced models are mostly specified for one goal (time-trial, triathlon, etc.) The aluminium bicycle ranges from €500,- to €2000,- where carbon ranges from €1300,- to €12.000,- (Mantel, 2019).

These brands all invest large amounts of money into the research and development of new bicycles. The big bicycle brands innovate very fast, almost every year new frame-models are released for every kind of frame in their product line. The bicycle is almost always optimized to be as light as possible. This is because a lighter bike equals better performance. The UCI (the international bicycle federation) has set a weight limit of 6.8Kg for professional road race bicycles. As (carbon) confection bicycles sometimes weighed less than the UCI limit, a new field of research was sought to keep on innovating and improving the bicycle. A new field of optimisation was developed, which became available during the rise of carbon bicycle frames. The last 2 years bicycles became more and more aerodynamically optimised. The aerodynamic shapes are increasingly becoming more integrated within the whole bicycle product range. This aerodynamic trend causes parts like brakes, cables, leavers and steering wheels to become more integrated within the frame causing less drag. An example of these aerodynamic shapes and the integration of the parts can be seen in Fig. 25.

Fig25: *The 2019 Trek Madone bicycle. This bicycle is totally aerodinamically optimised. This can be seen by the integration of the form into the frame and the flowing and smooth lines of the frame.*

Geometry

A lot of confection bicycles are made with a sloped back top-tube, an example of this can be seen in Fig.26. This style was introduced with the Aluminium TCR model from Giant in 1997. The downward angle of the tube has 3 advantages for the bicycle if compared to the classical shape of Braun-cycling.

More body types fit on the same frame as there is more space for adjustments on the seat height.

The frame gets stiffer when smaller triangles are used. If you compare a bicycle with smaller triangles to a bicycle with bigger triangles, made out of the same material, the conclusion will be that the smaller triangles are stiffer.

The frame gets lighter as a smaller triangle lowers the frame mass.

Fig26: *A trek bicycle with its sloped top tube. The sloped top tube came forth out of the mountain bike industry. This sloped tube increases the strength of the frame and makes it possible to fit people of different lengths on the same frame size, this due to the increased travel height of the saddle.*

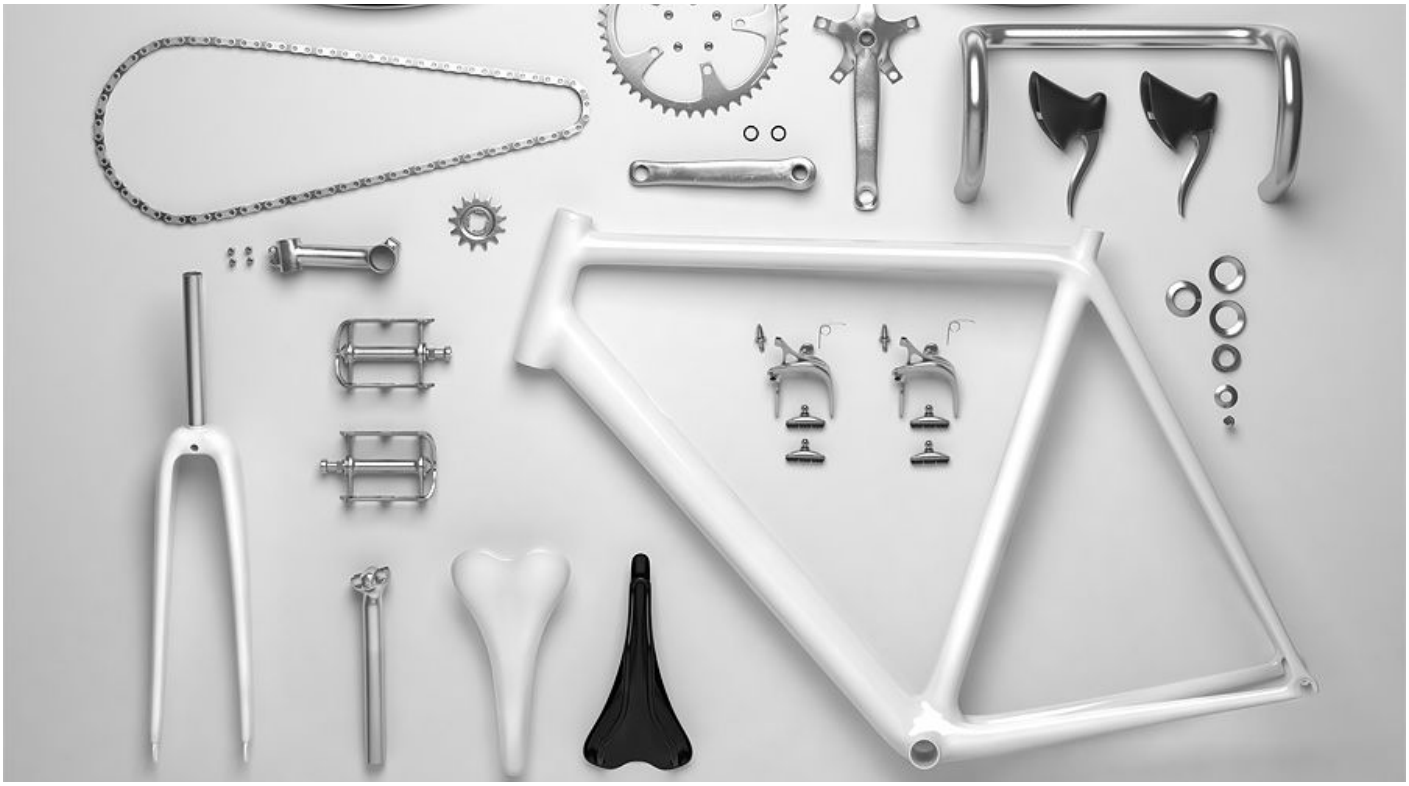
Bicycle part companies

Big influences on the frame design come forth from the bicycle part companies. Currently, there are three big brands that dominate the bicycle part market. First of all, there is Shimano, which is by far the biggest one of the three. Shimano has a 79% market share, followed by Campagnolo (14%) and Sram (6%) (NTFU, 2017).

Innovation
These companies are very innovation-driven. The principle of bicycle parts stays the same, so to sell new parts, it is important to keep innovating. Small incremental innovations are done to make parts a fraction lighter or more aerodynamic. The aerodynamic trend even creates some parts to be made exclusive for a frame edition, this where parts used to fit on every bicycle, as almost everything was standardised.

Implementation
For the larger bicycle companies, the change in all of the new bicycle parts is very welcome. The constant stream of innovations guarantees that they can sell new, upgraded versions of their models to the public. This is because, on most of the high end carbon bicycles, only one component fits. When a new model is made the component does not fit any more. For small companies as Braun cycling, the constant stream of innovation causes difficulties in keeping up with the bigger companies. Smaller companies have very high costs in updating their tooling and models. The high costs cannot be compensated for, because of the small market and sales numbers.

Fig27: *A deconstructed fixed gear bicycle and its components spread out over a table.*



Bicycle tube manufacturers

There are only a handful of 'real' road race bicycle tube manufacturers left in the world. Most of them are located in Italy or Japan. Upon visiting two of these tube manufacturers (Dedacciai and Columbus) located in Italy, the impact of the change of bicycle materials became clear. These companies, once giants of the road race cycling industry, were reduced to a big factory hall full of machinery and some racks stacked with tubing.

Dedacciai had switched to producing mainly parts for sporting goods, instead of bicycle tubes. Both companies started selling carbon frames next to their existing metal-alloy frames, as the market has shrunk drastically.

Shapes and sizes
Not every bicycle tube has the same shape, some are oval and others are round. The tube manufacturers make these tubes different per order for each company. Changing shape requires new tools with high investment costs and techniques. Thus new shapes can only be ordered per large quantity. Some of the shapes are 'off-limits' for other companies, as there are verbal agreements that only the owner of the shape can use the tube.

Most metal-alloy bicycle tubes are made lighter via a process called butting (patented by Reynolds in 1987). Butting can be compared to stretching out the tube to make the wall very thin. The ends of the tube are kept a bit thicker, as this guarantees a better weld. In the hay-days of the metal-alloy road race bicycle, tubes were butted in the sizes small, medium and large (length sizes). This was done so that the smallest and largest frame sizes could all be made as light as possible. With the fall of metal-tube sales, the stock needed to shrink. Nowadays, only large butted-tubes are produced. If a company wants other lengths of butted tubes, large quantity orders must be placed to change the production process.

Fig28: *(left) A rack full of bicycle tubes at Dedacciai*
Fig29: *(right) The tube fabrication hall of Columbus*

RDB
COLUMBUS
Ingegneria ciclistica
COLUMBUS
Ingegneria ciclistica

Custom bicycle companies

The Dutch road race bicycle production market used to be the biggest in the world. But with the introduction of carbon as a building material, the production of metal race frames almost stopped. Big Dutch bicycle brands, like Gazelle and Batavus, stopped producing road race bicycles. This was because there was more knowledge and cheaper labour available in Asia. Now, only the headquarters of multiple bicycle brands are based in the Netherlands and the Dutch bicycle industry has shifted from a producing one to a knowledge-based one (NRC, 2018).

Now there are multiple custom frame builders in the Netherlands. The number has been steadily growing over the last years (from about 10 to 20). These custom builders are mostly one manned companies. Gerard Vroomen, the owner of Cervelo, is not surprised by the increase in small bicycle brands. "Big bicycle brands are most of the time slow in their development of new products. This makes room for small and nimble brands that can do crazy and new things. Most consumers choose safety and go for a well-known brand, but a bicycle is also a means to distinguish oneself. In the last case, a cyclist can choose a small brand." (NRC, 2018)

Some of these brands are run on an almost hobby based manner. A good example of one of these bicycle companies is the company St. Joris bicycles. This company produces about 5 bicycles a year. Other companies have made the building of custom frames a full-time job, Braun-cycling is one of the latter. This two-manned company builds around 75 bicycles a year. The quality of the products of different companies can be very different. This can sometimes have big disadvantages. When the consumer wants to buy a bicycle, the custom bicycle sector is seen as a whole, compared to other confection bicycle brands. As an example: buying a Giant, a Trek or a custom bicycle. With the high-quality standards of Braun-cycling, this customer view of the branch could have a disadvantage on the potential customer base.

Fig30: *(left) Newly made custom bicycle frames hanging of a wall at the Braun-cycling company.*

Conclusion stakeholders

Road race bicycles have always been optimised to decrease the weight in order to get a higher performance. As bicycles dropped below the weight limit, the optimisation field of improved aerodynamics became more interesting. This made the producers of bicycle parts react by making new part sizes and frame specific integrated parts to optimise the aerodynamics of the bicycles even further. This greater variation of parts creates extra pressure on small bicycle companies, as they struggle to keep up with the current pace of innovation.

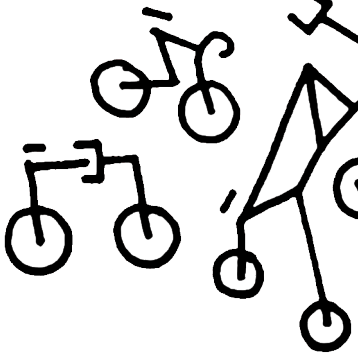
Carbon is a material that is more suited to optimise a bicycle for a certain goal. This is due to the fabrication principle of carbon layering, which gives shape freedom, versus the stiffness and un pliability of steel. This makes the high-end carbon bicycles be more specified for one goal versus the metal-alloy 'do-it-all' bicycles.

As the demand for metal-alloy bicycle tubes dropped, tube manufacturing companies have turned to other markets. Now, only a hand-full of bicycle tube producers exist who only make custom tubes if a high quantity is ordered. Otherwise, stock length and round tubes should suffice for the custom bicycle market. This creates a market in which a lot of custom frames are made from similar tubes, and thus, look alike. This is a disadvantage for Braun-cycling, as their product quality is higher than other 'hobbyist' custom frame companies.

1.3 Changing the bicycle

This chapter dives deeper into the product and its features. Where was the problem of the weight bias developed in the metal-alloy bicycle, and can it be traced back in history? By knowing more about the product, opportunities and possible pitfalls can be located for the development of the new product.

Fig31: *Velodrome racer on his bicycle in 1909.*



Frozen in time

The problem with metal-alloy road race bicycle frames is that they, at first glance, remained unchanged for many years. Steel bicycles have always been made out of steel round(ish) tubing. Frames from other materials, like carbon and aluminium, changed and became more ‘modern’. Modern metal-alloy frames are still produced with straight tubes, because they are easy and relatively cheap to produce and very easy to work with (saw and lathe). Aluminium tubes can be made into more exotic shapes, as this material is softer and more pliable. The coming of the carbon-fibre frame changed the shapes of bicycles radically. Carbon bicycles are not built out of tubes, but are formed out of stacked layers of carbon-fibre cloth. This production process gave the bicycle designers a lot of shaping opportunities. A good example of this is aerodynamic optimisation/style from the last 2 years. In the meantime, the metal-alloy bicycle maintained its ‘old’ round tube shape. In Fig.32. we can see a Colnago steel bicycle from the 70’s. Fig.33. shows the modern, yet classical, Braun titanium frame, made with the same shape tubes as the Colnago. If we compare this to the Trek bicycle from Fig.34 , we can see that in the Trek bicycle the round tubes have changed to elongated aerodynamic shaped and curved tubes.

Fig32: *Steel Colnago bicycle 1972.*

Fig33: *Braun-cycling Experience (titanium) 2017*

Fig34: *Trek Madone (carbon) 2018*

Losing uniqueness

Traditionally, steel road race bicycles have been made with the use of lugs. Lugs are sockets that connect the tubes of the bicycle frame together, which is almost the same principle as what plumbers use with pipe-fittings. From the ’50s on, these lugs were decorated almost until the point of artistry. Every frame builder and brand had different shaped lugs from which the brand could be recognised. Later on, around the ‘80s, lugs were being mass produced and more brands started to use the same stock lugs.

At the beginning of the ‘90s, the first mountain-bicycles entered the market. Mountain bicycles were the first bicycles that had welded tubular frames instead of frames with conventional brazed lugs. The method of welding frames was quickly adopted by the road race cycle industry as frames required less manual labour and became cheaper.

The switches from unique custom lugs, to mass-produced lugs and to welded frames made the road race bicycle frames look more alike over time. The custom bicycle brand frames started to become even more similar. Custom frame builders did not have the machinery nor the money to bend and form unique bicycle tubes. This is how the colour and graphic design of the bicycle frame became one of the most important factors in creating a unique frame design. In Fig.37 we can see metal-alloy frames, with the same geometry, almost the same size tubes, but a wide variety of colours and graphics.

Fig35: *Highly decorated lug from the ‘50s.*

Fig36: *Tig welded connection in between tubes.*

Fig37: *The diverse colour schemes and graphics on steel bicycles.*

An advantage of custom frames besides choosing a unique colour scheme, is that the consumer can choose which parts he wants to have mounted on the frame. This, like the colour, is an opportunity to create uniqueness. Despite all of the new colours, graphics and special parts, metal-alloy frames still looked too much like their heavy predecessors.

The aerodynamic optimisation trend causes most parts that are mounted on the frame to be integrated, thus making the parts not interchangeable. As the frames get more aerodynamically optimised, the parts that are normally mounted on the bicycle will become more fused into the bicycle. The integration of parts takes away the chance for the consumer to be unique by using different parts.

Conclusion 1.3

The metal-alloy bicycle looks like its predecessor, this is a result of multiple factors. The tubes are round shaped stock tubes that are used by multiple custom bicycle companies. These tubes are visually the same tubes that have been used in bicycle design for decades. This creates a big contrast compared to the visually faster developing, aerodynamically shaped bicycles made from carbon.

The lugs in a bicycle frame gave a platform for uniqueness in the steel bicycle production market. The change from lugged frames to welded frames made the metal-alloy frames look alike as the exotically, brand unique, shaped lugs were changed for weld beads. This made the colour of the bicycle and new part configurations on frames important ways to be unique in a market that started to look more alike. With the importance of aerodynamic optimisation increasing an easy conclusion that can be made is that the same thing that happened to the steel bicycle is also slowly happening to the carbon bicycle, uniqueness is fading.

1.4 Conclusion analysis

The core strength of Braun-cycling is making high-quality custom metal-alloy bicycle frames. A signature trademark of a Braun bicycle is its classical geometry, which is a thing that has been developed and optimised over time to give the bicycle better handling characteristics. The current Braun user group is mainly existing out of the purist cyclist group. The Braun bicycle is liked by the current consumer because of its high quality and classic look. Because of the long lifespan of a Braun bicycle, the purist market is getting saturated. This calls for a new product with a new focus/target group. With the developing trend of nostalgia, a new target group for Braun cycling arises, the lifestyle cyclist. This target group uses cycling and bicycles as a way of expression and fashion statement, this opposed to performance-minded cyclists. This makes a high-quality Braun bicycle with a classical look a suited product for the lifestyle group.

The second trend that will come forth in the new Braun product is the trend of uniqueness. The bicycle industry is always trying to balance between optimising products for their performance and optimising the products for their looks, this where the consumer tries to be unique by using parts and colours that no one else has. Two examples of developments that improved performance but made bicycles more alike are the switch from lugged to welded frames, and more recently, the trend of aerodynamic integration of parts. Furthermore, it is very important to be unique in the custom bicycle sector. Most custom bicycle producers have metal-alloy frames with a classic look. This makes the consumer see the custom bicycles as a product group with the same qualities, this where in reality, variations in quality and price in between custom brands can be big.

As the consumer has a bias about the weight of the bicycle, the main focus of the new bicycle design will be to make the bicycle lighter, or at least appear lighter, than the conventional custom Braun bicycle. This implicates that aerodynamic optimisation will not be included for the design. Aerodynamic optimisations would require very expensive tube shapes which are unaffordable for a small company like Braun-cycling.

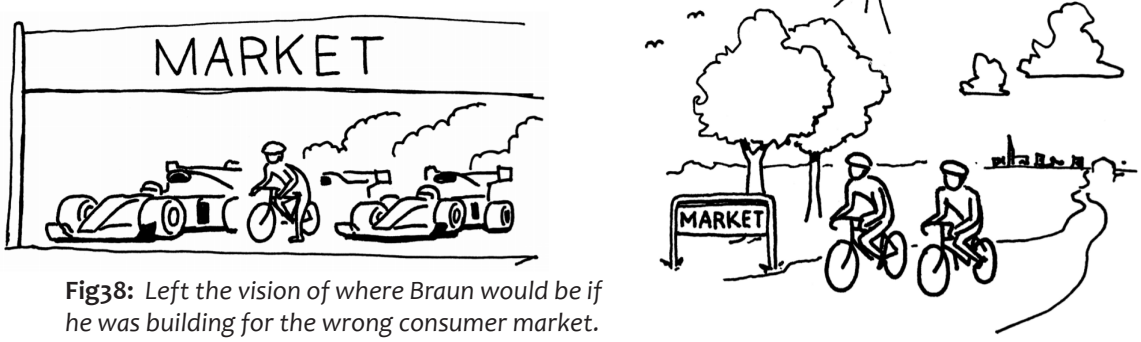
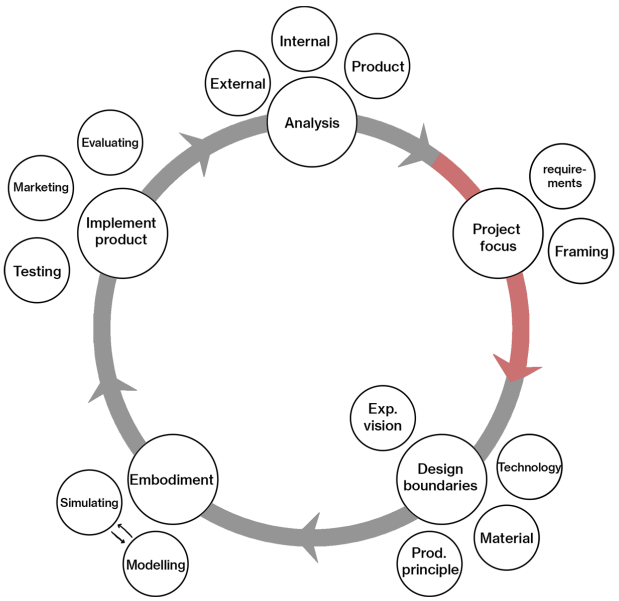


Fig38: *Left the vision of where Braun would be if he was building for the wrong consumer market. right the experience minded markt where braun is en should sell his product to.*

2. Narrowing the focus

Fig39: *Left a zoomed in picture of two drop outs that are just brazed into the seat stays. (Braun-cycling).*
Fig40: *A representation of chapter two in the design process.*

Normally, in this phase of a design cycle, an extensive ideation phase is initiated with multiple concepts and iterations. This project required a more focussed approach before further entering the ideation phase. This project had a timespan of 22 weeks, from start to end. The bicycle looks like a simple product but is very complex. Every millimetre that is changed has results on the performance and handling of the product. This, combined with certain wishes and requirements from the company, has made the design-project zoom in on a more specific region of the bicycle frame. A list is made to help quantify requirements on which the new product should suffice. This set of requirements is used to choose a focus for the design cycle of the new product.



2.1 The list of requirements

The information that was gathered during the company and context analysis is used to create a list of requirements. This list serves as a set of boundary conditions which the new product must meet. Pugh's checklist was used for generating the design requirements.

1.Performance: Which main functions does the product need to fulfil?
The bicycle is used for regular road race cycling on flat (Dutch) roads.
The bicycle should withstand the forces exerted by an experienced road race cyclist during normal use.
The bicycle is capable of carrying the weight of one adult cyclist during use.

2. Environment: What kind of environmental influences does the product need to withstand during use.
The bicycle shall be exposed to (rain) water. -> The bicycle shall not rust in under 1 year when placed inside or sheltered from the elements after use.
The bicycle shall be exposed to dirt/ sand. -> The bicycle will keep on working without the loss of functionality even after one month without cleaning.
The bicycle will be used in 'normal' sun conditions. -> The bicycle, including paint, will not defect/fade after 10 years when placed inside out of the sun after use.

3. Life in service: With what intensity will the product be used and how long should it last?
The bicycle will be used 5 times a week for commuting and leisure activity purposes (250 Km). -> The bicycle will not fail due to normal use in under 10 years.

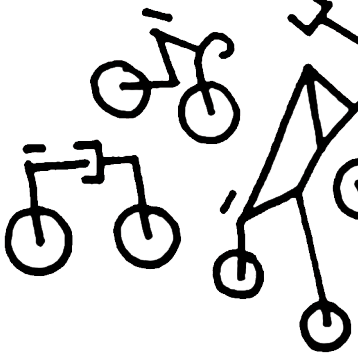
4. Maintenance: Is maintenance necessary and possible.
The product should be maintained by the consumer.
All of the parts of the bicycle should be detachable by the owner (if he/she has the proper tools) or by Braun-cycling.
The bicycle will be cleaned regularly (once a month) with water and a bicycle specific soap.

5. Target product cost: What is a realistic price for the product, considering similar products.
The bicycle's retail cost should be between eight-thousand and twenty-thousand euro for the complete custom bicycle.

6. Transport: What product requirements are set by transport during the use of the product?
The bicycle should fit on roof racks and back-racks for bicycles that are mounted on cars.

7. Packaging: Is packaging needed?
There is no packaging needed for the bicycle as the consumer will pick up the bicycle from the shop and put it on the roof/back rack on the car.

8. Quantity: What is the number of units to be produced?
The bicycle will be made separately per order, this because the bicycle frame will be fitted to the correct dimensions of the user's body.
There will be no part-stock for the bicycle



9. Production facilities: Should the product be designed for existing production facilities, or is it possible to invest in new production resources?
The bicycle needs to be manufactured on existing tooling of Braun-cycling.
The bicycle shall be assembled via existing knowledge of Braun-cycling.

10. Size and weight: Are there boundaries to the size and weight of t he product due to production, transport or use?
The bicycle should weigh less than an existing Braun bicycle. -> Less than 8Kg.

11. Aesthetic, appearance and finish: Which preferences do buyers and users have and should the product fit a house style?
The bicycle should be painted in colours which are preferred by the consumer.
Braun-cycling wants their new logo incorporated in the new bicycle aesthetics.

12. Materials: should certain materials (not) be used?
The bicycle shall be made from a material (metal-alloy) which Braun-cycling is already familiar with.
The bicycle shall be made from materials that can be welded together properly.
The bicycle shall be made with regular butted bicycle tubing.

13. Product life span: How long is the product expected to be produced and sold?
The product shall be made so it can be produced for 10 years.

14. Standard rules and regulations: Which standards, rules and regulations apply to the product.
The bicycle shall meet the UCI rules for a road race bicycle frame.

15. Ergonomics: what requirements result from observing, understanding, handling, operating the product?
The bicycle shall use the classic Braun-cycling geometry.
The bicycle shall be made to fit the owner.

16. Reliability: What chance of failure is acceptable?
The bicycle shall never fail under normal use.
the bicycle shall not fail during a standing start.
the bicycle shall not fail during sitting cycling.
the bicycle shall not fail during heavy braking.
the bicycle shall not fail during encountering road irregularities on cruising speed.

17. Storage: Are there long periods of storing time during production or usage of the product?
The product shall always be placed inside or sheltered from the elements (rain and sun) after use.

18. Testing: What quality tests are conducted on the product, both inside and outside of the company?
The product will be tested on use by Herman Braun.
The bicycle shall meet the ISO 4210 requirements (app xxx).

19. Safety: should specific precautions be taken with regards to the safety of the user and non-users.
The bicycle frame will never break during normal use of the bicycle.

20. Product policy: Are there requirements resulting from the current product portfolio?
The bicycle shall have the Classic Braun-geometry.
The bicycle shall be made from a metal-alloy material.

21. Societal and political implications: What are the current opinions about the product?
The product should help the consumer overcome the bias of the weight of a metal-alloy bicycle. -> the bicycle should look lightweight.

22. Product liability: For what kind of design, production and usage mistakes can the producer be held accountable.
If the frame bends or brakes during normal use of the bicycle Braun-cycling is held accountable.

23. Installation and initiation of use: What requirements resulting from the assembly, installation and other systems operate the product?
The product shall be fitted with aftermarket bicycle parts.
The bicycle shall have a tapered front fork.
The bicycle shall have a 31.6mm seat post.
The bicycle shall be fitted with a T47 bottom-bracket
The bicycle shall be fitted with a 'normal' dropout hub and derailleur

24. Reuse, recycle: Can the material cycle be extended by reuse of parts and materials?
Parts of the bicycle shall all be detachable.
The bicycle frame material (metal-alloy) shall be recyclable.

Fig41: *The computer screen of the electronical frame jig at the Braun-cycling company. By changing sizes on the screen the jig will be automatically set to the correspondending value.*

W 539.9
15.12
Y 143.8
14.12
14.5 O
Q 28.2
34.0 Z
Z1 28.0
38.2 P
28.0 R
46.0 U
44.9
G
74.00
12.8
560.0 K
611.1
45.63
V 35.0
Sa 23
Da 677
9 Sp
511.3
X 16.0
59.2
73.00
677 Dp
69.89
T
4.0
Sc 82
Rc 172
S 40.0
Ia 584.9
Ip 405.0
A 581.1
H 399.4

2.2 The base of the design

Looking at the list of requirements and the conclusion analysis, conclusions can be drawn that help to further limit the scope of the design. First, an approach to setting the basic parameters of the frame is described.t. This will help to calculate the final design of the frame during the embodiment design phase of the project. Secondly, different requirements, company strengths and the time limit of the project, have forced to limit the scope of the project to a smaller area of the bicycle. This will give a more manageable design scope which is more feasable to solve within the given time.

Frame geometry

As stated in the analysis and the list of requirements, the new Braun bicycle needs to have a 'classical Braun-geometry'. This is because it is a familiar and liked trait of the bicycle. The classic geometry also makes the bicycle behave in a way that Braun-cycling has perfected over the lifetime of the company. The geometry that Braun uses in its frame is a version of the classic diamond geometry as shown in Fig.42.

As a basis for the frame geometry, an existing bicycle of Braun-cycling will be chosen. This to guarantee the bicycle characteristics, but also have a good product to compare the new frame to in tests.

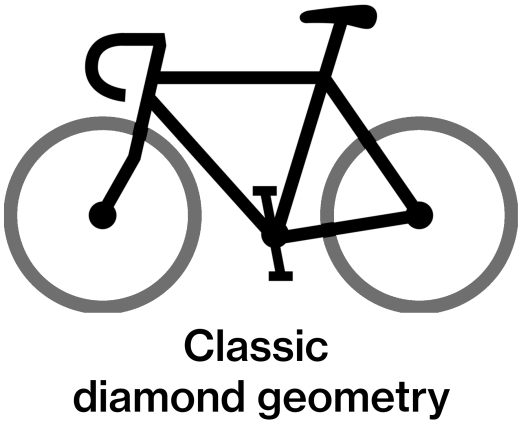


Fig42: *The classic geometry that Braun-cycling uses in all of its custom bicycles. The diamond geometry has been around since the '1900s.*

Focus on lugs

As the title of this paragraph tells us, the conclusion is made to focus the scope before the design phase. The focus of the project will be on reintroducing lugs into the bicycle frame. This decision was made due to three different factors. Firstly, in the analysis, the conclusion is drawn that the new product must be built upon the current strengths and knowledge of Braun-cycling. Secondly, new shapes of tubing are too expensive. And the third factor is that the product needs to be unique, differentiating Braun-cycling from the other custom-companies. The new bicycle will have lugs on all of the connection points of the tubes (the head tube, the seat tube, the drop-outs and the bottom bracket) this is shown in Fig.43.

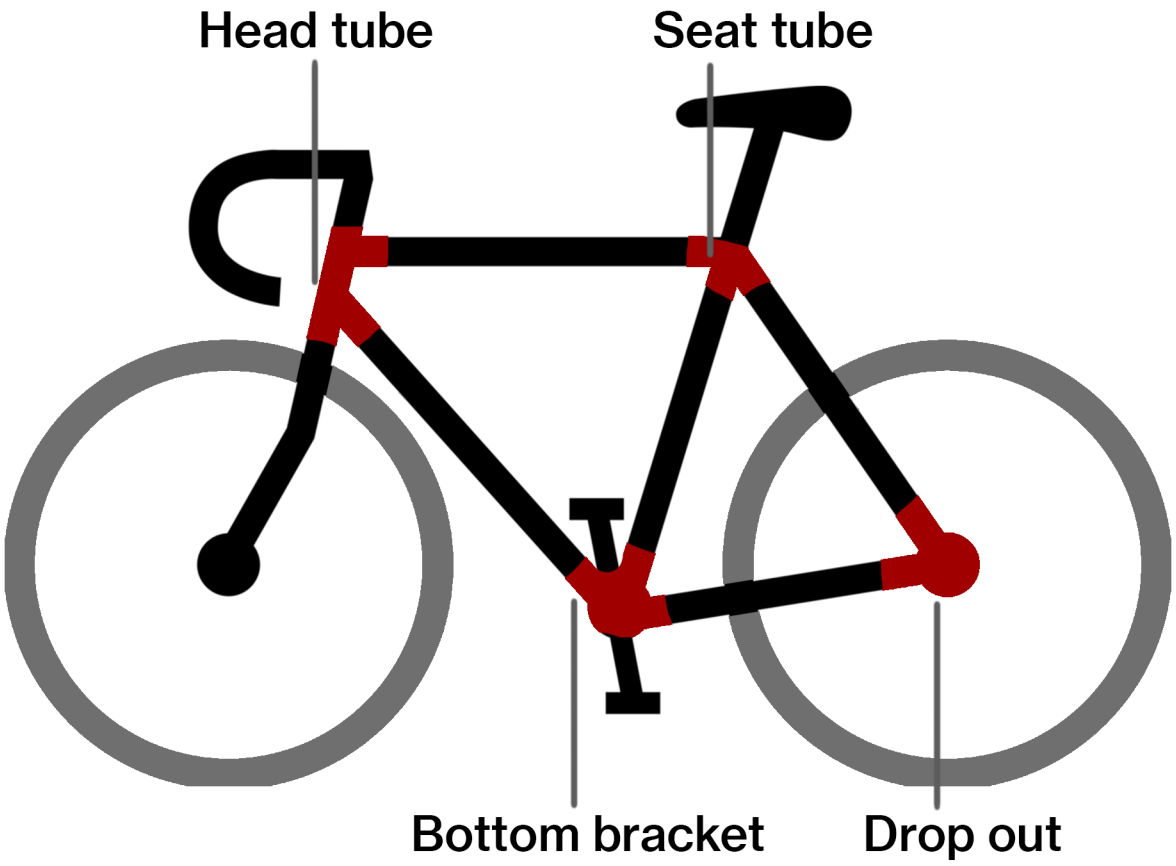


Fig43: *A visual representation of the different lugs than can be found on the bicycle frame. Note that the drop out has a left and right side.*

Focus on lugs:
Existing materials, knowledge and tooling

The core strengths of the Braun-cycling company are based on the custom metal-alloy bicycle and the knowledge behind the production process of the frame. It is also decided that the new product shall be made with existing technologies which Braun is already familiar with, so the company can keep on producing bicycles without having to stop production to develop and learn new production processes.

The production of a lugged frame is something very familiar for Braun-cycling. Herman has built countless of lugged frames for his clients. This is why reintroducing lugs into the new product would keep on using the core strengths of the Braun-cycling company.

Stock tubes

From the visit to the bicycle tubing manufacturers in Italy, the conclusion has arisen that to create new shapes of tubes for the bicycle frame the price of the tubes rises dramatically. This leads to the conclusion that the new bicycle must be made out of stock butted tubing, as described in the list of requirements point 12. If special shaped tubes are used in the new design, the only way to make it cheap is to buy large volumes of the product. As the bicycle shall be built per order and Braun-cycling does not have the storage space nor the money to buy and store large amounts of tubes this is not an option.

Need for uniqueness

From the analysis, it is concluded that the current custom road race bicycle looks too much alike and like their predecessors. This creates a consumer bias about the weight of custom metal-alloy frames and lets high-quality Braun bicycles easily be compared to other lesser quality custom brands. Furthermore, it is a trend to be unique and show your own unique products as a road race cyclist.

Chapter 1.3.2. describes how the loss of the lugs in frames has made the bicycle to lose its uniqueness. This is an opportunity to turn this around. The choice to make the bicycle out of stock tubing only leaves the option to improve the performance of the frame in the design of the lugs. By reintroducing lugs into a frame we make a platform to differentiate and be unique from the other custom-bicycle brands.

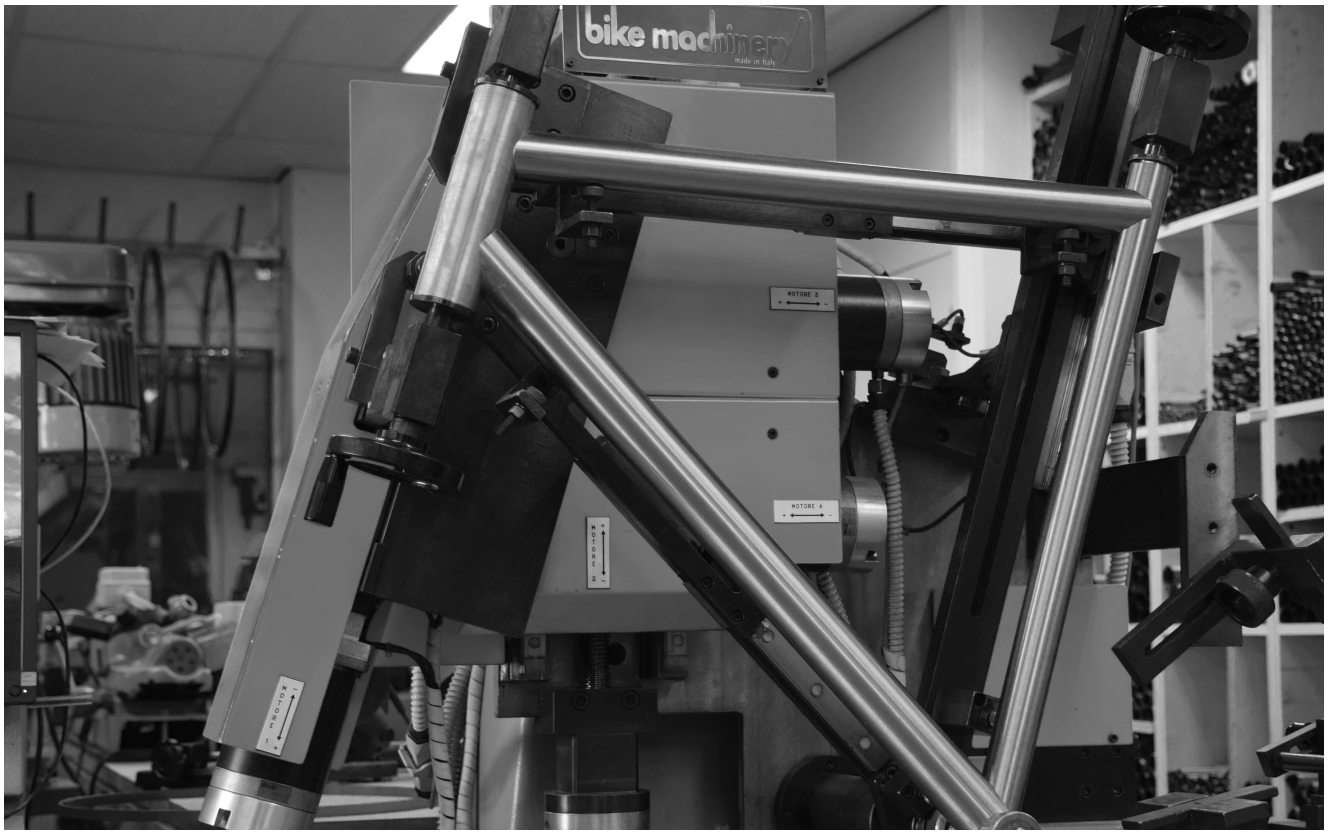
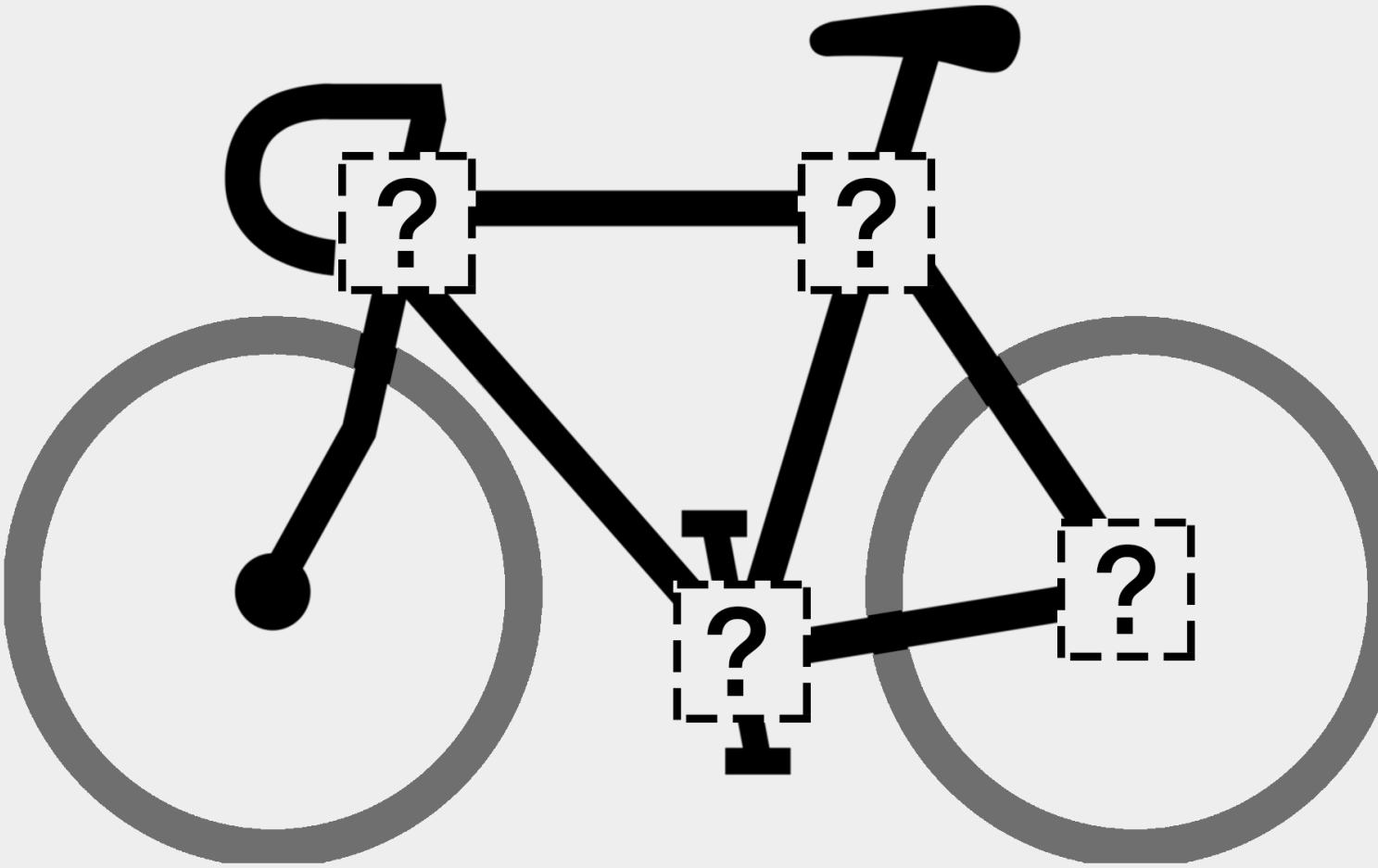
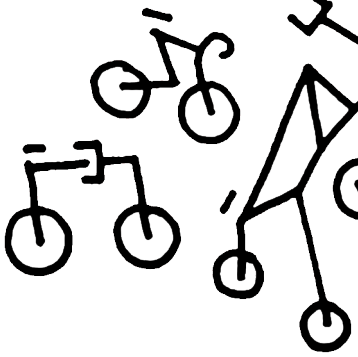


Fig44: *(top) The electronic frame jig at the Braun-cycling company. This jig is one of few in the whole world and helps to create very precise dimentioned frames.*
Fig45: *One of the many walls full of tools at the Braun-cycling company.*

3. The lug design





With the choice being made to design lugs for the new Braun bicycle, we can look further into the method that is needed to design a lug. The new lugs have the potential to improve certain qualities of the bicycle, this not only on an aesthetic level but also on a mechanical level. The chapter will go further into the choices and process of the method behind the design of the lugs. Fig.47. shows what will be explained in chapter 3. First opportunities for improvements of the bicycle are explained in chapter 3.1, this will be followed by an aesthetical guide for the lug design in chapter 3.2. Chapter 3.3 will describe the choice of methods that best suit the product requirements, product opportunities and the aesthetic guide for the design of the lug.

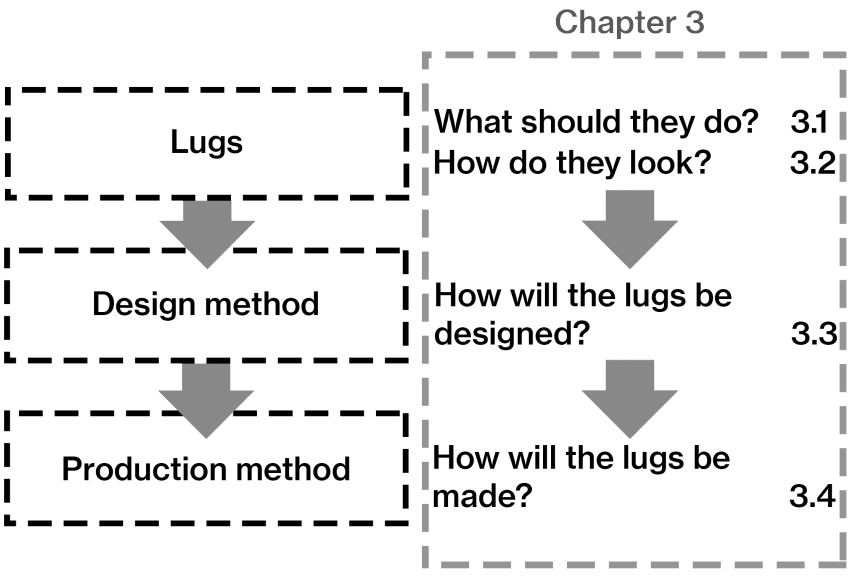


Fig46: *(left) a visual representation of the to be designed lugs.*
Fig47: *(right) The content of chapter 3*

3.1 Product opportunity

Lugs can be used to give Braun cycling their own unique 'signature' shape. This idea also makes the implementation fairly easy as the production process does not have to change much. Furthermore, the lugs also have the potential to improve the lifespan of the bicycle as they can lower the forces that are exerted on the welds of the frame. The introduction of the lugs also has the potential to lower the time spent on the production of a frame, this due to fewer steps that need to be taken during assembly.

Less force on weld

Welds have a tendency to weaken the parent material right next to the weld bead. This area is called the heat affected zone. The problem of the weakening of the material could be minimized by proper welding techniques and temperature control, nonetheless, the zone is still present (Lewis, 1962). This makes the weld be the potential weak-spot of the whole bicycle frame.

A simple solution to prevent potential failure and lower stresses that act on the weld is to move the weld away from the original joint section. In the conventional tig welded frames the tubes are joined at the end of the tube. This way of welding makes for a place where steep angles are common as the two straight tubes meet each other. The steep angles with only the weld bead as a rounded of shape are very prone to creating high-stress concentrations. The high-stress concentrations can lead to material failure if yield stresses are exceeded.

The use of the lug, as was done in the original steel lugged bicycle, made the weld from lug to tube to be placed away from the virtual crossing of the tubes. Increasing the distance between the crossing of the tubes and the weld makes the tube relatively shorter. A shorter tube makes the arm that forces act on smaller. This, in turn, lowers the moment-force transmitted on the weld and heat affected zone. An example can be seen in Fig.48.

From these two things, it is easy to conclude that the lug has the potential to decrease stress concentrations compared to a conventional welded frame. Using a lug gives room to make more rounded off shapes, instead of creating steeply angled spots. The lug also decreases the arm of the force, thus making the forces on the weld lower.

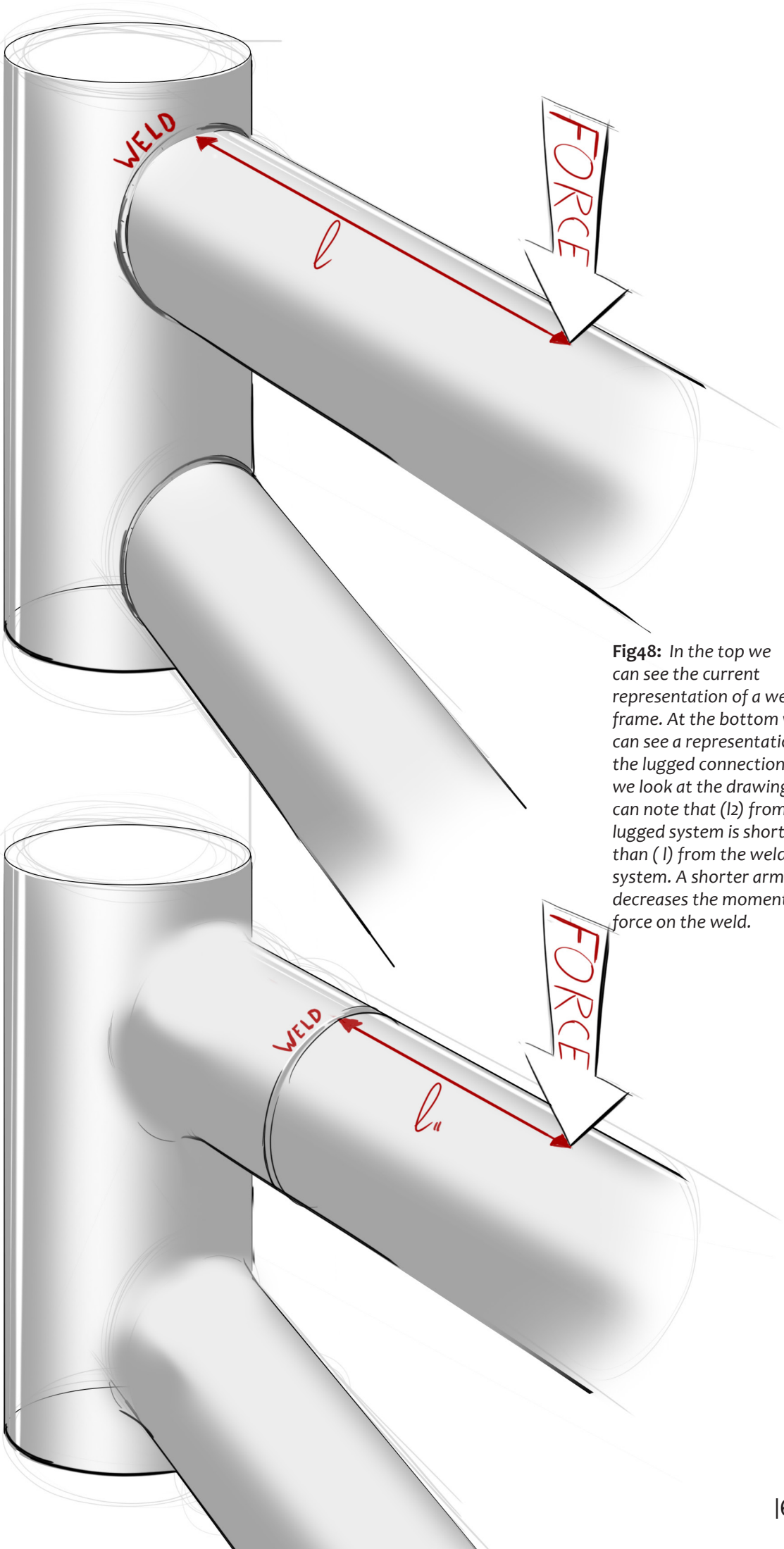


Fig48: *In the top we can see the current representation of a welded frame. At the bottom we can see a representation of the lugged connection. If we look at the drawings we can note that (l2) from the lugged system is shorter than (l) from the welded system. A shorter arm decreases the moment force on the weld.*

28.6
28.6

Production advantages

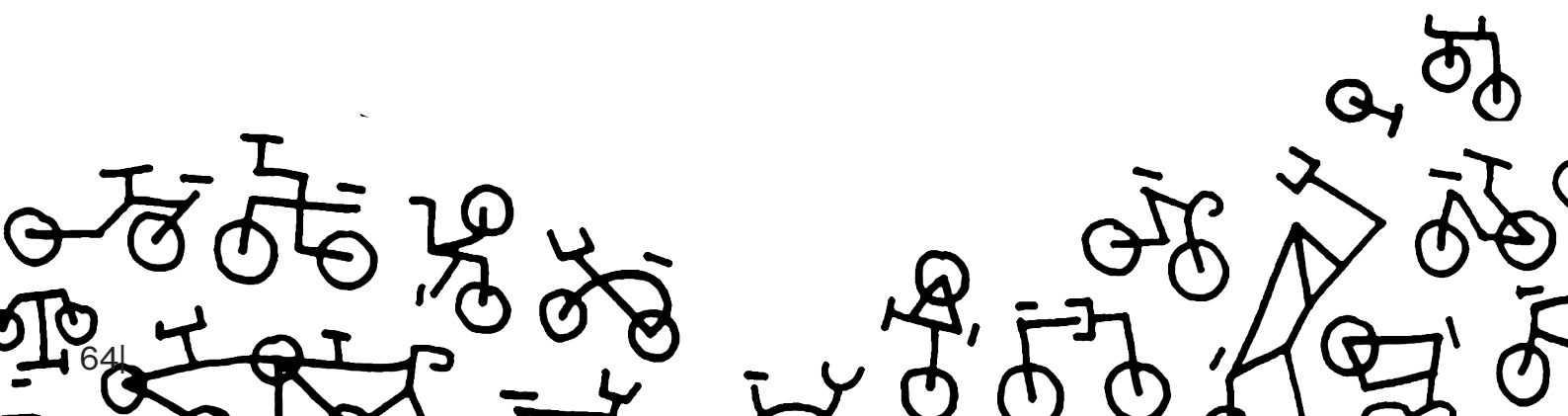
In conventional metal frames, tubes are mitred before they are welded together. Mitring is a process where a cutting head, with the diameter of the to-be-joined tube, is milled through the end/side of the tube. Fig.49 shows an example of a tube that is being mitred at Braun-cycling. Mitring is done to ensure a snug fit before welding the tubes together. A tighter fit before welding makes a better weld, as less material needs to be added to fill up holes and seams. For each mitred cut, the machine needs to be adjusted with precision, this makes the mitring process take about 10 to 15 minutes per cut. Each new shape tubing that is used for a bicycle needs its own set of clamps for the milling machine. The clamps are custom made in Italy by the tube manufacturer, because they need to be very precise to ensure a nice centred mitre cut, each set of clamps roughly costs 750 euro (Braun, 2019).

A lot of time could be saved if the steps of mitring the tubes could be taken out of the production process of the bicycle frame (13 mitred section x 15 min = 195 min/ 3.25 hours saved). The easiest way to cut out the step of mitring the tubes is to give the connection from the lug to the tube a straight edge. Making the transition from the tube to the lug straight makes the production time shorter. The tubes only need to be sawn to length and welded together. It also almost always ensures a snug fit in between the lug and the end of the tube, because the process of sawing straight is easier and less prone to mistakes as mitring tubes. Finally, there are no more extra costs for machinery as the mitre-milling machine does not need any new clamps.

Fig49: *A tube being mitred at the Braun-cycling company. The tube is placed in the machine using a specially made clamp. Next, the correct cutting head will be used to mitre the tube to a shape that fits neatly on the other tubes of the frame*

3.2 Collages

It can be very difficult to translate thoughts about shapes and emotions behind products into words. A collage can be a useful tool in making the idea more tangible and clear. This assignment asked for collages that are used as inspiration for the development of the product. It is always smart to make multiple collages about different subjects, never place multiple subjects into one collage (Brand,2018). For the bicycle, two collages about emotion are made (one for the new product, one for the cyclist and the emotion behind the sport). The third collage is about forms and shapes, it is made to get inspired with interesting forms and shapes.



Emotive

An emotive collage is made to visualise the feelings that should be evoked by the frame. The goal of the frame is to overcome the bias of the consumer that metal-alloy frames are old fashioned, heavy, slow and cheap. To overcome these biases the collage was based on the traits: speed, lightness.

Fig50: *Emotive collage speed and lightness.*

Emotive

Furthermore, a collage was made to show the emotions evoked with cycling. It was mentioned multiple times during interviews with road-race cyclists that cycling is an escape from a busy life. It gives freedom and joy to the cyclist. Lets you be out in nature, and is very easy and accessible to do.

Fig51: *Emotive collage freedom and escape.*

Form

Traditional metal-alloy frames are always built out of straight tubes that meet each other at clean angles. To do something new the straightness of the frame should be transformed, thus making the frame flow more. Making the lines in the frame bent opens up a lot of opportunities to make the frame look unique, compared to existing frames. Next, to differentiate from the current metal-alloy frames, the frame should also be different from the carbon look of frames (oversizing and making it out of one large shape). The goal is to make something that can only be made in metal-alloys and not in carbon.

To satisfy both target groups (the lifestyle group and the purists) a form language was made that is natural, calm, yet light and speedy. The calmness is kept by using only one vibrant colour together with only grey tones and black and whites. The vibrant colour can be used to emphasize the unique shapes in the product. The surfaces of the product are curved in natural planes mixed in with large holes. These holes can be used to make the product look light and fast.

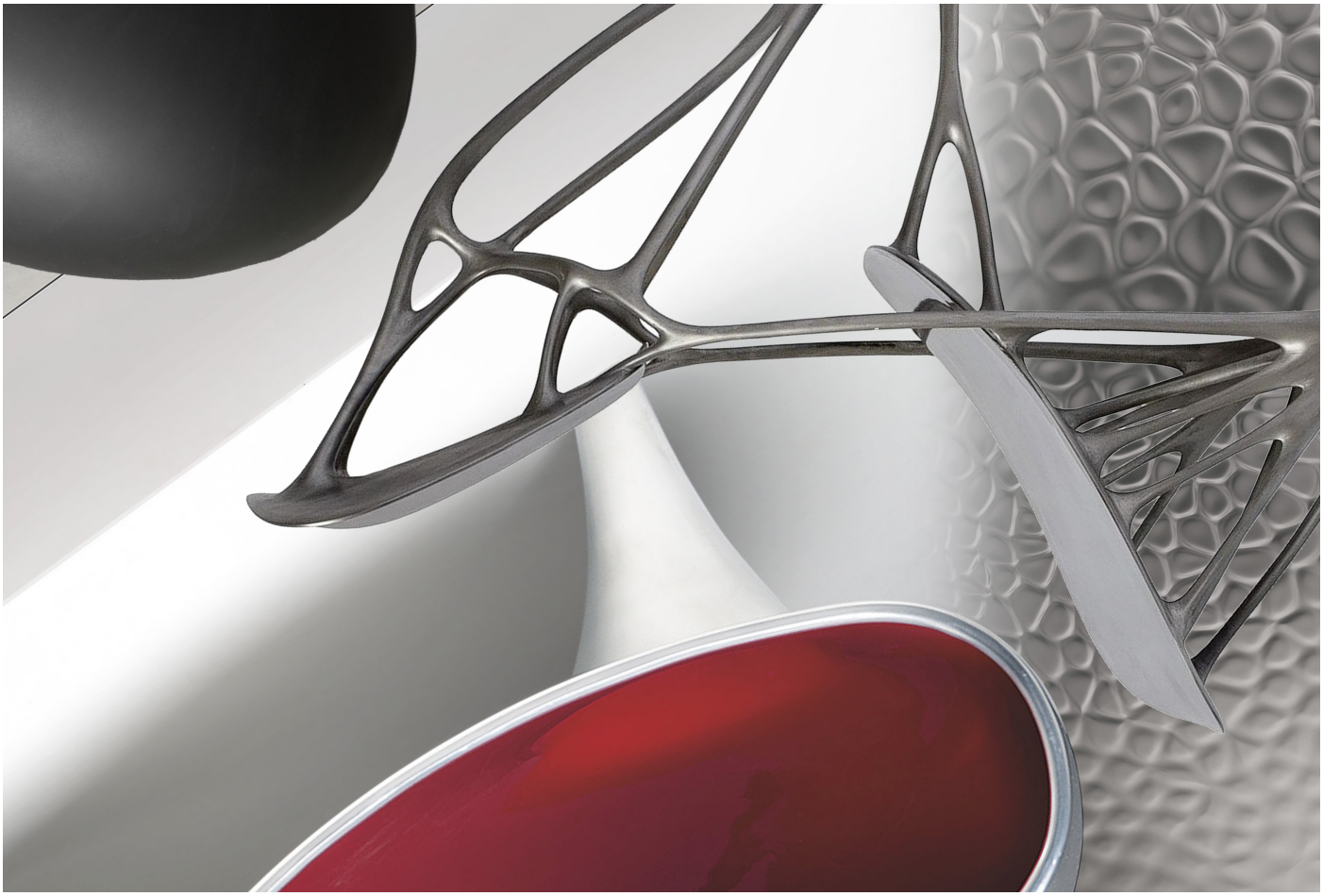


Fig52: *Collage forms and shapes*

3.3 Design method

Metal Bicycle frames have always been built solely out of tubes. For a new look, the habit of only thinking in term of the shape of metal tubes needs to be broken. The look of the new bicycle is the first barrier that could help the consumer overcome the prejudice of the heavy weight of metal-alloys frames. The change lies in making the bicycle frame appear lighter than a conventional road race frame.

Most natural materials are intrinsically either light or strong, think of the density of rock versus the lightness of a feather. However, some structures combine material properties and shape to have both the quality of strength and that of lightness. Usually, these structures are natural-biological such as wood, coral or our own human super-composite: bone. If we look at the structure of bone (Fig.53) it is very porous, thus making it very light. The strength of Bone comes from the natural growth of the material. It forms strands of bone where forces are applied, where there is surplus material the body breaks it down. If we borrow this form language and apply it to the lugs of the bicycle, the result is something that looks very light and is weight efficient, because of the structural geometry of the material and 'loss' of excess material.

Fig53: *3D printed bone structures.*

Topology optimisation

The natural structure of bone would be ideal to use in a bicycle frame. This because a bicycle frame needs to be both light and strong. These structures could be made by carefully designing and shaping the lugs to make it look like the natural structures of bone. This process would much likely be very time consuming, as every shape of the lug does not only affect the aesthetics but also the stiffness and weight of the lug. Shaping by hand makes for a method where designing, building and validating would need to be repeated many times to make a high-performance bicycle lug.

A more efficient strategy to give the lugs a natural bone-like structure would be to use topology optimisation. Topology optimisation (TO) is a mathematical method to optimize a material layout for a certain goal. In the case of the bicycle lug, stiffness and weight. Boundary conditions and constraints must be chosen with care as an input for the model. The system calculates via algorithms the shape that most sufficiently supports the set goal. The shapes that are generated with topology optimisation are unique to the input that is given to the software.
Most of the time, topology optimisation is only used for concept development in the aerospace and mechanical sector. This is because the software is still quite novel and in development. The free forms that are created in the final designs with TO are difficult and costly to manufacture most of the time (Yildiz, 2004). The set-up for the TO is very time costly, as all of the parameters need to be chosen with care. The next iterations that will be made are much less time consuming and can be made cheaper and faster than the original, this is because only the parameters need to be changed.

For the design of the lugs, the TO tool of SolidWorks is used. This finite element method based tool uses a subtractive method to chisel away material to get to the most optimised shape. The goals that can be set in the SolidWorks TO tool are optimisations for:

-Stiffness to weight
-Minimal mass
-Maximum displacement

For the design of the lugs, an optimisation of stiffness to weight was chosen. This was done because a bicycle frame needs to be as light as possible, without deflecting so much that the cyclist loses power in the pedal stroke. An optimisation for stiffness to weight was a compromise in between a minimal mass and a maximum displacement optimisation. To ensure that the material does not fail, the topology optimisation can be set to a maximum stress limit. This limit is set to a safety factor of 1.5. The safety factor of 1.5 times the yield strength of a material is a safe enough factor for the high-quality standards of the aircraft sector (Acar, Kale, Haftka & Stroud, 2006).

The conclusion can be drawn that topology optimisation is the optimal tool to use for this project and Braun-cycling. The shapes that are generated look like the natural shapes proposed in Fig.52. The lugs have the potential to be lighter and stiffer than the original welded connections as the TO will optimise the shape to these set goals. The generated forms will be unique for the Braun-cycling company and will be very difficult to replicate for other companies. The combination of these three points will give Braun-cycling the competitor advantage in the (custom) cycling market.

3.4 Production method

3D-printing

The combination of company requirements (made per order, no stock, etc.) and the TO makes for an interesting set of requirements that need to be met when looking for a suitable production method for the lugs.
-The number of parts that need to be produced is low per order.
- Braun-cycling cannot afford stocking parts.
-Every bicycle is custom.
-High changing rate of parts.
-The shapes from the TO are non-releasing shapes as they are very complicated and free-flowing.
-The metal alloys used in the Braun-cycling frames (Chromoly, titanium grade 9/5, stainless-steel) must be suited for the production method.

Fig54: *SLM printed cubes being brushed down. The left over titanium powder can be used for a new printing cycle.*

Choosing between casting and printing

The non-releasing shapes were a big factor in choosing the right production method for the lugs. A lot of production methods work via a principle of moulds that can be split into multiple parts so they can be used again. A shape that is non-releasing would not come out of a multiple part mould without breaking the mould. Two methods that are suitable for low production quantities with non-releasing shapes are 3D-printing and investment casting. Investment casting works by making a mould in which the material is poured, the mould is later removed by braking or washing it away from the cooled, setted part. 3d printing builds up the new part layer by layer thus not needing a mould.

To manufacture the final lugs a 3D-printing process was used. This because the 3D printing method has less waste that is generated in the production of the part. Furthermore, Braun-cycling likes to visit and stay in personal contact with the suppliers of their parts. Investment casting is pretty expensive to do in the Netherlands and Europe.

Type of 3D print technique

The choice is made to use Selective Laser Melting (SLM) printing. SLM has been widely used in the metal additive manufacturing industry. The process illustrated in Fig.55, typically uses a layer of really fine powder of the material that is used in the final product. The powder is spread evenly across the platform, usually in between 30 and 100 micrometres thick. A laser is used to melt the fine powder together in the sections where the part needs to be formed. The process is repeated, building up the layers until the final product is made. To prevent oxidation in between layers of powder, the chamber where the part is printed in is filled with a constant flow of inert gas (Argon / Nitrogen) (Brandt, 2016).

The process of SLM metal printing is different to ‘conventional’ plastic printing solutions in the way that there is no loss in strength by the layering of material. In plastic printing, the bond in between weakens the structural integrity of the product. This is because the layers are not melted together. By the use of a laser to melt the material together, not only the top layer is melted but also the material below the top layer, thus fusing layers together to create a homogenous material. Still, there may be downsides to SLM if we compare it to conventional production methods. In the lugs for the bicycle, Titanium was used as a building material. The choice for the material titanium will be explained further on.

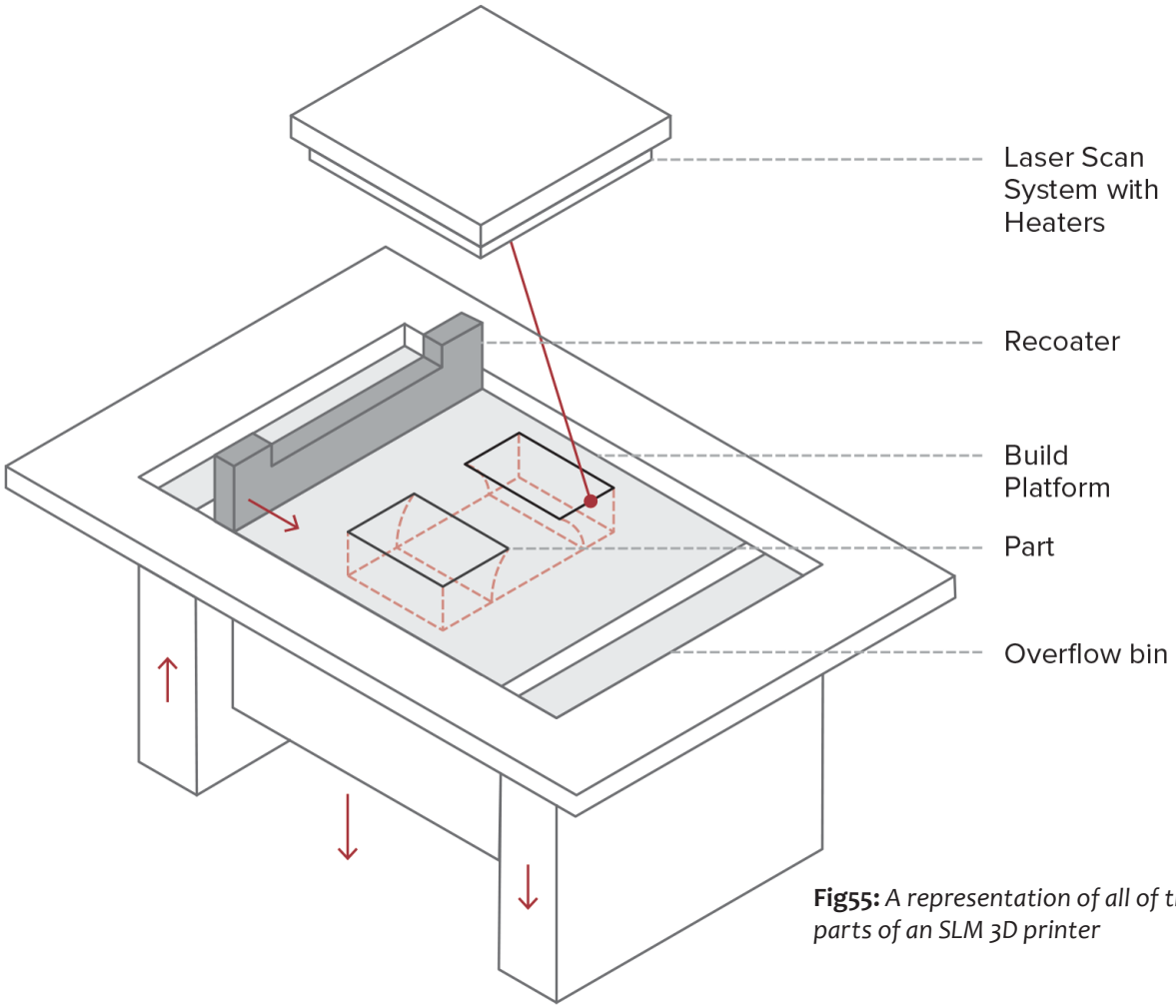


Fig55: *A representation of all of the parts of an SLM 3D printer*

If titanium is used in SLM processes, the yield-strength of the material is increased next to a longer elongation and higher strain hardening. This due to the forming of martensite (grainy rice like structures) structures in the material(see Fig.56). The downside of the combination of SLM and titanium is that the fatigue strength of the material is lowered (Benedetti,2016). This is due to the surface roughness on the finished part. This could be overcome by polishing the final surfaces of the product, but becomes difficult on internal surfaces. The other factor in lowering the fatigue strength of the product is the increased strain hardening, making the material stiffer and more brittle over time.

The combination of the product size and shape changing per order, the factor that Braun-cycling cannot afford or keep stock and the product that has a non-releasing shape requires a production method where no reusable-moulds should be used. Selective laser melting will be used for the new product. This is because the technique has little waste made in production, is done in the Netherlands and is relatively low cost compared to alternative methods. The method of selective laser melting creates parts that have very high structural strength with no layering defficients. The downside to SLM is that it slightly lowers the fatigue strength of titanium, but this effect can be lowered by polishing the surface of the printed part.

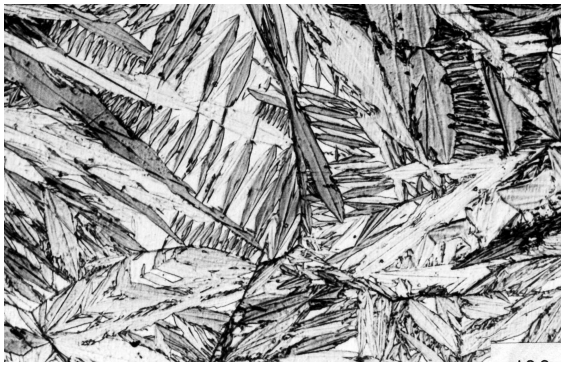
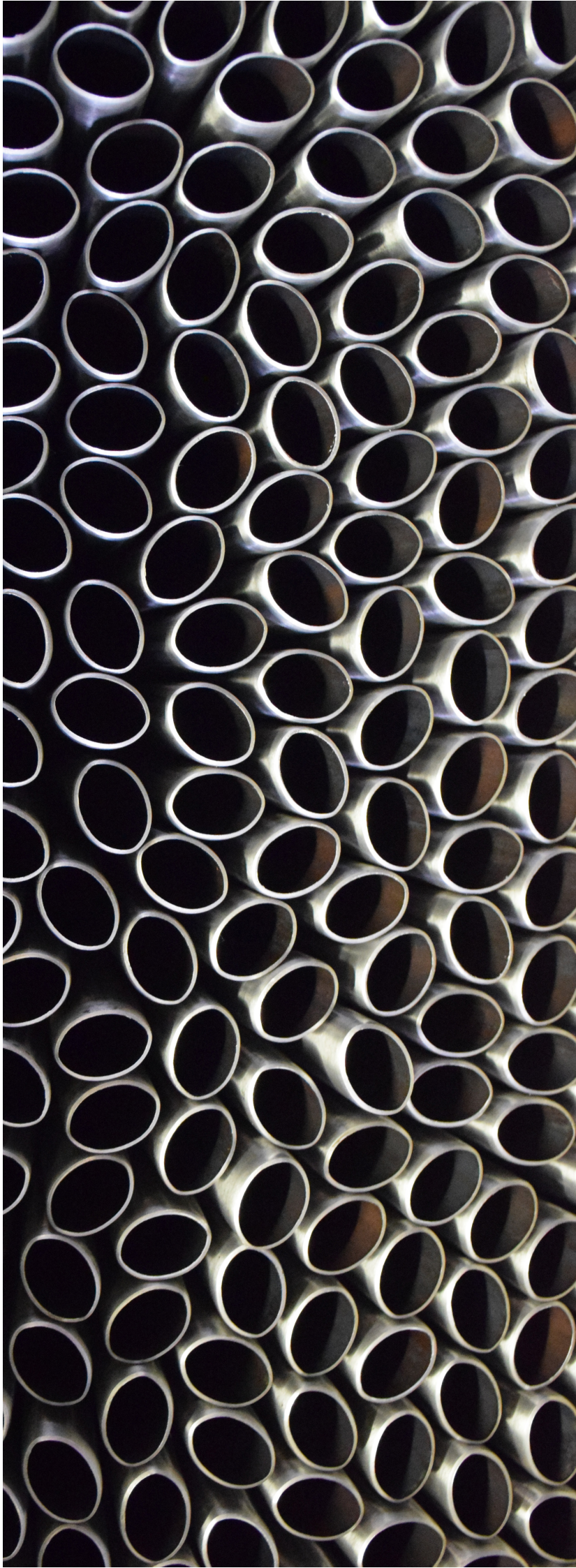


Fig56: *The martensenite structures in titanium. The smaller the structures are the stronger the material is.*

Materials

The choice is made to use titanium for both the tubes and the lugs that will be used in the frame. Titanium is a material that is already used in the bicycles of Braun-cycling. This made for an easy adaptation for the company to create the new bicycle, because the company is already familiar with making bicycles out of titanium tubing. Braun always tries to use tubes that are manufactured by one company in their bicycles, this is because they noticed that the quality of material could differ much per brand.



Mysterious

Titanium has a mysterious status inside the consumer market. It is known as a very exotic material that is known for its use in the aerospace and medical sector. The consumer's attitude towards metal-alloy materials is less biased towards this mystery material. Making the bicycle out of titanium could be an added value when the consumer makes his/her decision to buy a custom Braun-cycling frame or a competitor frame.

3D-printing

The SLM production principle of 3D-printing that is used has the disadvantage that only certain alloys are available for printing. This is why a steel bicycle (chrome-molybdenum) was already taken out of the equation as this material is not printable (yet). As the method of SLM printing is being developed at a high pace, more materials will become available for production in the near future. For now, the materials of titanium (grade 5) and stainless steel (316) are available for printing with SLM (Oceanz, 2019). The choice fell on titanium as this material is already used in an existing frame of Braun-cycling and thus gives a better comparison of the added benefit of 3d-printed lugs.

Fig57: *(left) Stacked chain stay tubes at the Columbus tube factory in Italy.*
Fig58: *(below) The Lockheed Blackbird aircraft. This aircraft was used in the cold war to spy on the russians. These planes were totally made out of titanium, which was obtained out of Russia.*

Sustainability

Using metal-alloys over carbon is already a big step towards a better future. Steel (chrome-molybdenum) and stainless steel have excellent recycling abilities compared to carbon fibre. Carbon fibre can only be downcycled, the properties of the material come from the fibre lengths which are destroyed when shredded during recycling.

Titanium can be melted down but also loses a lot of its properties during recycling. This makes that titanium is also downgraded during recycling. There are promising strategies that could make recycling titanium more sustainable (O'Leary, 2015). Fig. 59 shows an example of a recycled titanium product.

The benefit of using titanium is that the material has excellent corrosion resistance. This makes the frame almost impervious to rust and dirt corrosion. Thus bumping up the expected lifetime of the frame indefinitelly on this part. The elastic qualities of titanium make the material be very resilient to bumps and heavy use. The elasticity makes the frame less brittle compared to a carbon bicycle frame.

Fig59: *A pair of watches made from recycled titanium chips left over after lathing processes.*

	Titanium grade 5
Youngs modulus (GPa)	110
Elongation (breal %	8.6 / 11
Fatigue strength (MPa)	530 / 630
Possion's ratio	0.32
Shear modulus (GPa)	40
Shear strength (MPa)	600 / 710
Tensile yield (MPa)	910 / 1100

Titanium alloys of the new design

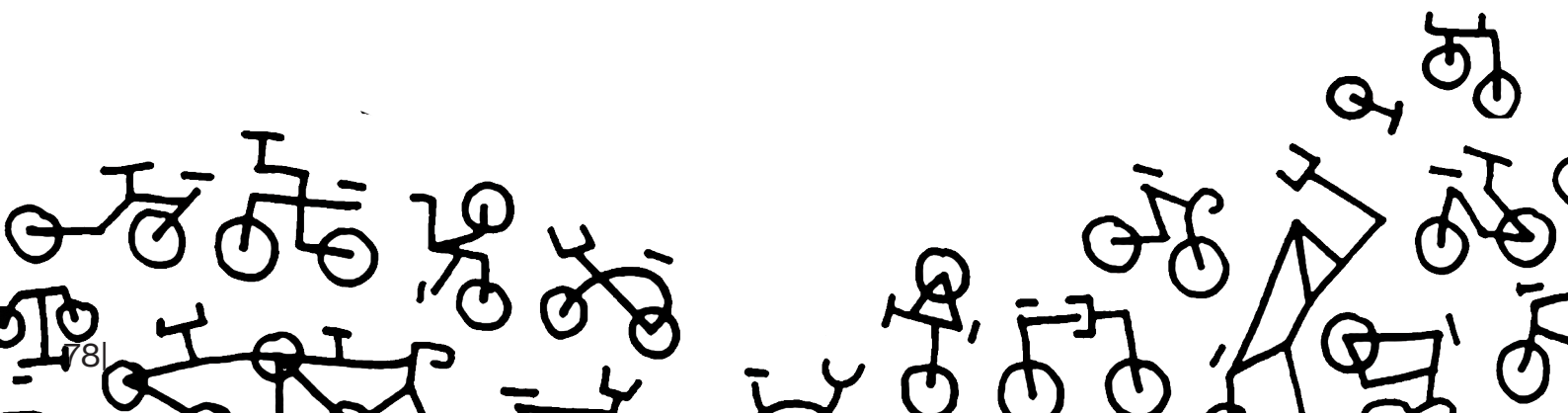
The tubes are made from grade 9 titanium (3.5% aluminium, 2% vanadium). This alloy tube is preferred by Braun-cycling and is used in the current Braun titanium bicycle. The 3D printed lugs are made out of titanium grade 5 (6% aluminium, 4% vanadium), the same material as the chain- and seat-stays of the Braun titanium bicycle. The grade 5 titanium has excellent strength to weight ratios, is extremely corrosive resistant, 3D printable and weldable. The combination of these two alloys will make for an extremely corrosion resistant, stiff and lightweight frame.

3.4 Conclusions of ‘The lug design’

In this chapter the next decisions are made that concern the method of the design of the lug for the bicycle. There lie opportunities in creating a lug that decreases peak tensions on the weld of the bicycle frame. Furthermore, the implementation of a lug in bicycle can improve the simplicity of the production of the bicycle frame. The frame should be made to resemble natural curved shapes. A good example of these shapes are natural bone structures. These structures are naturally very strong and light, two attributes that a good bicycle frame needs. These natural bone shapes fit the image that is created for the target group.

The bone like shapes can be created most easily with the use of topology software. This topology software will calculate the most light and strong shape for the bicycle. It does so by a strictly defined set of input forces and boundaries. This set needs to be defined before the shape can be generated.

The generated topology shapes will be non releasing. This in combination with the fact that Braun-cycling does not want to build up a stock of parts makes SLM printing the lugs a great choice. Braun-cycling would like to make the new bicycle out of titanium. Titanium has excellent material properties that are great for a bicycle. Titanium also has an exotic image which could help with the decrease of the consumer bias of metal-alloy bicycles.



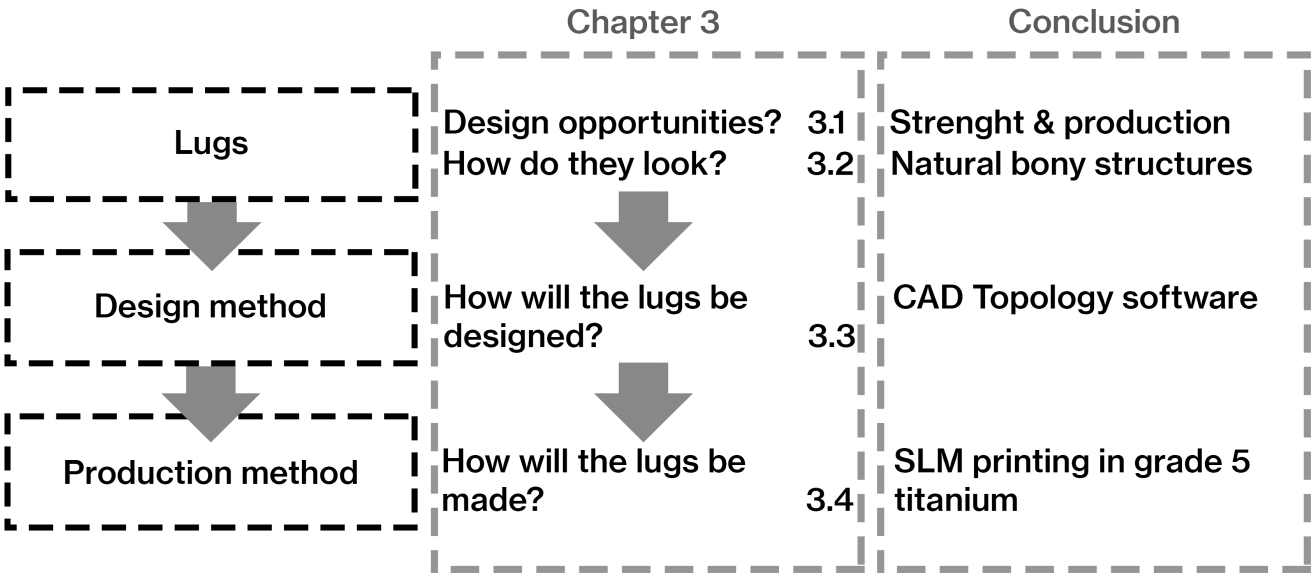
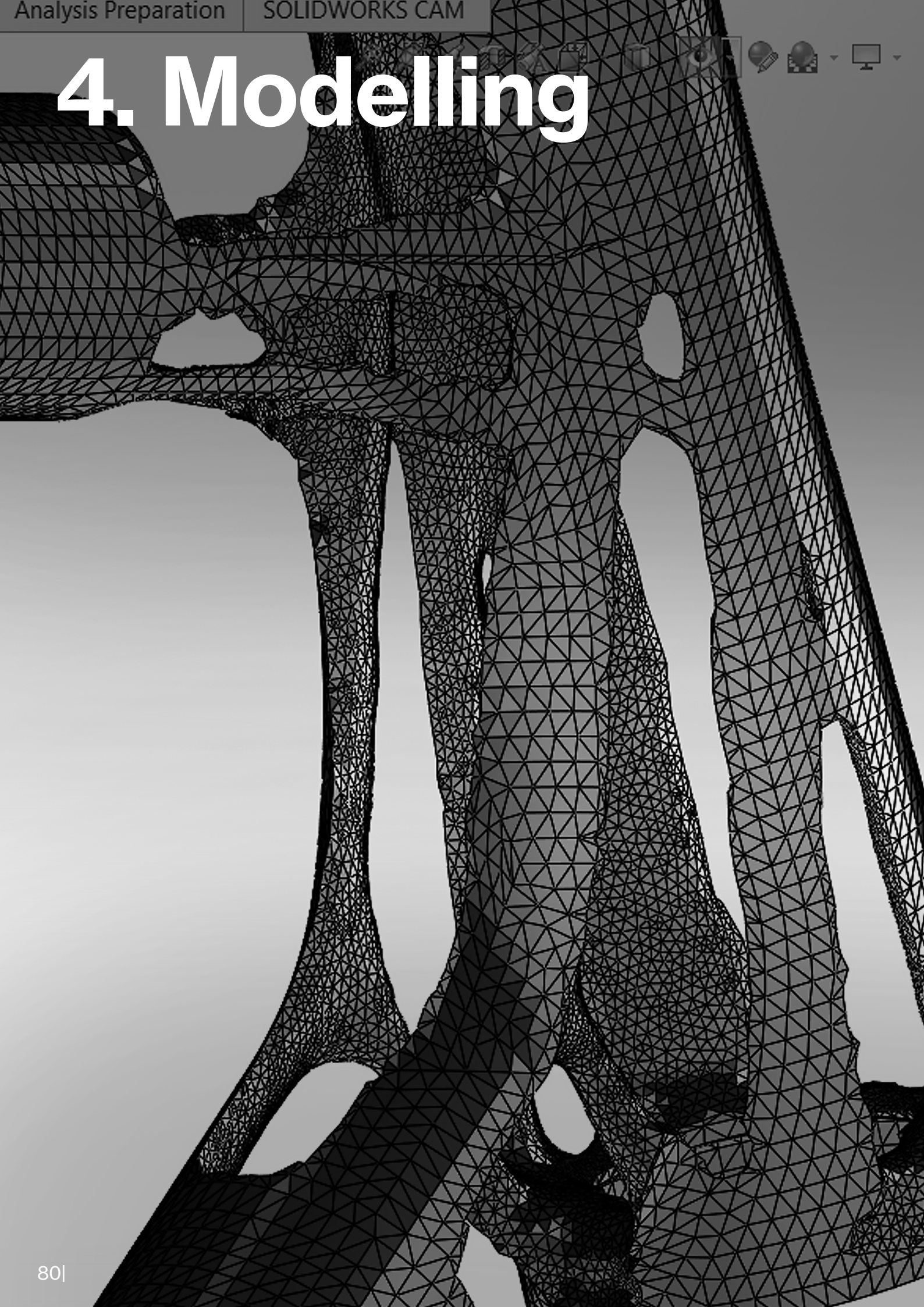
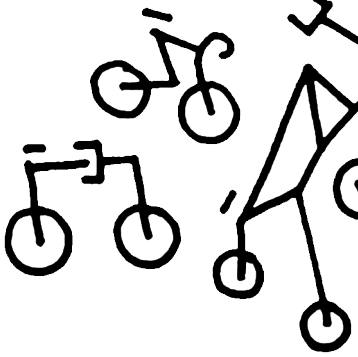


Fig60: *A visual representation of the answers and conclusions that have been drawn in chapter 3.*



4. Modelling



The next step in the design cycle is to start with the modeling of the lug. This chapter will go into the calculations and boundary conditions of the topology optimisation. First, a choice must be made what sort of frame will be used for the calculations of the topology software. The second part will explain and decide the set of input forces on which the shape of the lug will be calculated. Finally, the operation boundaries of the topology calculation will be decided and explained.

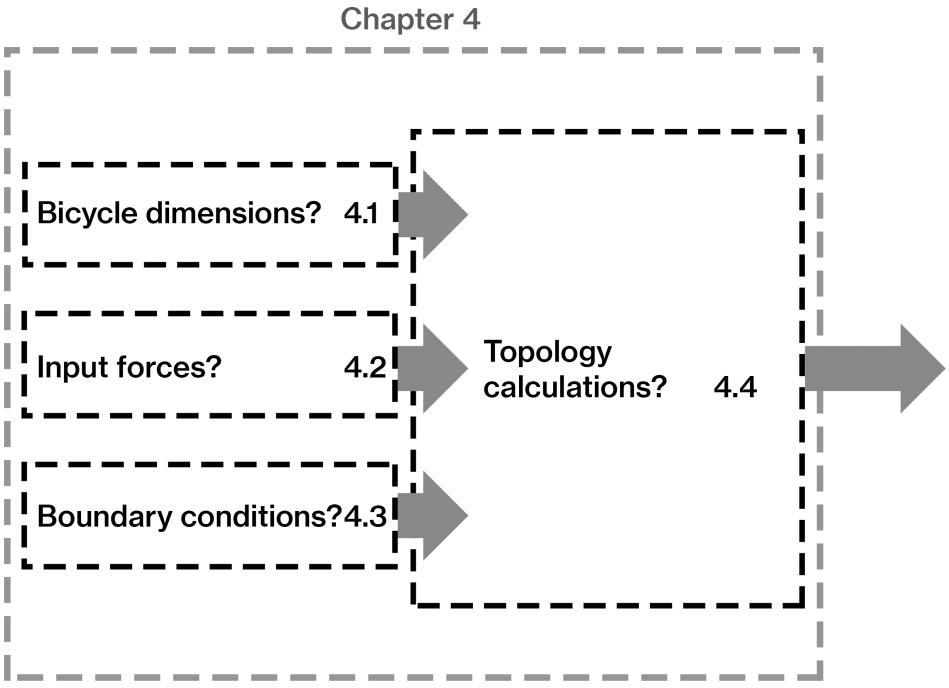


Fig61: *(left) A TO calculated shape of the head tube.*
Fig62: *(top) the content of chapter 4. This image shows the different inputs that the topology needs before running its simulation.*

The tool of TO has always interested me as the shapes that are generated are always very flowing, natural and fascinating. This was my first time working with topology optimisation. As the input and boundary conditions are very critical for the final output of the model, I sought help from an expert in the field of TO. Ir. Max van der Kolk is a PhD. candidate in the field of Structural Optimization and Mechanics research.

He helped me to set up and validate the input and boundaries for the TO.

4.1 Bicycle dimensions

Chapter two describes that the classic geometry of Braun-cycling must be used as the basis for the new bicycle. A simple choice would be to use the dimensions of a frame that already had been built. If the dimensions of an already existing bicycle frame are used in the new frame, a good comparison can be made to the bicycle of Braun. If a new frame with new dimensions and geometry is chosen for the final build, there would be too many variables to truly compare the effect of TO on the lugs in the bicycle.

Braun-cycling has a frame which is made for Herman Braun. The frame is always in the store in case someone wants to test drive the Titanium bicycle. It is a logical choice to model the new bicycle on the same dimensions and geometry as the frame of Herman. This so that Herman being an expert bicycle builder could test the new frame himself. This final test will ensure that the new bicycle has the characteristics of a true Braun-cycling bicycle.

From this, it is an easy decision to model the new bicycle using the same dimensions as the titanium bicycle of Herman Braun. The bicycle has the classical geometry that Braun always uses in its models (the diamond geometry). The average bottom bracket drop of 6.7 cm and seat-tube angle of 74 degrees make the bicycle a comfortable all-around performing bicycle. For more information about bicycle geometry and its history read App.B For more dimensions of the bicycle see Fig.63.

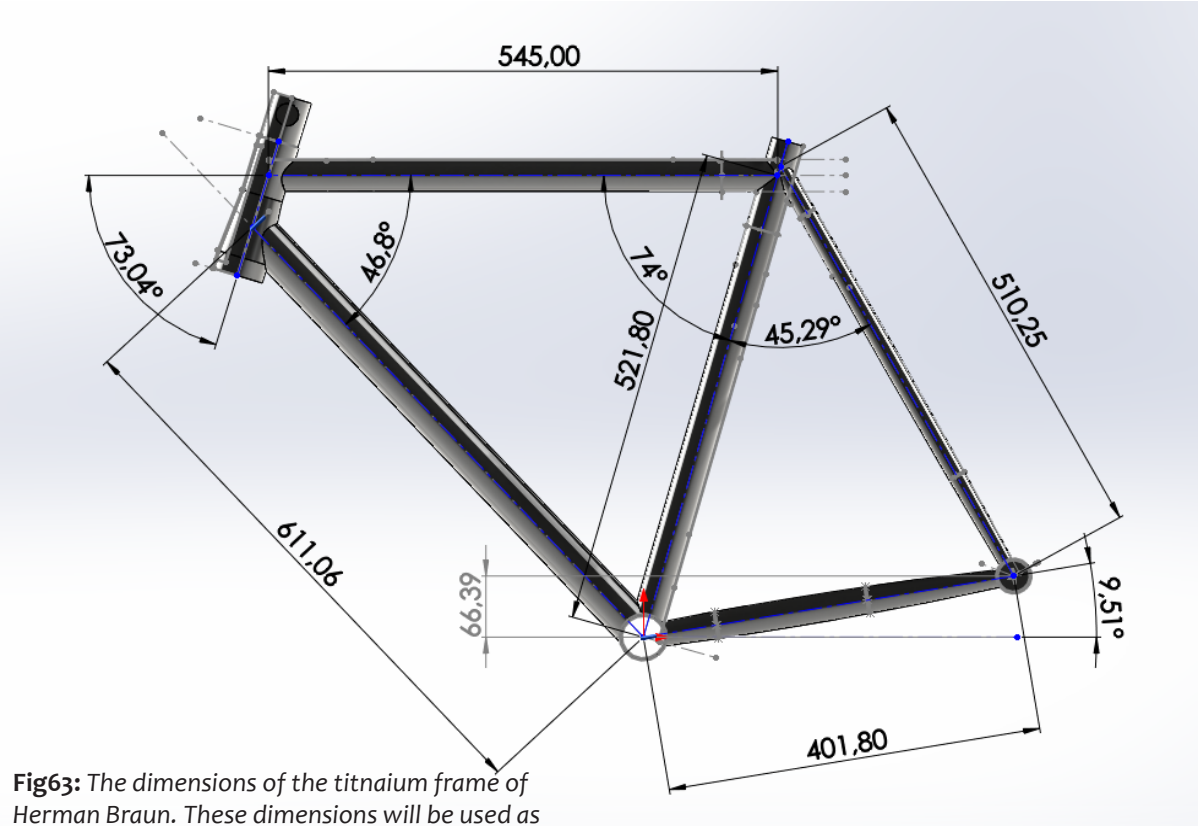


Fig63: *The dimensions of the titnaium frame of Herman Braun. These dimensions will be used as the blueprint for the new frame.*

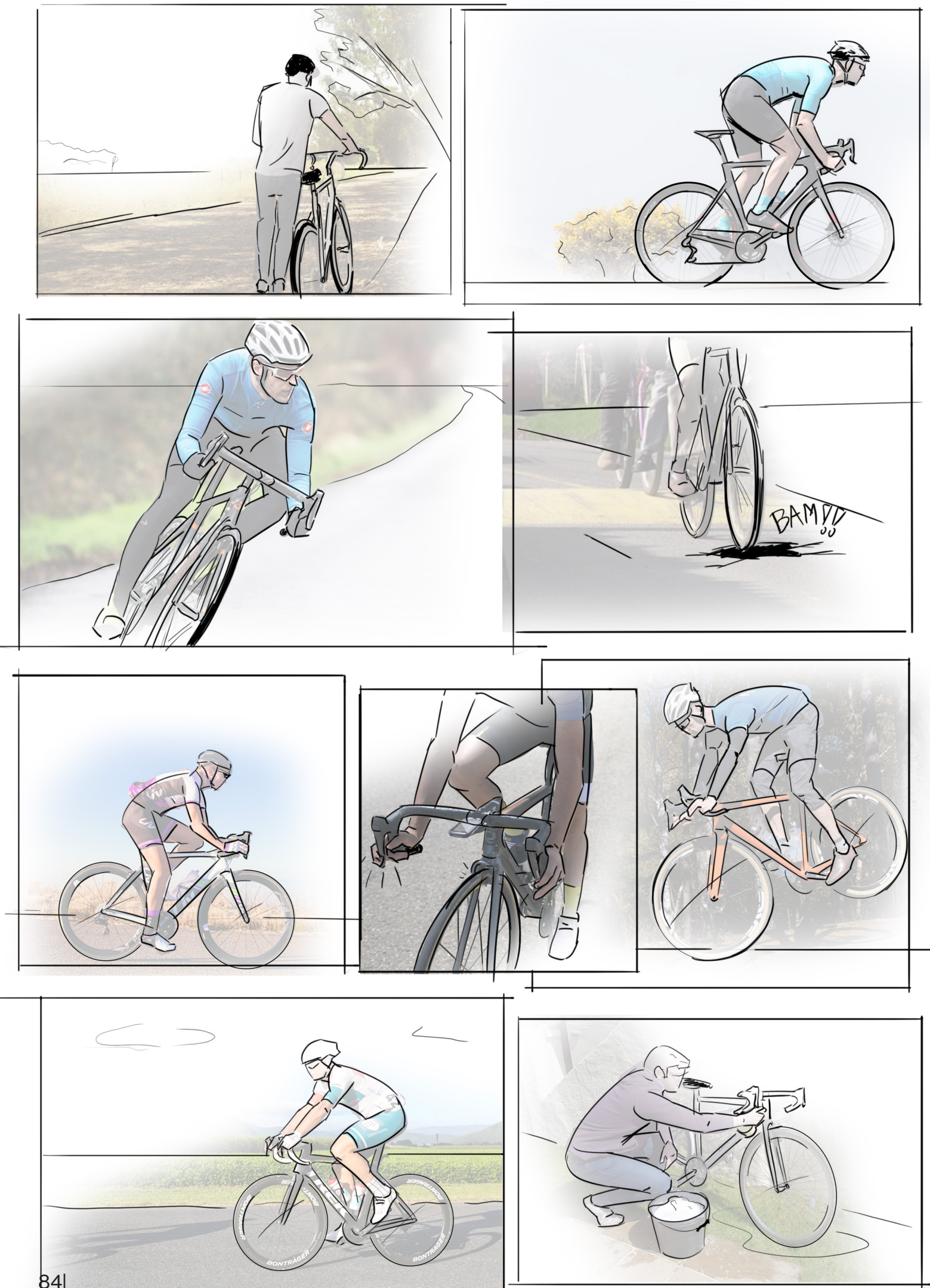


Fig64:*The user scenario of a road race cyclist.*

4.2 Input forces

A topology optimisation calculates its output shapes based on a carefully constructed set of input forces and boundaries. If forces on the bicycle frame are forgotten in the calculation, the resulting shape of the TO will be too weak when used in real life.

To get a better view of the load-situations of the bicycle frame, the use of the bicycle is analysed. A user scenario of the bicycle is depicted in Fig.64. From this scenario, different critical situations are extracted. These situations are later compared to papers that go into the field of bicycle loads and frame optimisations (Hull,1988 ; Soden,1986,1979 ; Stone,1995). For the load cases, the force inputs form these papers are used that define the peak power inputs on the bicycle frame.

The load cases that have been used to describe the force inputs are:
Standing start (Fig.65)
Heavy braking (Fig.66)
Sitting rider (Fig.67)
Road irregularity (Fig.68)

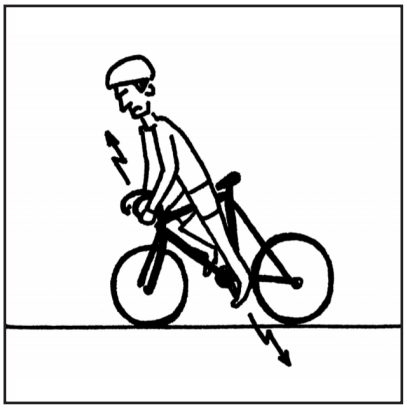


Fig65: *Standing start*

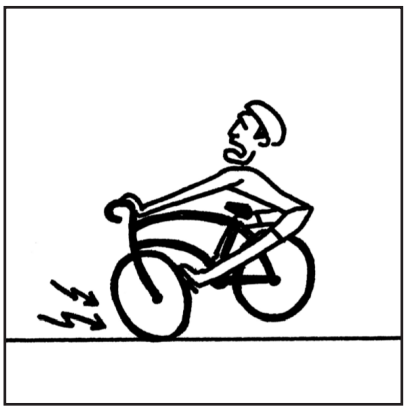


Fig66:*Heavy braking*

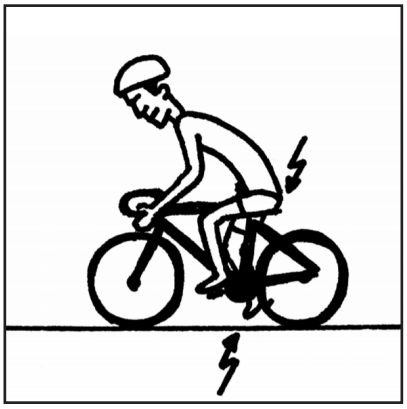


Fig67:*Sitting rider*

Fig68:*Road irregularity*

Changing the cycle

The first few calculations were made by taking the situation with the highest forces as input to generate the shape (standing start). This shape was later simulated in stress studies on the other situations (sitting, irregularities and braking). This method was very time consuming as it took 3 simulations to validate one shape. Together with Ir. Max v.d. Kolk, the 'super scenario' was created. This super scenario is a mix of all of the situations. This super situation would give a more 'robust' shape as a result of all of the different shapes and forms. After modelling the final shape the stress simulation can be done using the same input forces from the super scenario. Both methods are depicted in Fig.69, showing clearly that method 2 is much faster and easier compared to the first one.

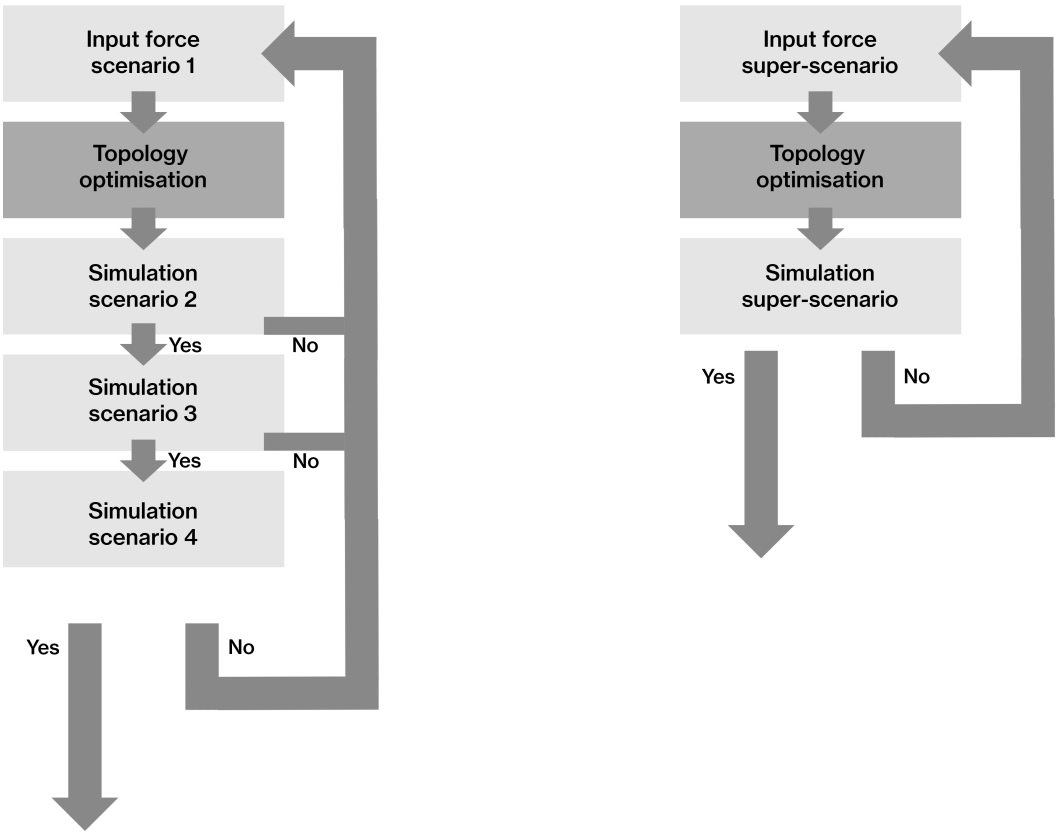


Fig69: *(left) the old modelling method where all of the scenarios were validated seperately. (right) shows the new design loop where the super scenario implements all of the forces and also acts as the simulation condition.*

The super scenario

The four cases described in Fig.65 to Fig.68 give the force inputs that have the highest inputs on the handlebars, saddle and pedals. These four inputs are added up into one big 'super' scenario. This super scenario is used for the TO as input and will generate a robust shape that is made to withstand all of the proposed situations. Some forces from scenarios have an overlap (they go into the same direction at the same point). These forces are critically looked at and weighed if they can manifest at the same time. For example forces that are generated with standing and sitting cannot be added up at the same point, as there is no situation where someone stands and sits at the same time. In these special cases, the highest force is used as input, the lesser one can be left out of the equation (Maestrelli, 2008).

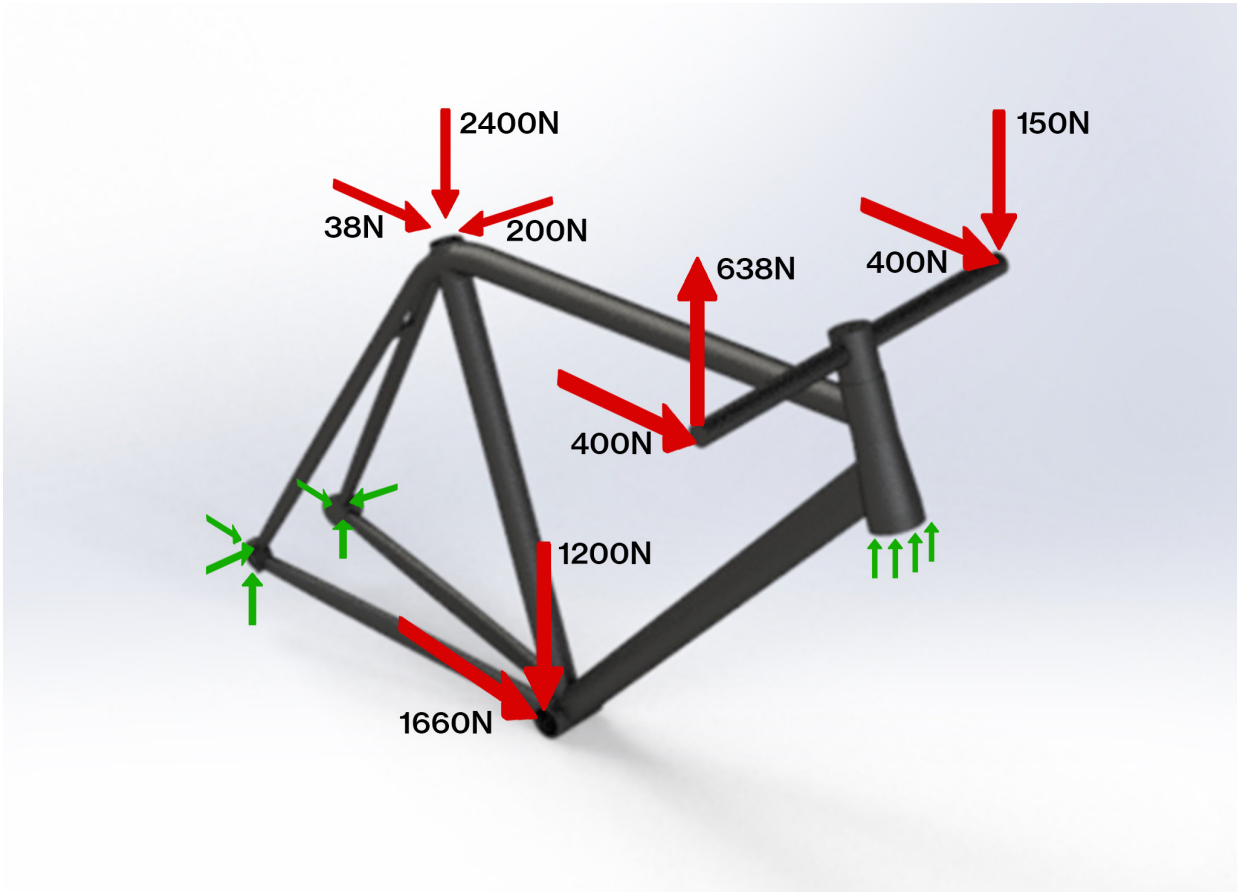


Fig70: *A visual representation of the forces of the super scenario that is used as input for the topology optimisation.*

4.3 Boundary conditions

As mentioned before in chapter 2, the TO tool from SolidWorks, works via a subtractive principle. This means that the raw uncut shape for the calculation must first be defined. If we compare the new bicycle to the conventional titanium frame of Braun cycling, we can see that the outline of the lug is much more rounded in the new design.

The rounding of the outline is done deliberately. Looking back at Fig.52 and the form language in chapter 3 it is described that: the new shape must flow, and stop the 'old' straight tube-to-tube shape. The quick assumption can be made that the TO would remove material in the middle sections of the raw shape, as most of the strength comes from the outer perimeter of the material. So if the old outline of the bicycle was kept we would have a bone-like structure, but made within the perimeter of the old straight-edged bicycle frame. Such a shape would not meet the required shapes described in the form language. The raw shape of the lugs was therefore formed to get a shape that blended the straight geometric shapes together to form a smooth and flowing whole. Examples of the raw shapes of the lugs can be seen in Figures 71,72,73.

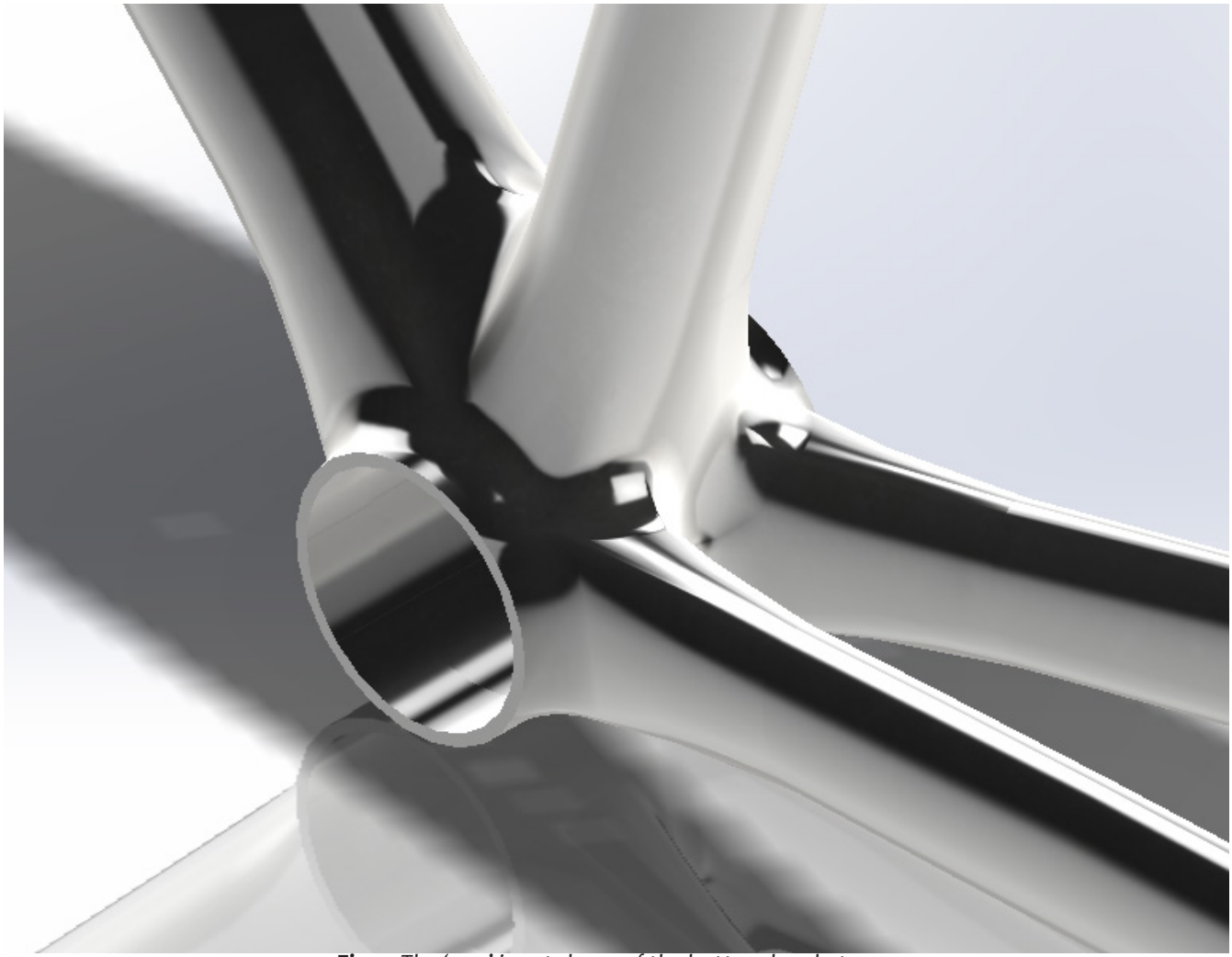


Fig71: *The 'raw' input shape of the bottom bracket*

Fig72: *(right) The 'raw' input shape of the seat tube lug.*
Fig73: *(below) The input shape of the head tube lug.*

Parts

There are aftermarket parts that need to be mounted on to the frame before it can ride. Examples of these parts are the fork, derailleur, cables and wiring. These products need to be excluded as forms from the raw shape of the TO. This is so the TO would not generate material where in real life a part needs to be. A full list of the parts and their negative workspace can be found in appendice. C.

Cyclist

The seat-tube lug was given a bit more material on the sides to make the raw shape a bit broader and more flowing. The first optimisation of the seat tube lug had a too broad shape. This makes the sides of the lug hit the inside of the hips of the user during cycling. In Fig.74 the mock-up for the test can be seen for the first lug test. The final raw-shape was made so the rider would not feel the lug during the use of the bicycle.

Mirror

During the use of the bicycle, the forces that are exerted on the bicycle frame alternate from the left side to the right side as the user uses the left and right foot to push on the pedals. The force input is static, making the calculation only working on one of the situations (the right pedal stroke). This, of course, must be taken into account with the final result as the real-life user will also use the left leg. This can be done by mirroring the calculated result over the middle (lengthwise of the side plane) of the bicycle. Mirroring will ensure that the forces of the left and right pedal stroke will be accounted for by the TO.

Fig74: *A quick mock-up for a test to feel if the generated TO shape would touch the inside of the leg during cycling.*

4.4 Topology calculations

With the forces, starting shapes and boundaries defined in 4.1, 4.2 and 4.3 the topology simulation is ready to generate its first shapes. A topology simulation can take a lot of time to calculate the final shape. Figures 75,76 show the output of the topology calculations of the head tube and the bottom bracket. For a more detailed view of all of the separate parts see app. D. With these 'raw' shapes the next step in the design process can be started, the embodiment phase.

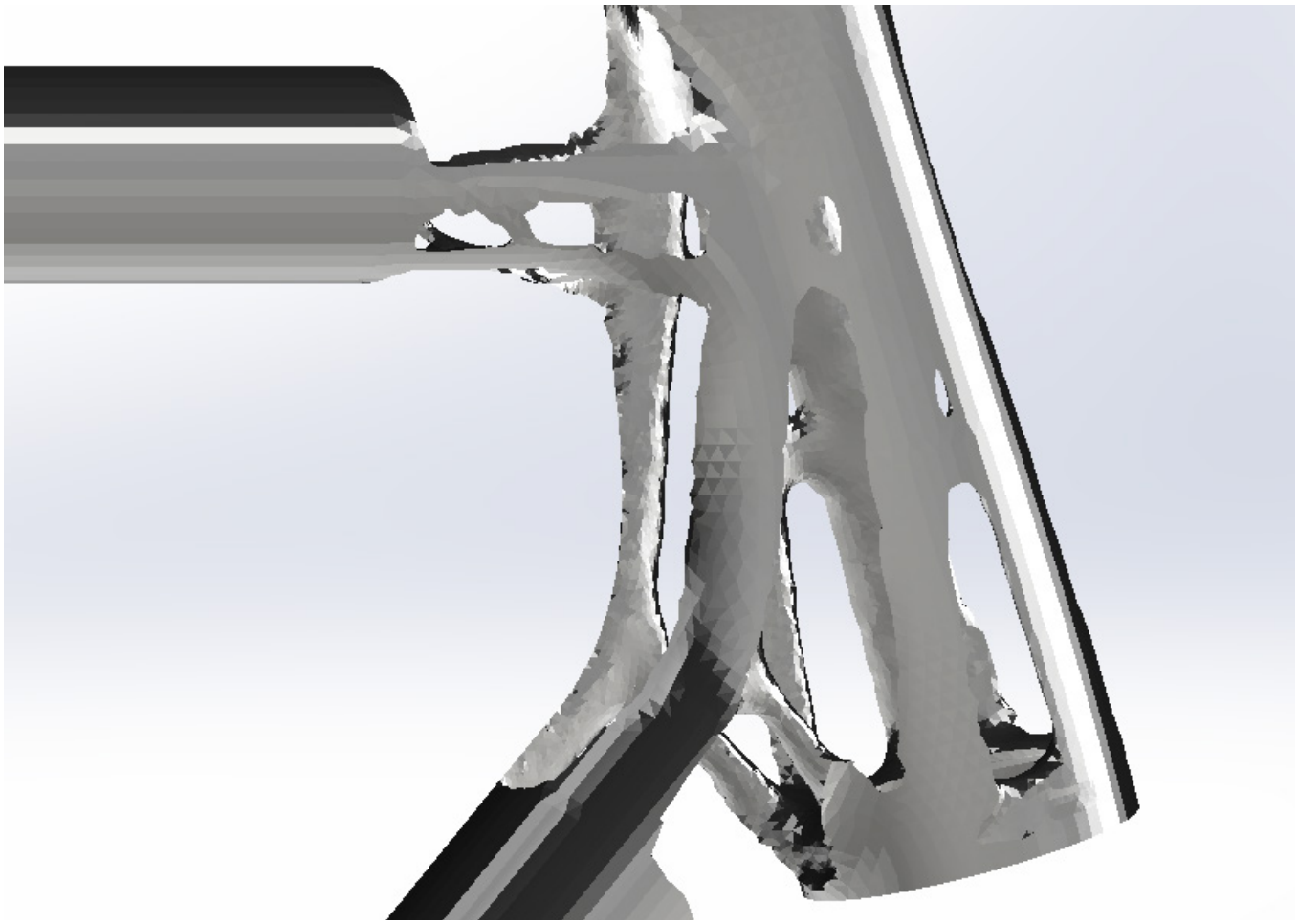
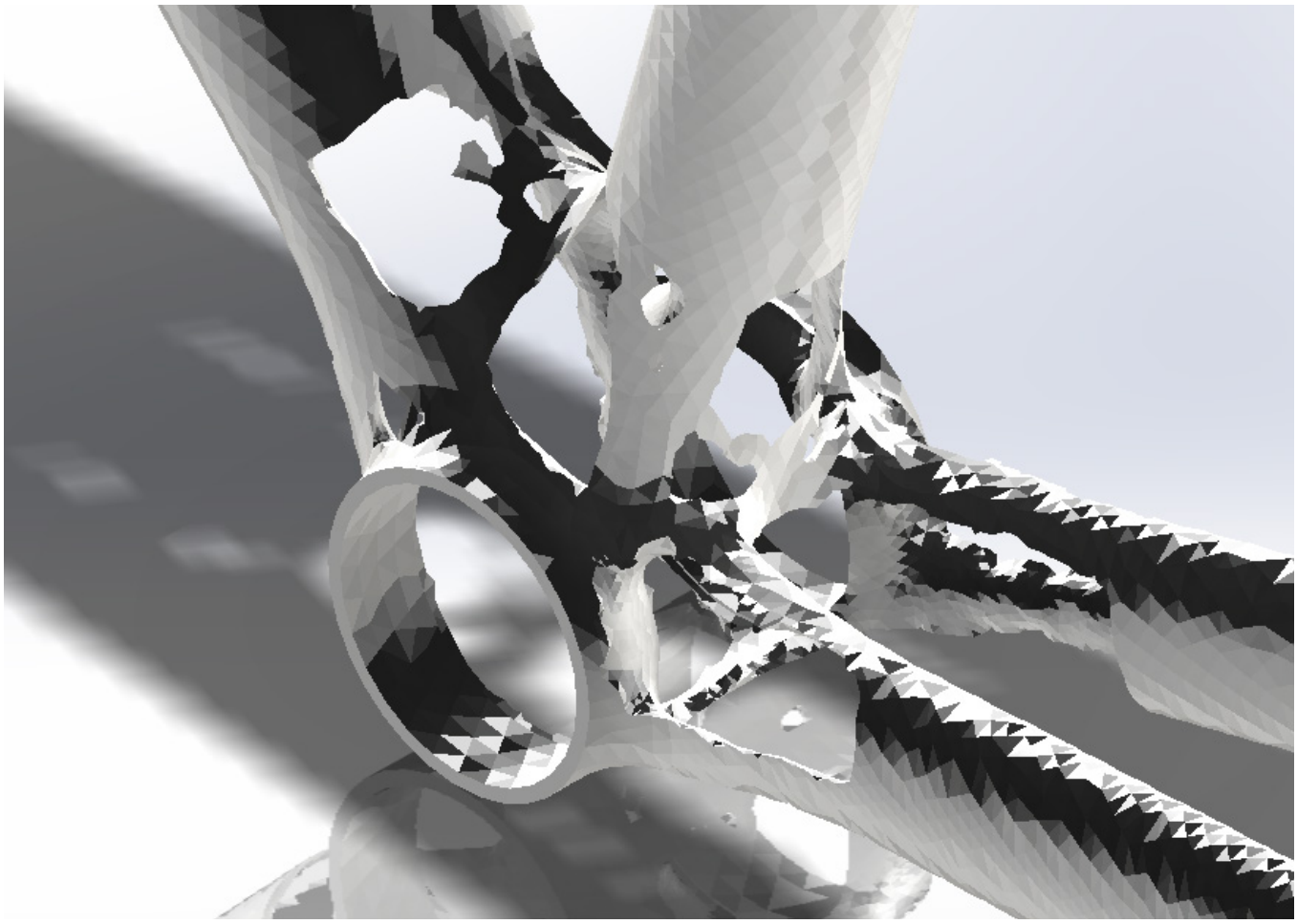
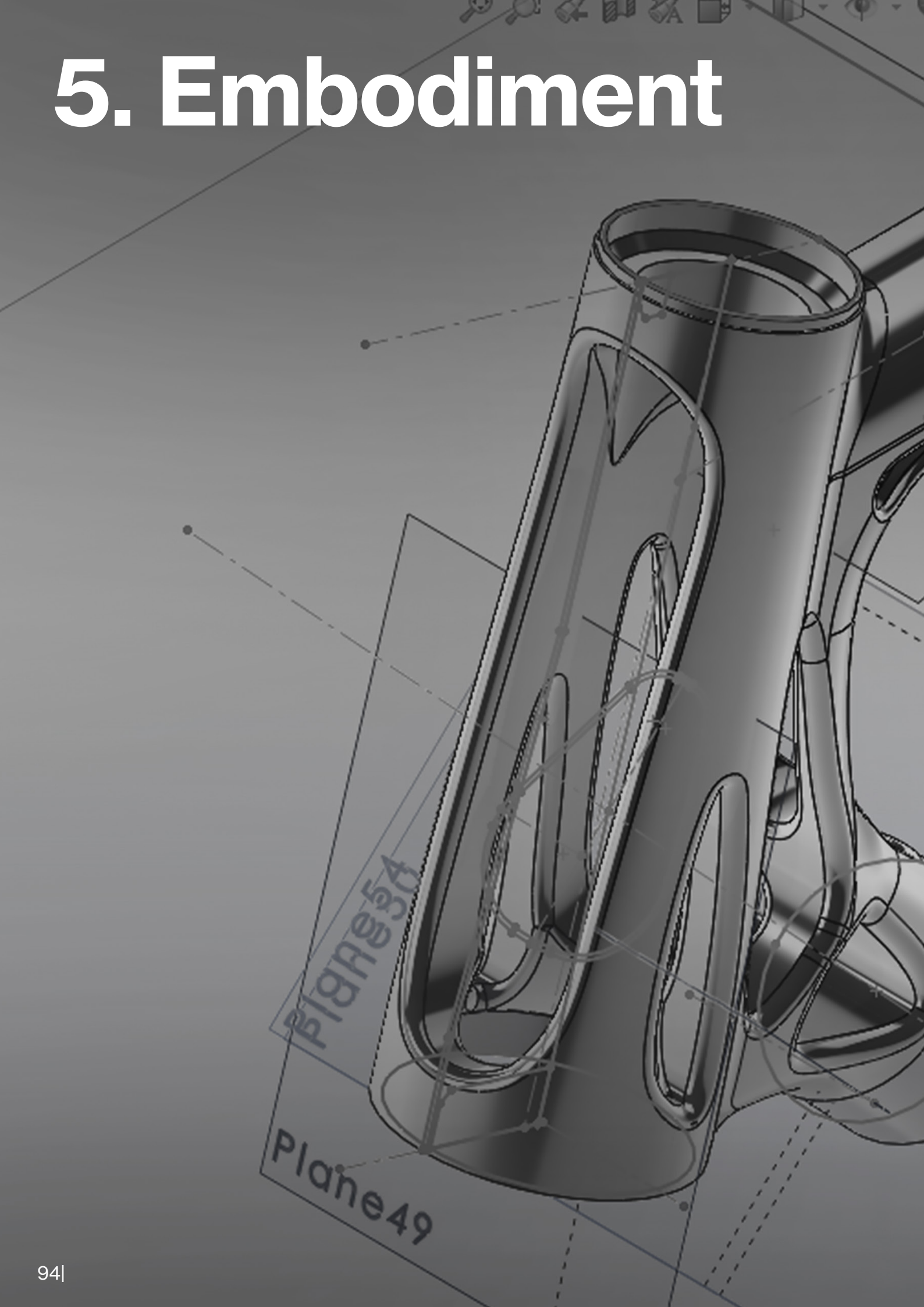
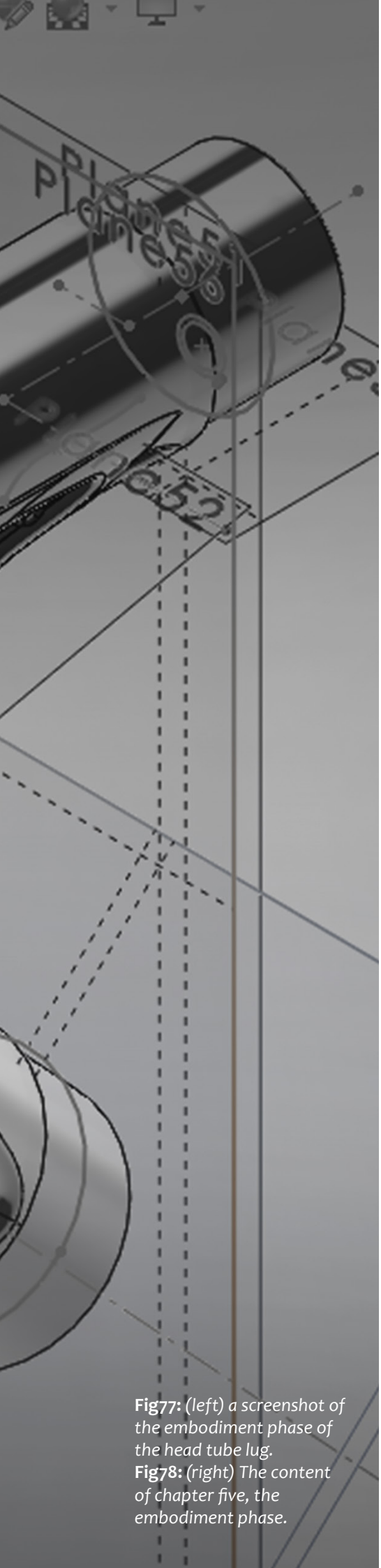


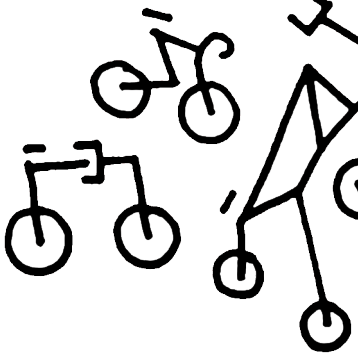
Fig75: *(above) The TO calculated shape of the head tube lug.*
Fig76: *(below) The TO calculated shape of the bottom bracket.*



5. Embodiment







With the shapes of the lugs being made with the topology calculation, the next step is to make them production ready. This chapter will dive into the process of going from a 'raw' and unprocessed topology shape, to a product that is made to fit the requirements of consumer and company. Chapter 5.1 will focus on the process of designing the raw TO shape to a smooth and trustworthy looking product. In chapter 5.2 the lug connections, parts that will be mounted on the lug and other context factors will be explained. The final smoothenend and production ready shapes will be simulated and validated in chapter 5.3.

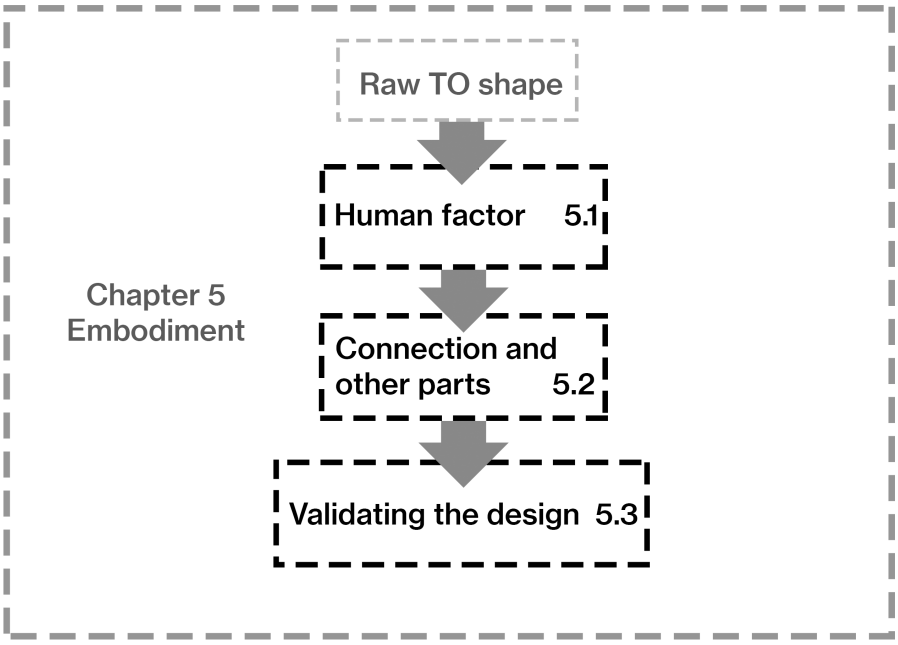


Fig77: *(left) a screenshot of the embodiment phase of the head tube lug.*
Fig78: *(right) The content of chapter five, the embodiment phase.*

5.1 The human factor

The bicycle TO calculates the model on the minimal necessary material for the maximal strength of the frame. The outcome of these calculations can look very 'extreme' and unfinished, this can be seen in Figures 79,80. During client- and coach meetings a distrust in the generated shapes became apparent. The perception and intuition of consumer and expert was that the generated shapes of the lugs were being observed as too weak to safely use in a bicycle frame. This, of course, whilst the calculations of the computer stated that the generated shapes are safe to use.

Extreme shapes

To overcome the distrust in the generated shapes of the TO, the shape could not be used directly into the final model. The transitions from straight tubes, to bone-like structures, were too hard and the generated structures looked flimsy, an example of such a form can be seen in figures 79 and 80. The solution to the problem lays in the same approach as the one that has been used for the raw TO shapes; namely, the outline of the product needed to be flowy, yet robust. This generates a platform to cut out the bone structure with the topology at the basis of the shape. This makes this way of using the TO a most advanced, yet acceptable product.

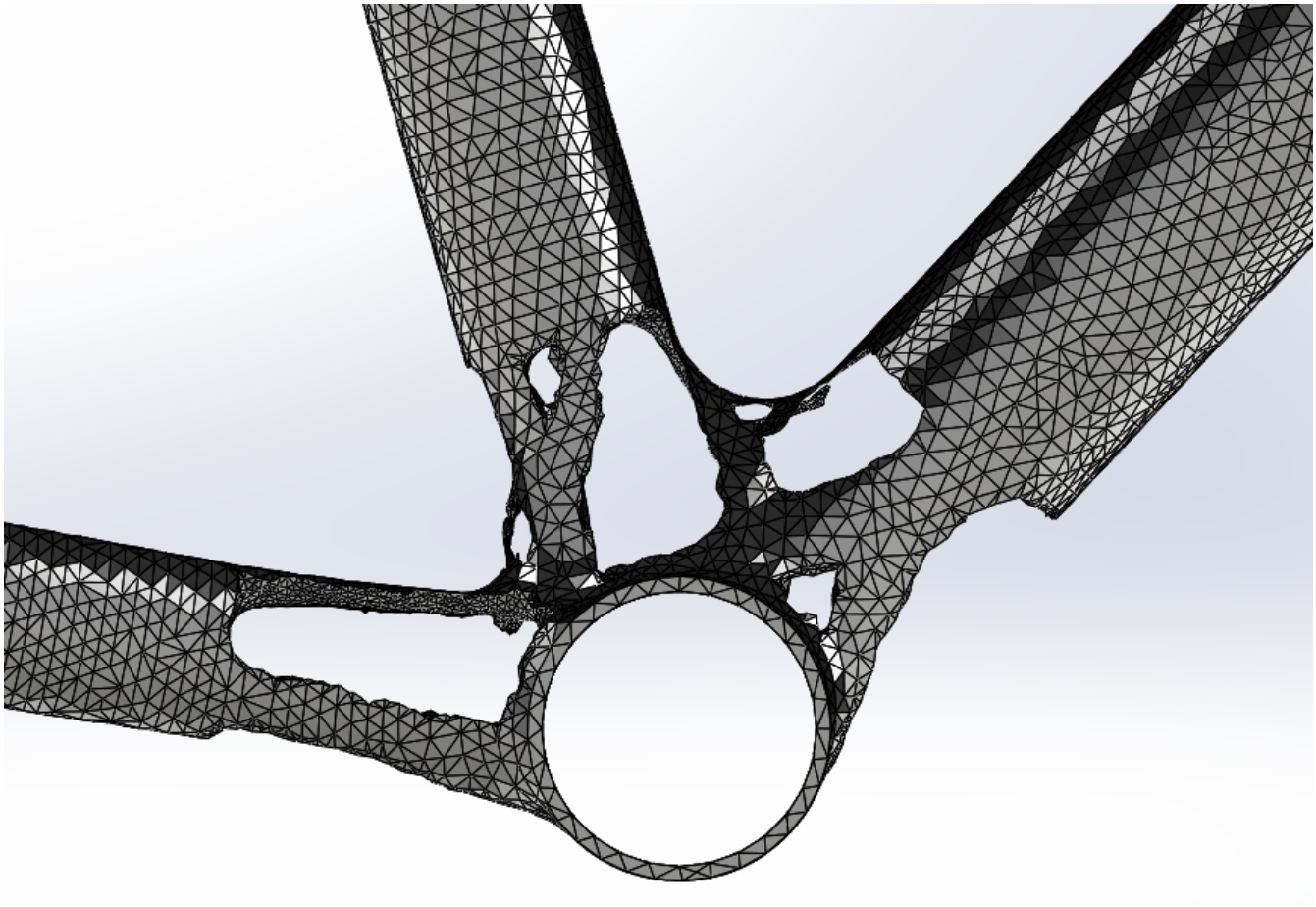
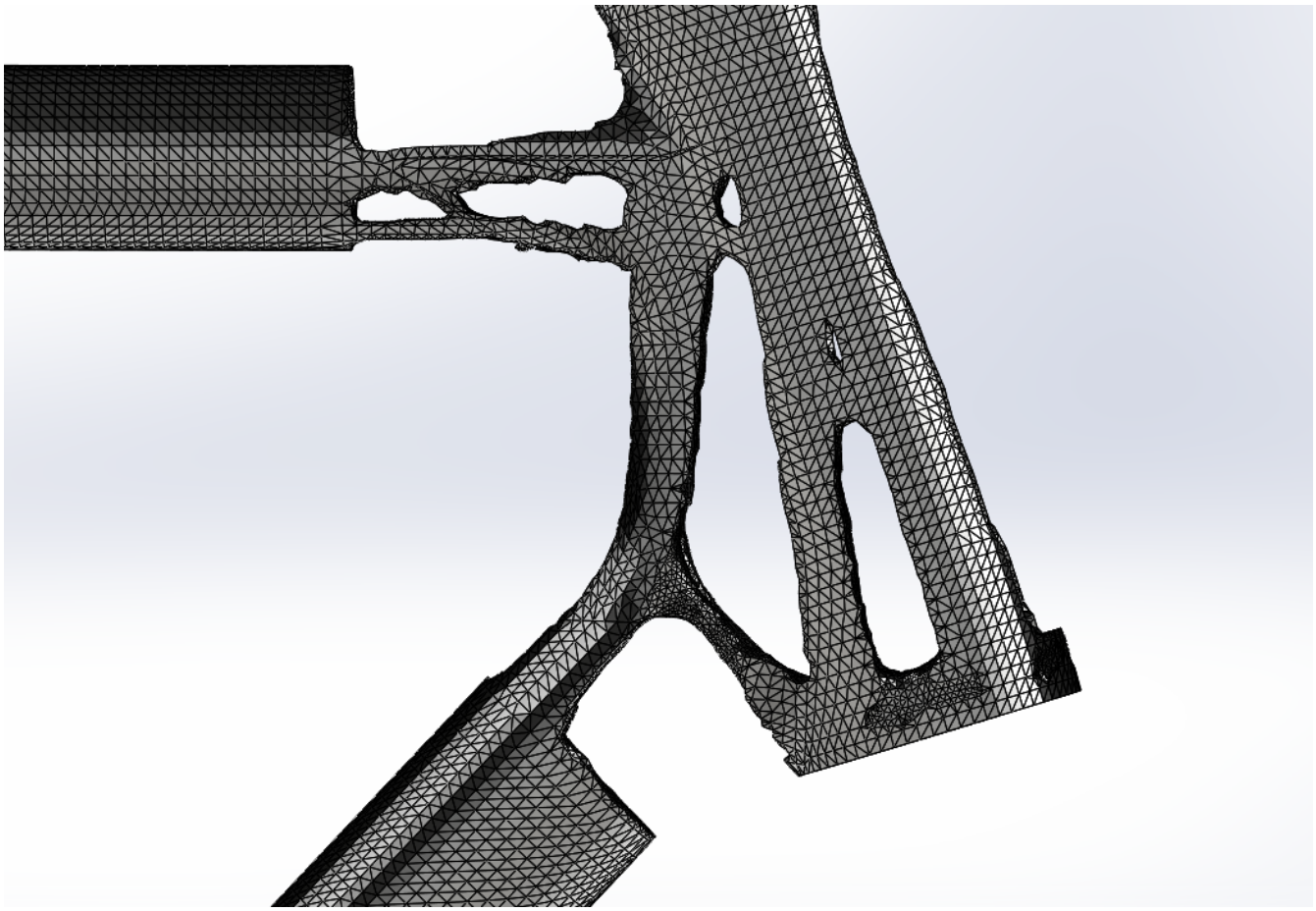
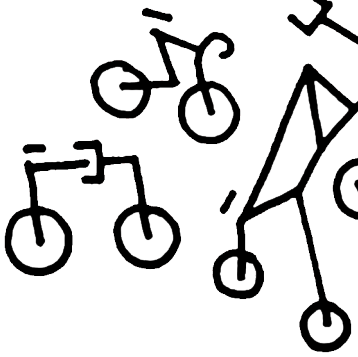


Fig79: *The flimsy looking shape of the bottom bracket.*
Fig80: *The unsafe looking TO shape of the head tube lug.*





Efficiency of TO

This, ofcourse, implied that the TO is not as efficient anymore as it could be. The TO generated shape used as an underlayer to guide the designer where to remove and where not to remove material. By doing so, the designer could be the final judge in making the decision in removing material that is surplus or leaving the material to not corrupt the perception of trust of the user. An example of one of these choices is given in Fig.81. In this case, the transition from the straight 35mm tube to the small TO shape was too hard, the choice was made to leave the side outline (viewed from the side) the same width as the tube, but to incorporate the negative shape generated by the TO. Combining both into one shape makes for a slightly heavier part, but one that looks more robust and trustworthy. This cycle has been repeated several times, checking with the client if the shape matched their expectations. As an example of the iterations that have been made for the design of the seat post is given in Fig.81. Here it becomes clear that per design iteration the decision is made to round-of the TO generated shape more, creating a more coherent and minimal look.

The advantage of this strategy with using TO as an underlay for the final design, is that in the final simulations minor adjustments can be made to the shape, in order to decrease any peak stresses that show during the simulation. This makes for a short feedback and optimisation loop in the design process.

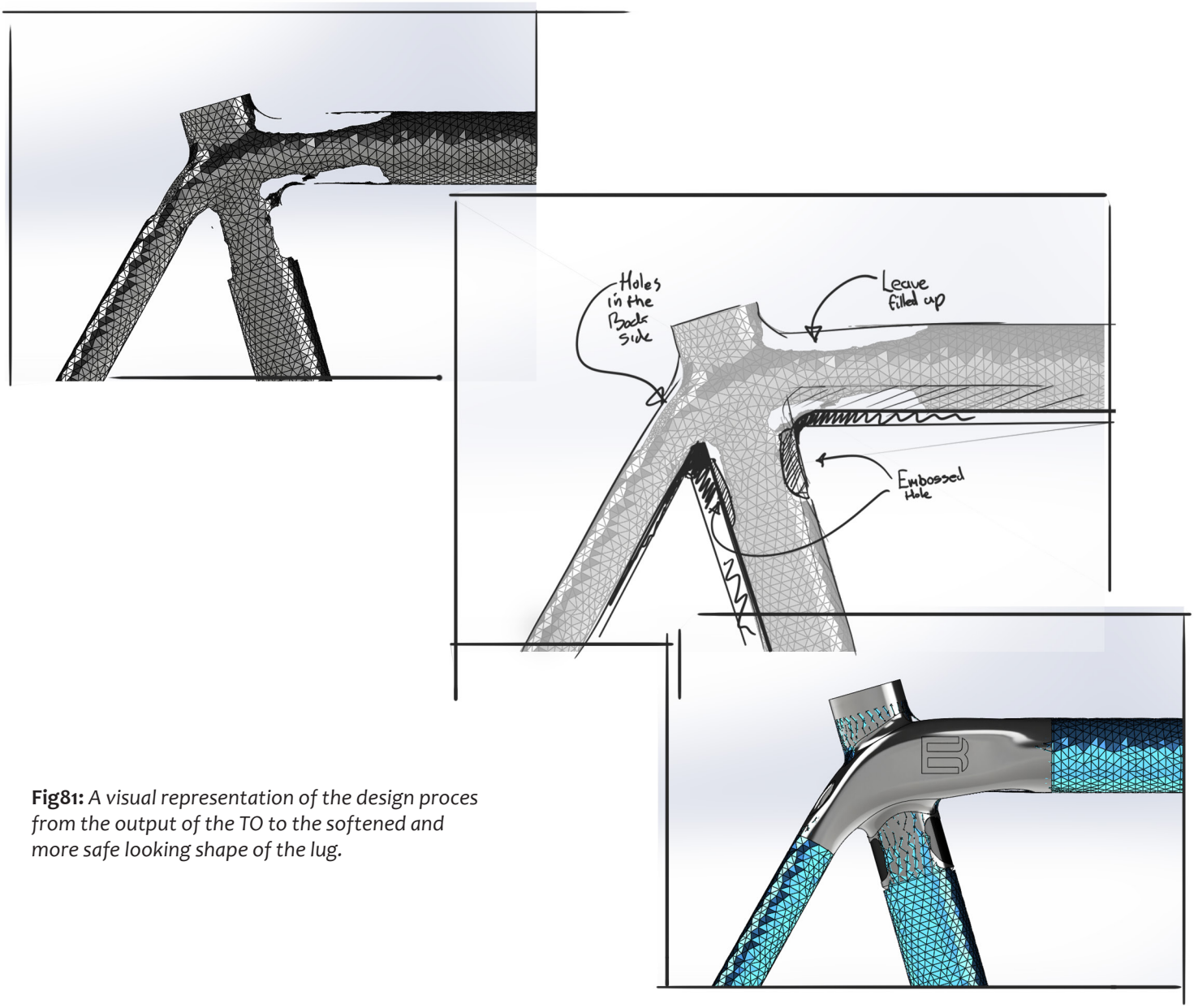
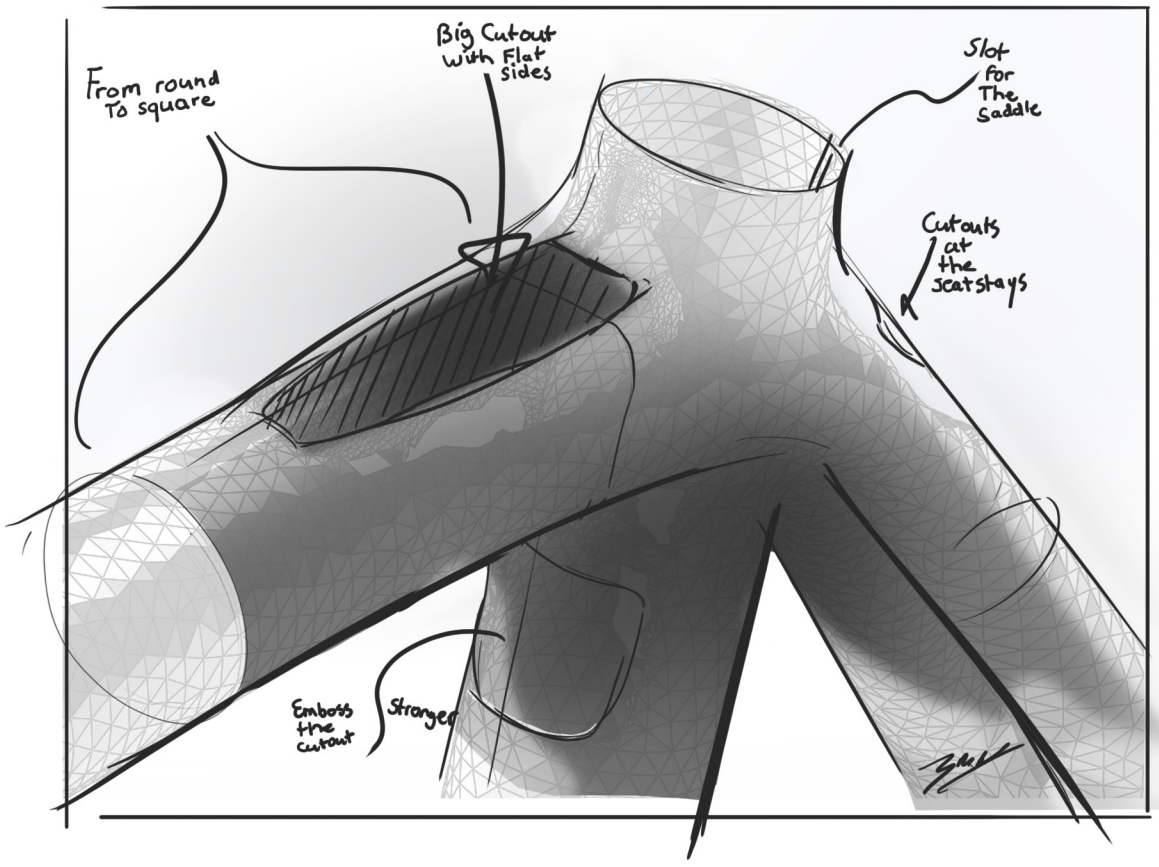


Fig81: *A visual representation of the design proces from the output of the TO to the softened and more safe looking shape of the lug.*



5.2 Connection and other parts.

The five designed lugs that are made do not form a whole bicycle by themselves. The lugs are welded to tubes and other external parts are mounted or function around the lug. This chapter will dive into the parts that surround the lug and how these will interact with the product.

Fig82:*The bottom bracket of the Braun-cycling experience model. In this picture we can see that there are multiple parts that ened to be mounted onto the bottom bracket.*

The connection from lug to tube

One of the big questions that arose during the project was how to connect the 3D printed lugs to the metal tubes. There were multiple options to do so: glue, weld, bol and etc. Yet, the choice fell quickly on welding the prints to the tubes. This because it is the strongest bond of the 3, fusing the parts together to form a strong connection. The other reason being that Dave Braun, the next in line to manage Braun-cycling, is an excellent welder. It is one of the signatures of Braun and therefore a must for Braun-cycling to keep in the product.

Stiffness

With the choice being made of welding the print and tube together the next question arose; would the lugs be too stiff for the tube? This is a fear that finds its foundation in the use of the old lugs on old steel road race bicycles. The first lugs were made out of chunky blocks of steel and were very stiff. Much stiffer than the thin-walled tubes used for the frame. Connecting these stiff lugs onto the weaker tubes gave a force concentration at the seam of the connection during heavy use of the bicycle, this because a normal lug bents a bit, thus making it absorb force. These forces, generated on the weld by the stiffness of the lug, could reach such heights that the tubes would fail at the connection seam. To overcome this problem, lugs were given curved shaped edges instead of straight edges. The curved edge shape distributes the load on the seam over a larger surface and the thinner lugs absorbed some of the power.

In the new lug design, the shape of the lug is generated with TO so the material will not fail during use. In theory, the peak loads that manifested at the seams of the old lugs should be lower in the new lug design, this is because the forces are evenly spread across the bone-like structure of the lug making it bend just enough to divert the stresses away from the seam. This is backed by the simulations of the computer model, which show no big peak stresses at the edge of the seams. An example of this can be seen if we compare Fig.83 and Fig.84 which resemble the results of the new and the conventional frame.

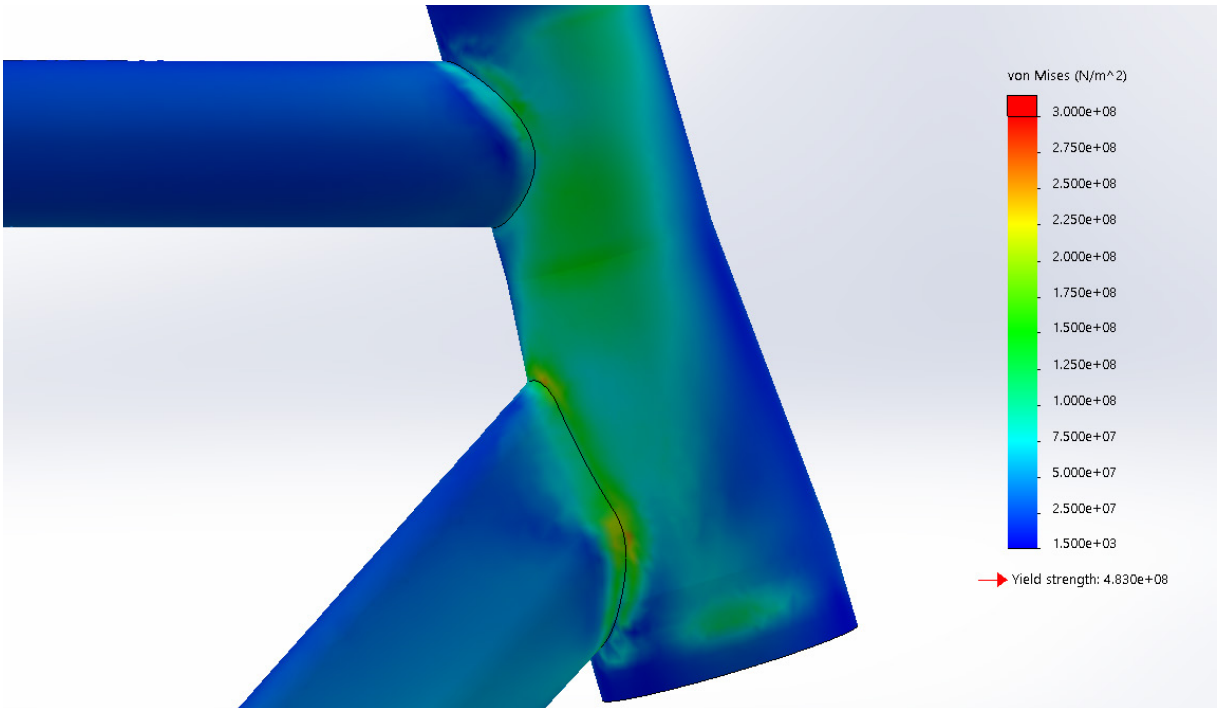
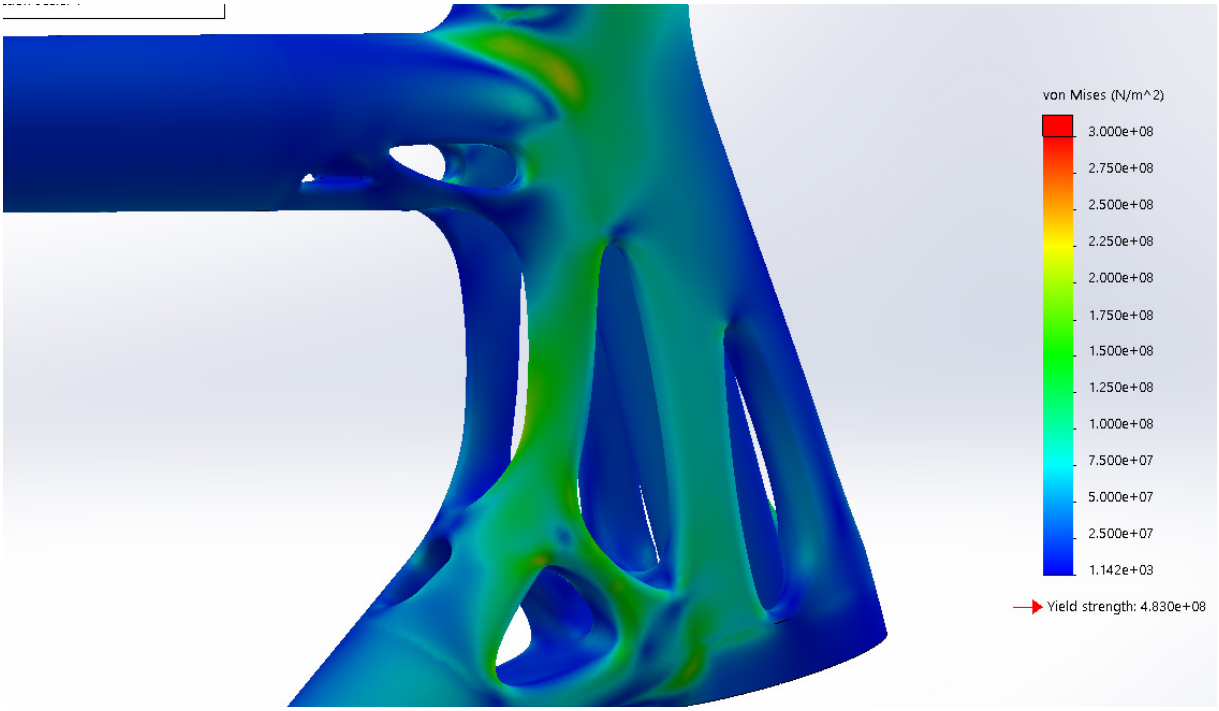


Fig83: *(above) The yield strength simuation results of the current titanium bicycle. We can see smal peak stress point coloured light red.*
Fig84: *(below) The yield strength simulation results of the new bicycle. we can see that there are less (high) peak pressure points.*



Straight edge

With the 3D printed lugs, the minimal wall thickness that can be reached is 1mm due to the printing machine properties. This is 0.1mm more than the wall thickness of the tubes that are used in the bicycle. This, at first glance, gives the same problem as the old straight-edged lugs on steel bicycles, namely that the lug was too stiff compared to the tube. Giving the new lug a curved edge was not an option as one of the big advantages of the new lug principle was that the tubes could be sawn of straight instead of the conventional mitred principle.

Tube insert

To overcome the bias created by previous experiences of the client, a new design was made that incorporated the straight edge but diverted the 'forces' away from the seam. To create this situation the assumption was made that the lugs would not bend in any way making them extremely stiff. This made for a situation where all of the forces were concentrated at the seam of the connection between lug and tube.

To divert the loads away from the seam, multiple inserts are modelled on to the lug. These inserts go into the tube. These shapes and forms were generated through multiple iterations, slowly making small adjustments to improve the final shape. Examples of these shapes are shown in Fig. 85, simulation results of the force distributions can be seen in appendice E .

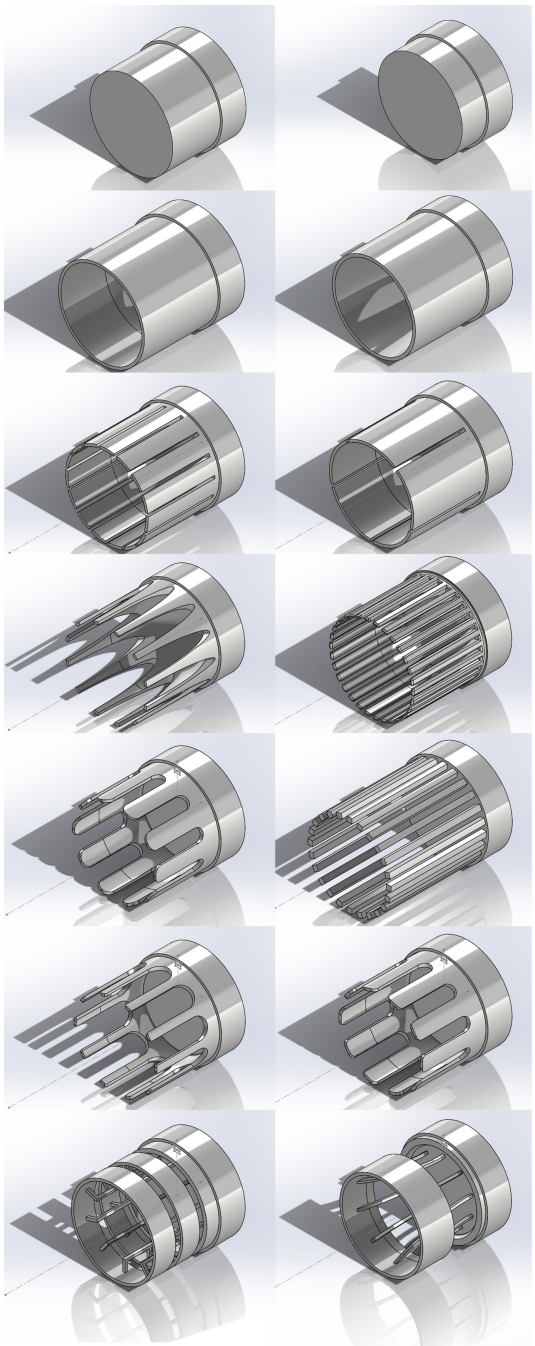
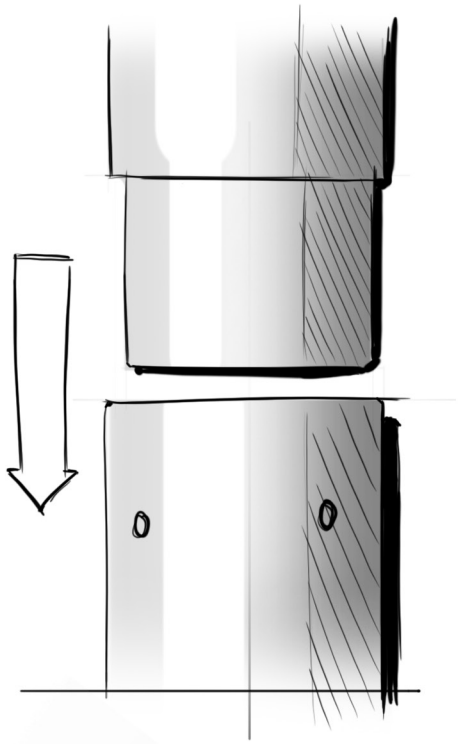


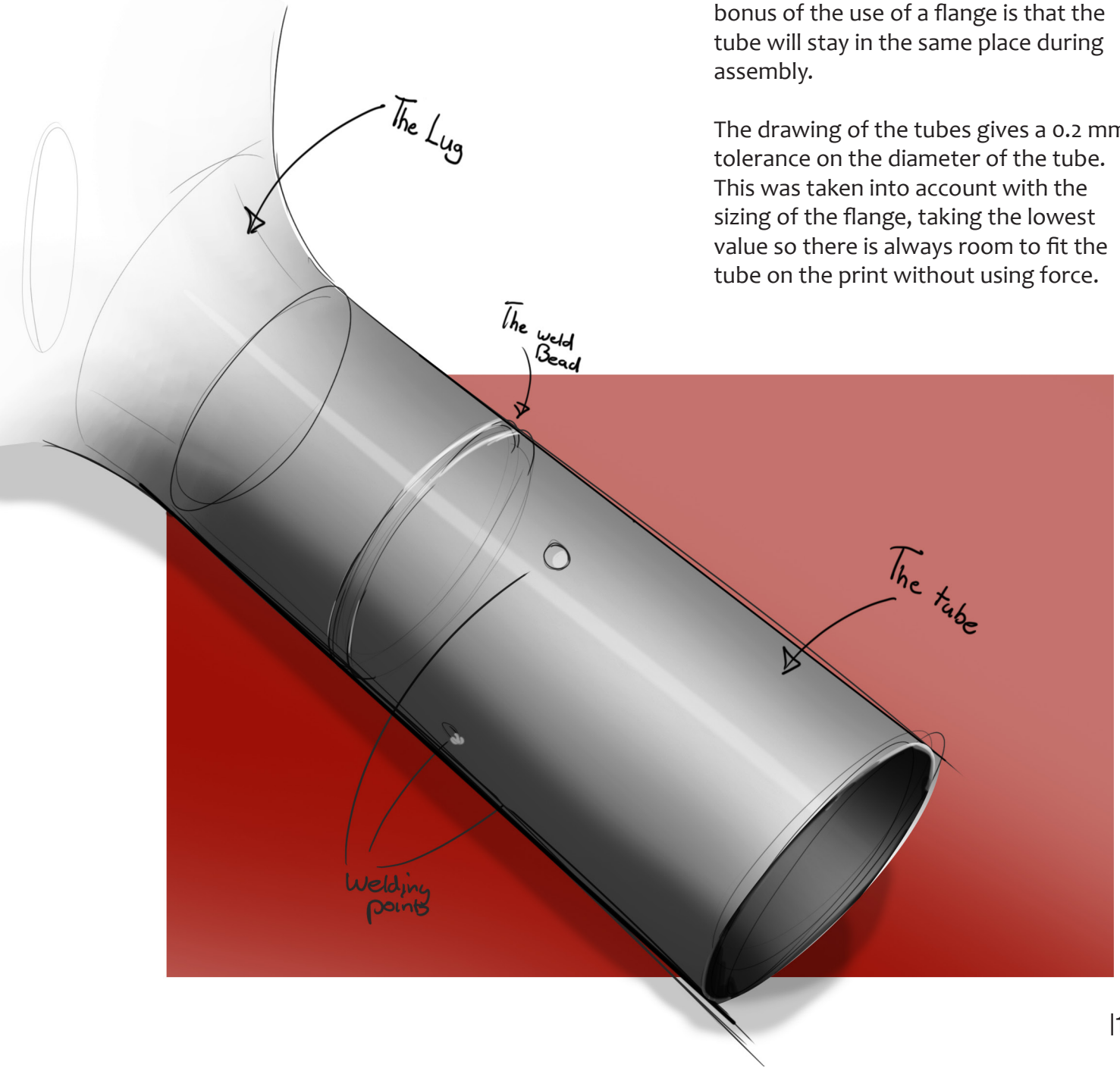
Fig85: *(above)The shapes of the tested inserts.*
Fig86: *(right) the final design of the tube insert of the lugs. A flange will go into the tube where it will be welded on the flange and on 3 point around the tube.*



Conclusion

In deliberation with the client, the choice was made to make a flange on the lug that reaches 25mm into the tube. Making the flange too long would cause creaking noises during heavy use of the frame. To ensure that there are no creaking noises and make the bond between tube and lug even stronger, the tube is spot welded at 3 points to the flange (see Fig.86). If any peak stresses will occur at the seam the flange will divert them away from the weld area. An added bonus of the use of a flange is that the tube will stay in the same place during assembly.

The drawing of the tubes gives a 0.2 mm tolerance on the diameter of the tube. This was taken into account with the sizing of the flange, taking the lowest value so there is always room to fit the tube on the print without using force.



Aftermarket parts mounted on or interacting with the lugs

The five lugs that are welded into the frame are not only fitted to the tubes. Sometimes external aftermarket parts need to be mounted on the lug and in other cases, other parts go through or alongside the lug. This chapter will describe these cases per lug.

Head-tube

The head-tube lug is the housing for the fork of the bicycle. This implicates that the fork needs to have enough room to move freely and needs to be fitted with bearings that support the fork and keep it in place.

The fork
One of the wishes of Braun-cycling was to fit the fork as snug as possible into the head-tube lug. To do so, the room in between the fork and the lug was made to not exceed 1mm. A smaller distance would increase the chance of dirt and sand, getting in between the fork and head-tube, decreasing the steerability of the bicycle. The fork is the standard aftermarket tapered front fork that Braun-cycling uses in their conventional titanium bicycle (Fig.88). A tapered front fork implicates that the tube from the fork is wider (40mm) at the bottom than the top (28.6mm).

Fig87: *(left) The final shape of the head tube lug after modelling all of the extra parts.*
Fig88: *(right) The tapered front fork of the new Braun-titanium bicycle.*

The headset bearings

To fit the tapered fork into the head-tube lug and make it steer freely, we need a set of bearings to be mounted into the lug. A fixed fit is needed to mount a bearing, this is so the bearing will not pop out of the lug during heavy use. The fixed fit that is used for bearings is called an H6 fit. The number H6 is an (ISO) standard that is used for the maximum deviation that can be made of the original size that needs to be produced. The top bearing of the head-tube lug is 42mm, so the size of the hole is made with a 42 H6 fit. This means that the shape that is made must be reamed after printing to ensure the fit. The same goes for the bottom bearing which has a 52 H6 fixed fit.

Brake cable

The third part that comes into contact with the lug, is the brake-cable of the rear-brake of the bicycle. On a conventional bicycle, there are two options, the first is to fix the cable and its housing on the outside of the tube. This requires extra steps in production by soldering fixtures for the cable housing on the tube. The other option is to make the cable run through the tube. This requires a hole in the headset lug and in the seat tube lug. To counteract any clanking or ticking noises made by the cable housing beating on the inside of the tube during use, a copper pipe is mounted in between the headset and the seat tube lug. Fig.90 shows the section views of the guide-hole of the cable and the connection point to the copper tube that have been made to guide and hold the cable housing. The braking cable and its housing can simply be installed by sliding them into the hole. The location of the cable guide has been strategically chosen on the inside of one of the cut-outs from the topology optimisation, thus making the bicycle seem simpler and more minimalistic.

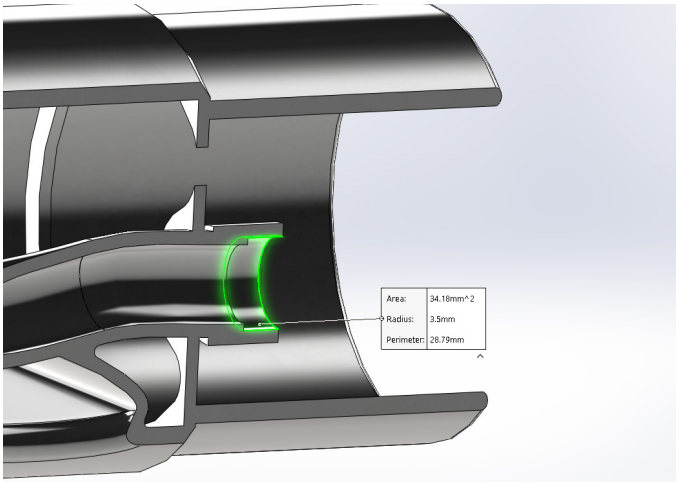


Fig89: *(left) The dropset 2 headset bearings made by ChrisKing.*
Fig90: *(right) The mount of the copper tube that guides the brake cable through the top tube.*

Fig91: *The back side of the final design of the head tube lug. In this picture it is clear where the break cable will leave the lug into the head tube (top left).*

Seat-tube

There are three parts that interact with the seat tube lug. The most important of the three is the seat post. The seat post is the tube that can slide up and down to fit the right seat height of the cyclist. In the conventional frames of Braun-cycling, an external tube is placed into the seat-tube to ensure a snug fit with the seat-post. The external tube is not needed in the new design as this is printed and thus can be made in every seat post size. The inside of the seat post guiding hole will be printed to a diameter of 31.6mm and be reamed before the instalment of the seat post.

Seat post clamp
To keep the seat post in place during use, it must be clamped down inside of the seat tube. In the conventional frames, a slot is milled into the seat tube, so that the tube can be clamped down to a smaller diameter. The new product has the same solution as the conventional frame. Fig.92 shows the slot that is made during the printing of the part. This makes for fewer post-production steps. To clamp down the seatpost, a regular seat clamp will be used. Fig.93 shows an example of one of these clamps that will be placed over the 35mm wide seat tube lug end. The end will be clamped together on the seat post by tightening the screws.

Braking cable
The braking cable and housing that are rung through the copper pipe, described in the previous paragraph, hit the seat tube lug at the end of the top tube. To guide the cable housing through the lug a pipe is cut out of the lug. The same principles that have been used in the head tube lug will be used to connect the copper pipe and 'hide' the exit of the brake cable.

Fig92: *(above) The final design of the seat tube lug. we can clearly see the cut out in the top of the tube where the clamp needs to be mounted onto the lug to secure the seat post.*
Fig93: *(below) The clamp that secures the seatpost onto the lug.*

Fig94: *The final design of the seat tube lug. at the back in one of the holes we can see where the break cable will leave the lug.*

Bottom bracket

The bottom bracket is the housing for the axle where the pedals are fixed on. It has a close fit with the back wheel, which must not touch the back side of the lug.

The pedal-axle
There are multiple sizes available as pedal axle size. A wish of the company was to use the new T47 standard as the new axle size. This axle is made with a 47mm thread that has opposing threads on each side. The opposing threads are made, so that the axle does not unscrew itself during forward-pedalling. It is said that the T47 size axle has a longer lifespan than conventional smaller axles. This because it has more mass and larger bearings thus making it longer lasting. The downside to the T47 axle is that is a bit heavier than a conventional axle.

The wheel clearing
To make sure that the wheel does not touch the surface of the bottom bracket lug in the simulations on the computer, a wheel was simulated to make clearance of the wheel. The wheel was simulated with a 28mm tire. Tire sizes of 28 mm are one of the newest trends in the road race bicycling industry. It is chosen to have a clearance of at least 2 mm around the wheel, this so the wheel will never touch the frame even when deformed by high speeds.

The down tube
The last thing that was modelled into the bottom bracket lug, is a change of the down tube of the bicycle. The conventional Braun-cycling titanium bicycle has a down tube that changes shape over the length of the tube. At the top of the tube it is shaped in an oval shape, lower in the tube it is shaped like a rounded hexagon. If this tube is used in the new bicycle, the mounting point of the down tube of the bottom bracket and head tube lugs would change with every frame size, this because a different length of down tube has a slightly different shape when cut off. An extra problem that comes forth with the difficult shape of the conventional down tube, is that the production process does not guarantee the same shape of the tube over time. This is why, for the new bicycle frame, the decision is made to use a normal round down tube. This tube will be cheaper to buy and easier to produce.

Fig95:*The final design of the bottom bracket lugs. We can see a small hole at the flange of the down tube of the frame. This hole is made to release the argon gass that will be used during the welding of the frame.*

Fig96: *The final design of (right) drop out lug. the left lug will be a mirrored version of the right side lug.*

Drop-out right and left

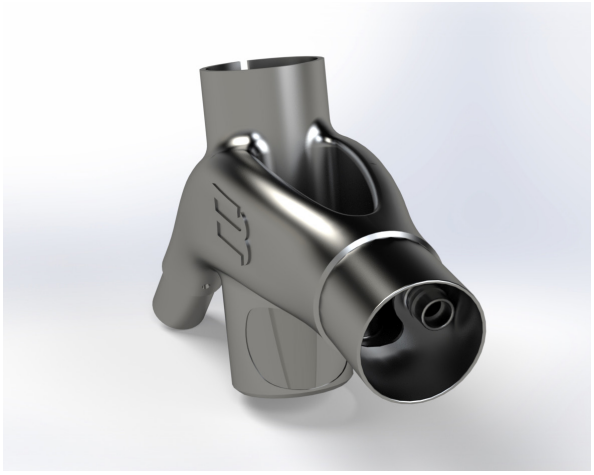
Fig97: *(above) the drop outs that are being used on the current Braun-cycling titanium bicycle.*
Fig98: *(below) the right drop out, showing the cut out for the same derailleur mounting plate as being used in the current drop-out system.*

The drop-outs at the back of the bicycle are used to mount the axle and the derailleur. To mount the axle, the standard vertical dropout was chosen. Braun-cycling uses the vertical dropout in all of their rim brake bicycle frames. The advantage of the vertical drop out is that the wheel can be switched very quickly compared to other mounting methods (etru, horizontal mount). The vertical dropout system is depicted in Fig.97. The axle that will be used in the dropout to fix the wheel is the normal standard sized 10mm axle.

Derailleur
To change gears, a derailleur is used. This product is placed on the right side of the bicycle. The conventional dropout shown in Fig.97 has an aftermarket aluminium plate fixed into the right dropout.
The plate is interchangeable, because it damages quickly during falls. This conclusion made the new right dropout be fitted with the same interchangeable plate as in the conventional dropout system. Fig.98 shows the slot that is made into the right dropout to fit the aluminium mounting plate.

5.3 Validating the design

When a product is designed using 3D modelling software, it is critical to perform simulations before starting production of the part. This because simulations give a good and cheap indication if the designed part will withstand forces that are developed during the use of the product. In this project, the validation of the design was consisting out of two steps. The lugs were all designed and modelled separately, because a TO that calculates five lugs at the same time was too much input for the used cad software (SolidWorks). The first step of the process was to simulate and validate the lugs separately. The second step was to assemble the whole bicycle and compare the simulation results to the results of the existing Braun-bicycle simulations.



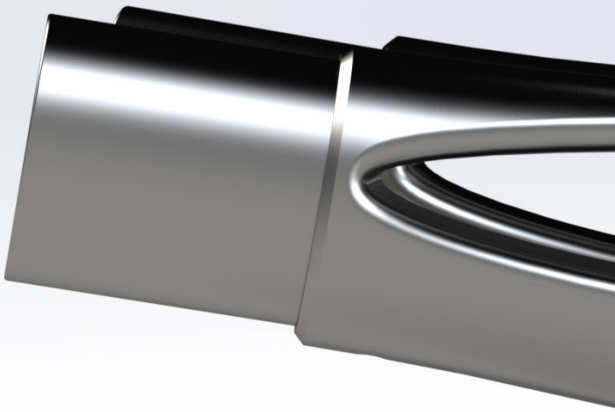
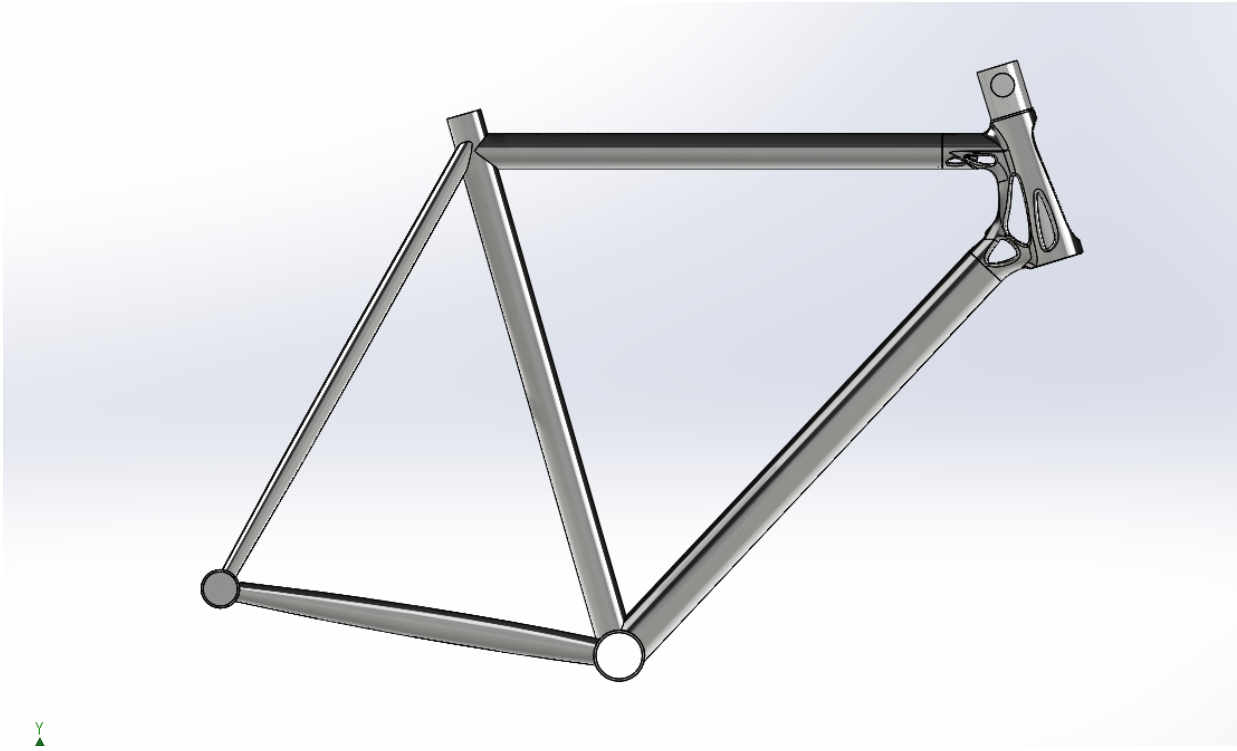


Fig99: *(above) the front side of the final design of the seat tube lug.*
Fig100: *(right) a side view of the final design of the bottom bracket lug.*

Partial simulations

Simulating the parts separately was an important step in the process. This partial validation shortens the feedback loop of the design drastically. If the results of a fully assembled frame exceed the yield limit, troubleshooting on where to change the design becomes much more difficult with so many variables. If in a partial simulation the yield limit of the design is exceeded, the flaw must be in the design of the part that is simulated.

Fig101: *A view of the original frame with the new head tube mounted in the front for a simulation.*
Fig102: *Side view ot the original frame with the new head tube ready for simulations.*



For the partial simulation, the original Braun titanium frame is used as a basis for the designed part. Figures 101,102 show how the original frame is fitted with the newly designed lug, in this example the head-tube lug. The forces that are used in the partial simulations are the same that have been used in the TO. This simulation is mainly used to validate if the 'human factor', as described in 4.1.4, has not made the part weaker compared to the calculated 'raw' TO shape. It was chosen to keep the maximum yield and strain stresses of the parts below the limits with a factor of 1.5, as an extra safety. An example of these stress calculations can be seen in Fig.103. For more information on the full simulation reports, look at app. F

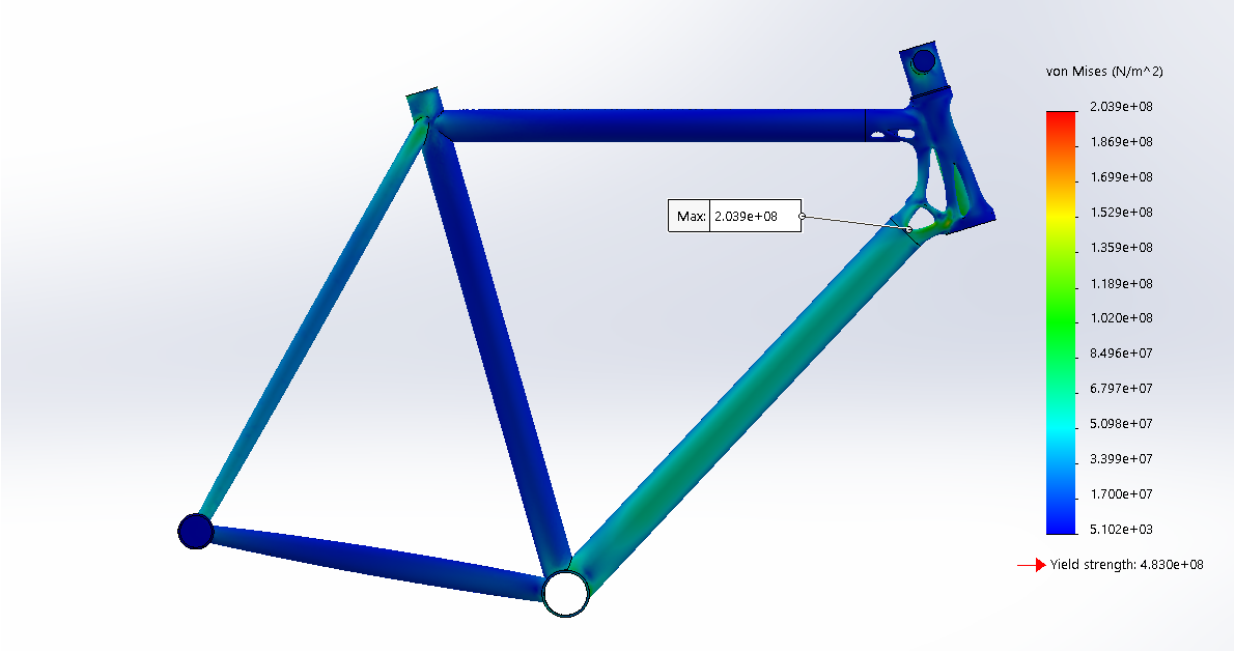


Fig103: *The results of the partial simulations showing the peak stresses in the final design of the head tube lug.*

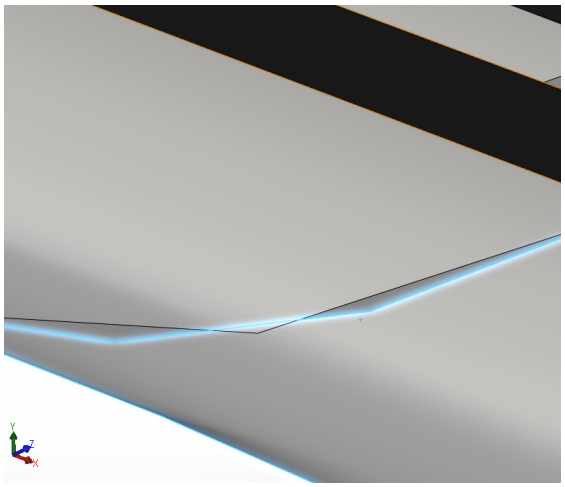
Final simulation

The final simulation is the most important and most difficult simulation. This simulation is the first time that all of the parts are placed in the same frame. The fact that all of the lugs were designed separately, makes the simulation of all of the lugs combined into one frame critical in validating the design.

Simplifying the design

A big hurdle that needed to be overcome to make the final simulation run, was the same one as of the previous from the partial TO simulations. A simulation with that many parts is, simply said, too much input for the CAD software. To perform a simulation in CAD software, the model must be meshed. Meshing is dividing surfaces into countless triangular shaped forms that can be calculated separately. The problem arises when all of the parts mesh separately. This makes some triangles of other parts run through each other. An example of such a problem is depicted in Fig.104. This example shows 2 meshed parts that touch or even blend, such situations can make a simulation fail.

Fig104: *A close-up view of two meshes that collide with one another.*



The solution to the problem was to combine all of the parts into one big part. Combining the assembly into one part makes the simulation lose some of the information of defined welds and or bonded contacts. After combining the objects into one object, the part can be meshed into one big mesh. Thus making it suited for simulations as the different mesh surfaces do not intertwine.
The difference before and after the combination of the parts is depicted in Figures 105,106. The information that will be lost due to leaving out the welds can be neglected as the welds are made from the same material as the bicycle and the shapes play a much bigger role in the development of stresses.

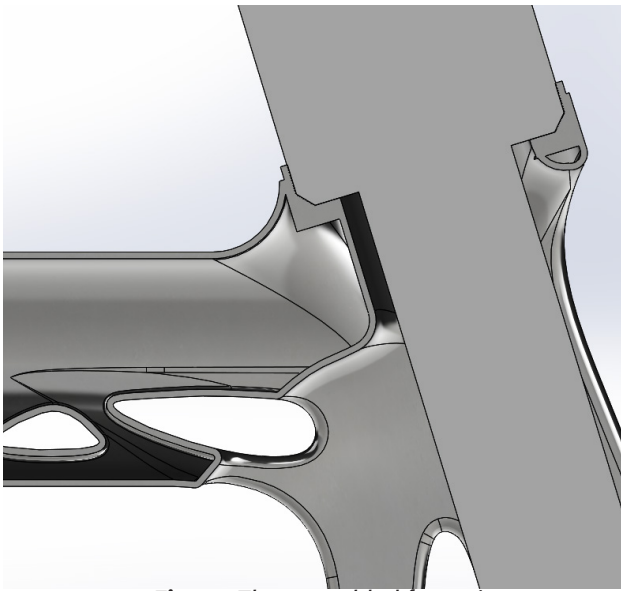


Fig105: *The assembled frame in parts*

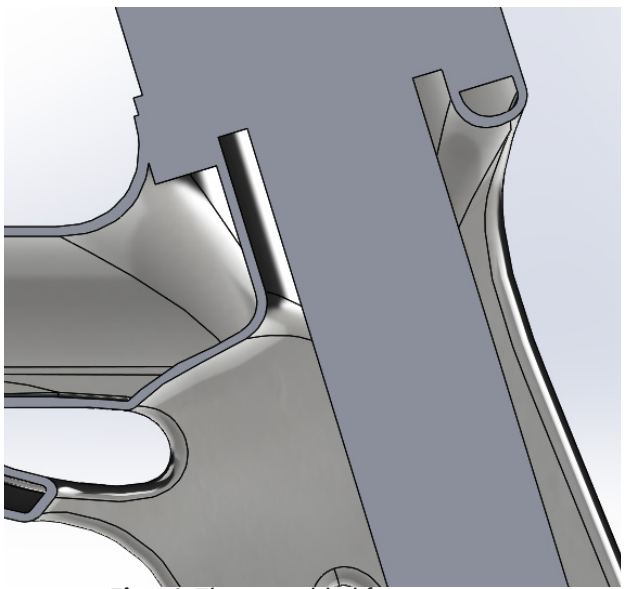


Fig106: *The assembled frame merged into one part*

The safety factor

For simulations and calculations, it is very common to use a safety factor. These safety factors are used to give a margin of error that sometimes is needed in the final product due to unforeseen circumstances (production flaws, bad welds and etc.). In the product design industry, it is common to use a safety factor of 1.5 (Mascarenhas W.N., 2003). This safety factor is applied to the forces that are used in the simulation. Fig.107 depicts the new force scenario after the safety factor that is used for the simulation of the frame.

The results that are obtained from the simulation of the frame assembly can not only be used to conclude if the frame will withstand normal use. It can also be used to compare to the results that are obtained from the simulation of the conventional titanium Braun-cycling frame. When the results are compared, the conclusions can be drawn about what the effects of the TO optimised lug are on the performance of the bicycle. To make this comparison, the original Braun-cycling frame was tested under the same input values as the new titanium Braun frame. The simulation reports of the new frame and the original frame can be found in app. G

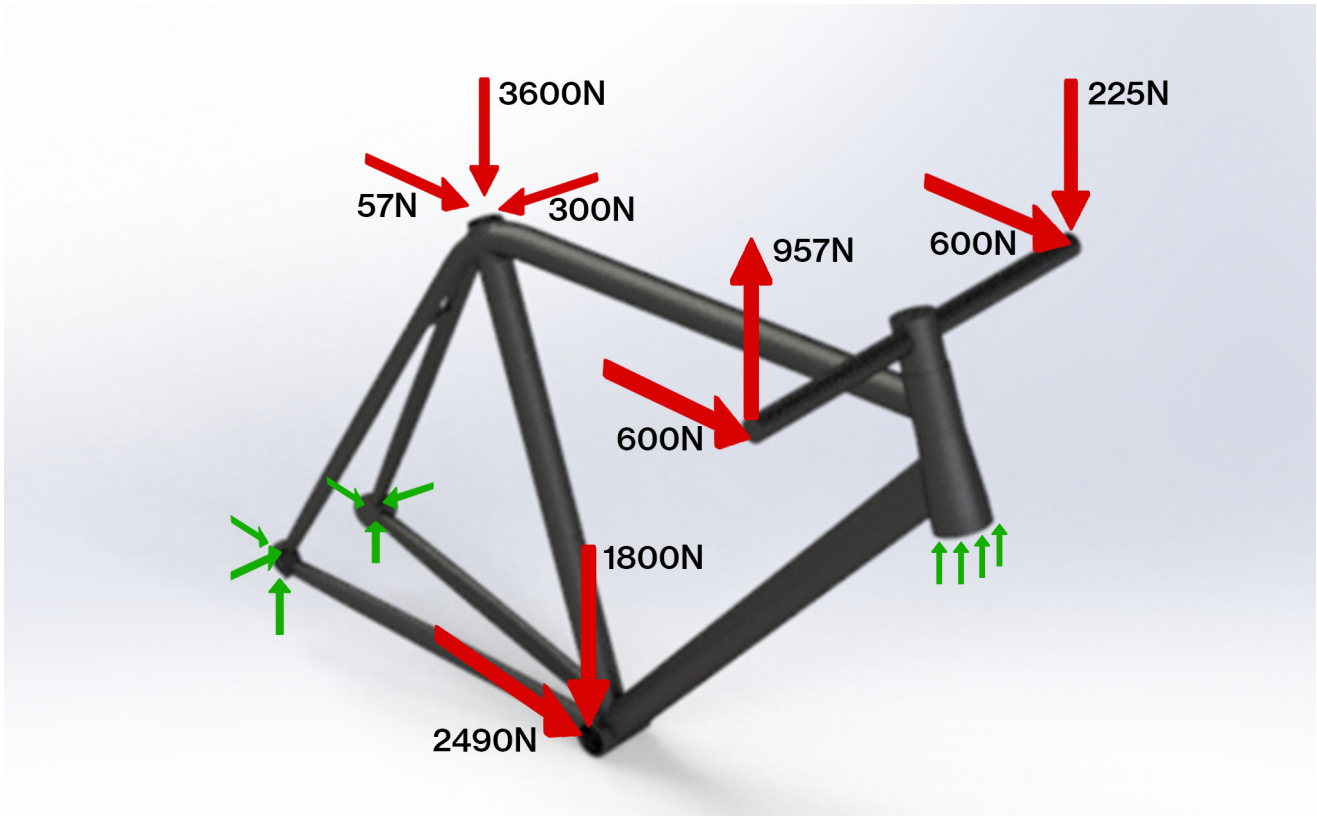


Fig107: *The super scenario forces with the safety factor of 1.5*

Conclusions of the simulation

The new frame

The topology optimised frame passes the final simulation without failure. Fig.108 shows the peak yield stresses that are generated by the 1.5-factor forces. The maximum annotation is set at 291 MPa, where the yield limit of titanium grade 5 lies at 483 MPa (Dedacciai, 2019). It can also be noted that the maximum value is not located in the frame but in the handlebars of the bicycle. From this observation, it is easy to conclude that the frame has become so stiff that the handlebars will deform instead of the frame. The other conclusion that can be easily made from observations of the simulation report, is that there are no strange stress concentrations in the frame due to sharp angles in the frame. The rounded shapes generated by the TO are spreading the forces on the frame evenly over the structures of the frame. An example of such a spread force can be seen in Fig.109. In this figure, we see the right side of the head-tube lug. This side has an even shade of green, this even colour shows the spread of the forces over a larger area.

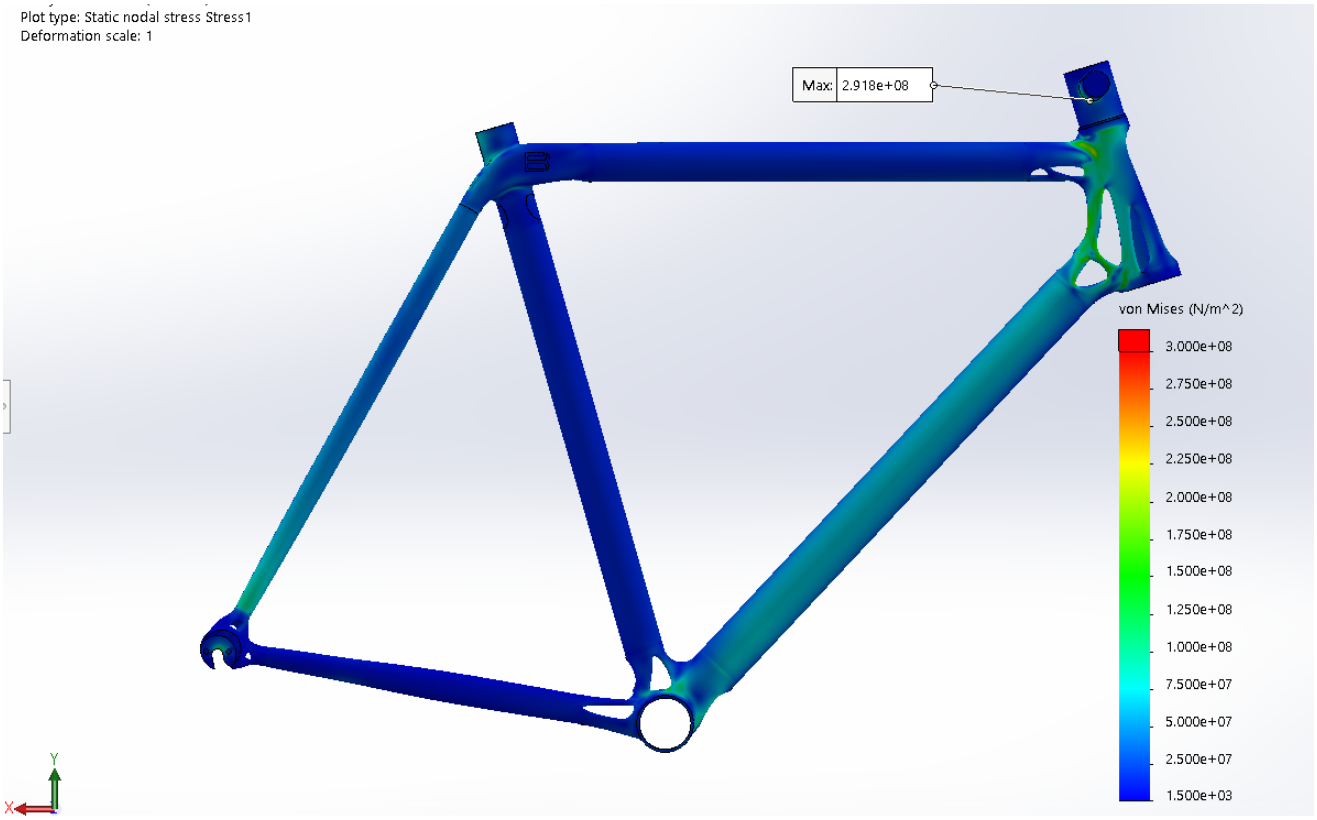


Fig108: *A result of the yield stresses in the assembled bicycle frame. All of the stresses are safely below the yield strength of the titanium alloys.*

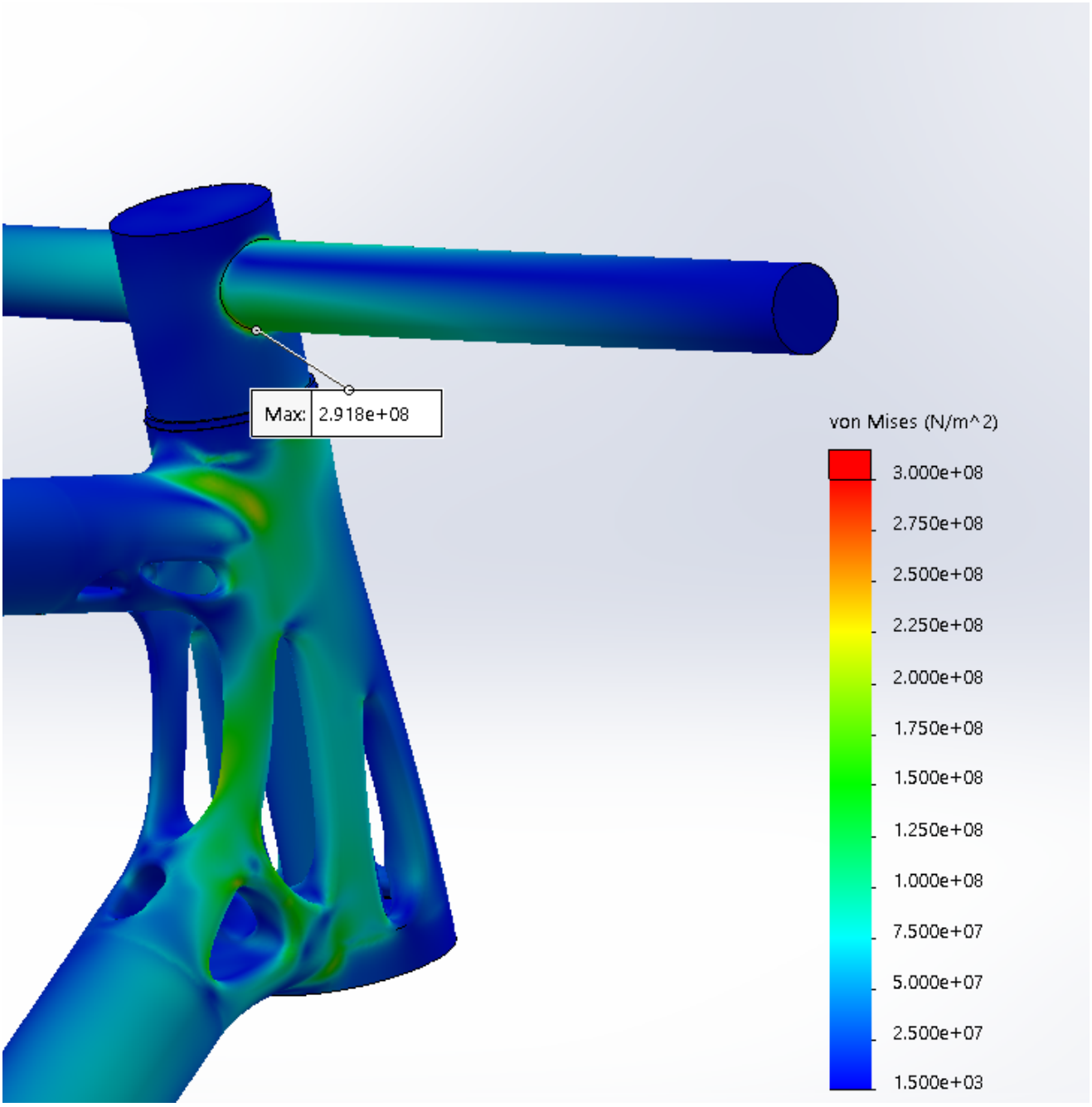


Fig109: *A close-up of the yield stress result of the simulation. Note that the peak stress in the frame is actually shifted outside of the modelled frame into the handlebars.*

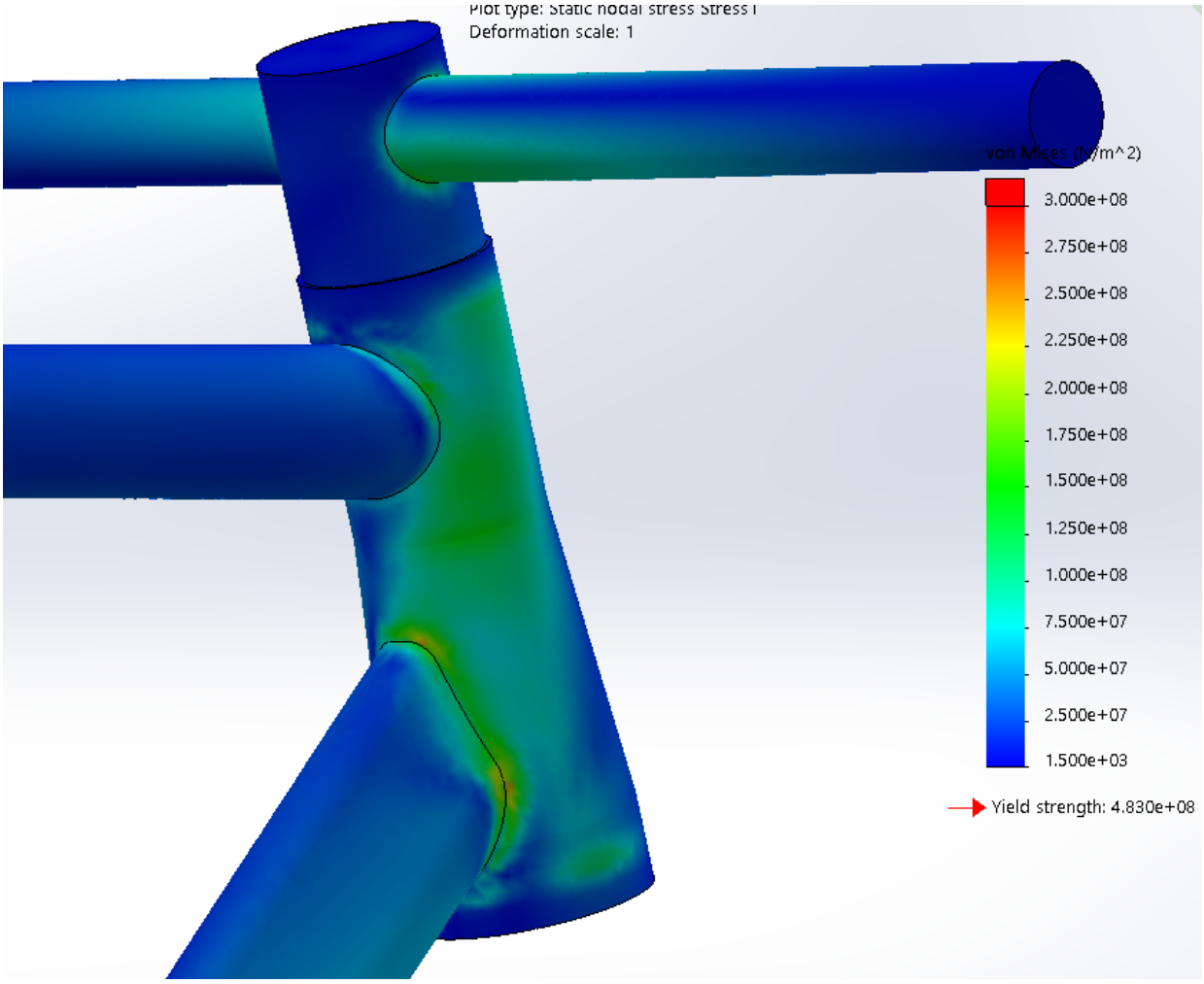
Comparison to the conventional frame

If we compare the results of the simulations of the new and conventional frames to each other we can observe what the effect is of the topology optimised lugs on the performance of the frame.

Weight.
The new frame has a weight of 1.59Kg. This makes it 90 grams heavier than the original Braun titanium bicycle. 90 grams is not that big of a difference, but in the road race cycling business, it certainly is something to think about. The increase in weight is probably the cause of the combination of the design interpretation of the TO and the adding of the flanges for the welds.

Yield stresses.
The new bicycle frame has a peak yield stress of 293 Mpa, this is an almost 22.5% reduction compared to the 378 Mpa of the conventional Braun frame. If we compare fig 110 and fig 109 we can also draw the conclusion that the conventional Braun frame has little orange stress concentrations, this compared to the evenly spread green of the new Braun frame. The loss of stress concentrations and the lower peak stresses can lead to an increased lifespan of the new Braun frame.

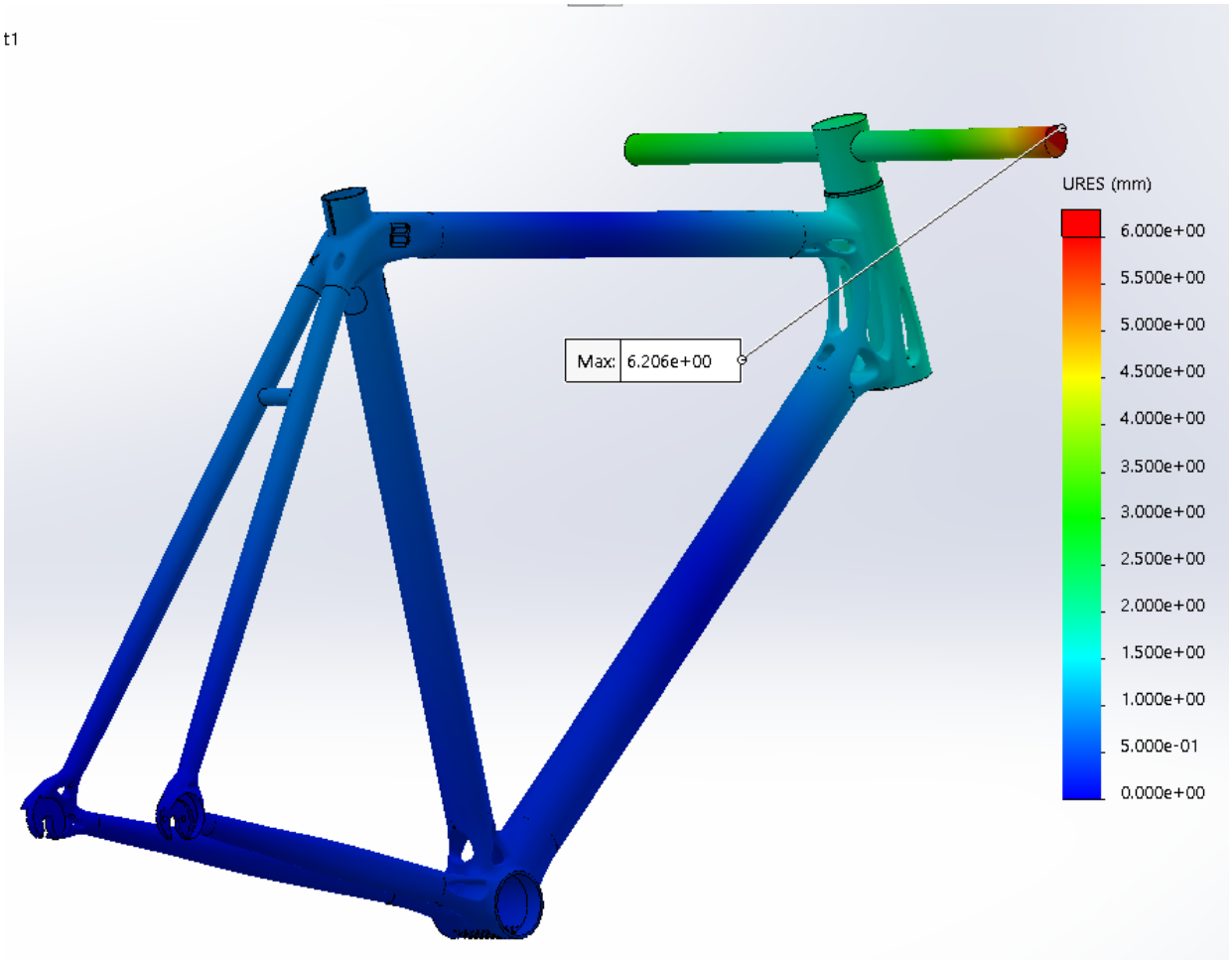
Fig110: *A close-up of the yield stress result of the simulation on the old frame. Note the two stress peaks at the weld at the down tube.*



Displacement

The new Braun bicycle has a maximum displacement of 6.2 mm measured on the tip of the handlebar (see Fig.111). This compared to the 5.9mm displacement of the conventional Braun bicycle (also measured on the tip of the handlebar). This is a displacement increase of 5% in the new frame. The increase is probably the cause of the way that the shapes are modelled in the 'human factor' phase. In the design, a wall thickness of 1mm is used where sometimes the TO needed thicker walled shape. Still, an increase of 0.3mm will probably not be felt by any cyclist so the difference is negligible.

Fig111: *The result of the simulation on the displacement of the new frame. The peak displacement is 6.2mm.*



5.4 Embodiment conclusion

Looking at the results of the simulation, the conclusion can be drawn that using TO for the design of bicycles is a very promising technique. The bicycle, as it is right now, is very much comparable to the conventional titanium frame of Braun-cycling. The better spread of stress areas and lower peak stresses in the new frame give room for further optimisation.

Lowering the weight and relocating material via more TO iterations can lead to better results which do have the potential to surpass those of the conventional titanium frame. This, of course, may lead to higher stresses in the frame, which decreases the lifespan. One thing is sure: if the peak stresses are kept below those that are generated in the conventional frame, we know that the frame will probably work fine in real life.

There is another thing that is very promising, but which requires more attention and research. As described before, the human factor or design interpretation of the TO is a very interesting subject. TO is, and has always been, a very practical tool, but in this project, it has also become a form language. The products of Braun-cycling need to perform well, but do not have to win the Tour-the-France. So where lies the optimum between using the TO as a practical, performance-enhancing tool and using the TO as a guideline to increase the aesthetics of the bicycle?

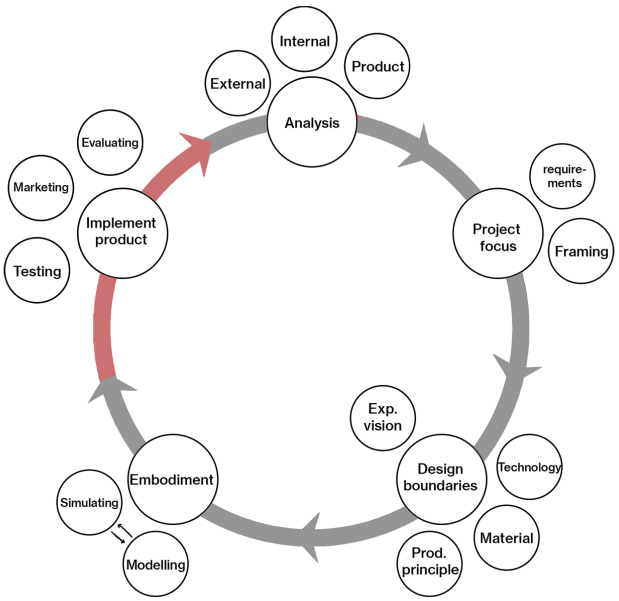
Fig112: *Render of the back side of the complete frame assembly.*

Fig113: *(left)Render of the front side of the complete frame assembly.*
Fig114: *(above) Render of the side view of the complete frame assembly.*

6.0 Hone titanium bicycle

The Hone is a marriage between craftsmanship and cutting edge technology. This product incorporates the characteristics and core strengths of the Braun-cycling company and the developments of CAD modelling software and additive manufacturing into a unique, high-quality product. The Hone is built to be the new flag-ship bicycle of the Braun company. It shows that metal-alloy bicycles are in no way outdated, but are futureproof.

Fig115: *(left) a picture of the assembly of the 3D printed titanium parts.*
Fig116: *(below)The last step in the design process and content of chapter 6.*



6.1 Hone

Hone is the name of the new Braun titanium bicycle. The word Hone sounds soft. The softness of the word resembles the flowing shapes that are generated in the lugs of the bicycle. Hone has no harsh sounding letters at the beginning of the word, this combined with the shortness of the word makes it almost sound like a whisper. A whispered word sounds very light and airy, and whispers and rumours travel very fast.

The word hone is the Japanese word for bones and frame. The bones are resembled by the structures that are generated in the TO optimisation. Honing is also a technique that is used to deburr or finely sharpen something. This resembles the quality and eye for detail that the Braun-cycling company has for its products.

Fig117: *The japanese character (kanji) of the word hone. Hone is the word that resembles bones and frame.*

Hone

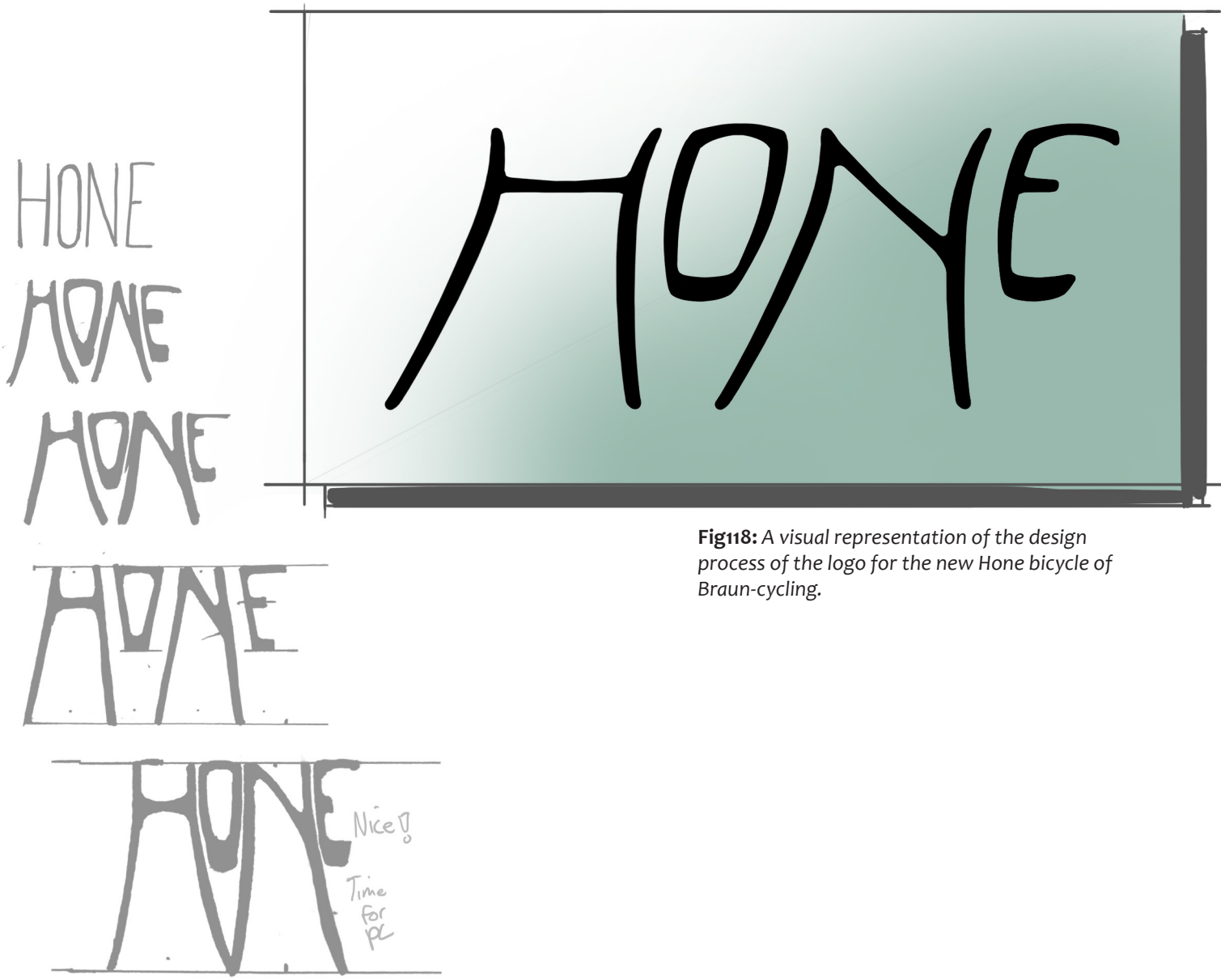


Fig118: *A visual representation of the design process of the logo for the new Hone bicycle of Braun-cycling.*

6.2 Product colours

One of Braun-cyclings wishes was to perform a short colour study to give some recommendations about colours that suit the Hone. As a method for the colour study, renders have been altered in photoshop to give quick indications of what effect colours will have on the bicycle. One of the requirements for the colours of the bicycle was that Braun-cycling wanted to show to the consumer of what material the bicycle was made.

Picking a colour
One of the unique selling point of the bicycle is that it is made out of titanium. To cover the whole bicycle in one colour would hide this selling point. The unique structures that are generated by the TO are, besides the titanium, another unique selling point. These two things can be combined perfectly, by leaving the inside of the TO structures blank. In this way we can emphasize the structure with the shininess of the titanium.

During colour tests, the conclusion was drawn that bright and fully saturated colours draw the attention away from the titanium TO structures. This should not be the case. The structures should be the point of attention when someone is looking to the frame. An easy conclusion that can be made from this information is that the colours should be toned down. I would even recommend to not use colour at all and make the bicycle black. This because the reflections in the titanium will reflect colours from the surroundings. This gives the bicycle colour, but only in the most important parts of the bicycle: the TO structures. An example of the hone with this black paintjob is given in fig.119.

Combining geometric and natural
In figure 119 an example of a graphical design can be seen. This design has the goal to combine the flowing shapes of the lugs with the geometrical and straight shapes of the tube. It does so by creating smooth lines over the tubes that flow out of the cut-out structures of the lug. The lines will also be made out of blank titanium. These long reflective lines will give the bicycle speed as the reflections move over the length of the bicycle.

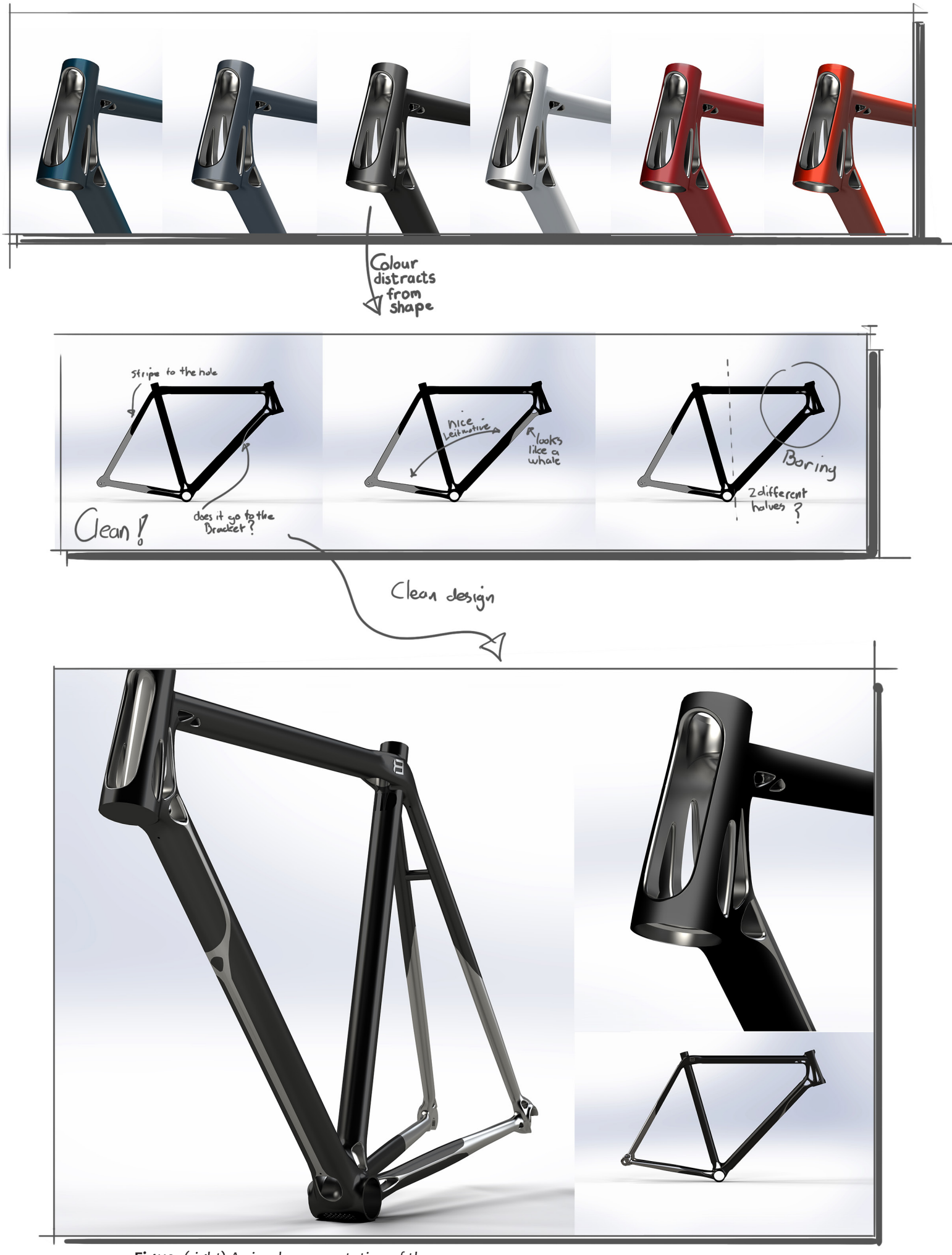


Fig119: *(right) A visual representation of the design process of thecolour and visual of the Hone bicycle.*

6.3 Production

The Hone bicycle is designed to be built and assembled using the techniques that the Braun-company is familiar with. The parts that are made with SLM printing techniques have a rough surface texture with a difference in height of 100 microns (comparable to sandpaper). These parts must first be polished. This process can take up to one day. In the future, this process will probably cost less time as the powders for the laser sintering develop to make a better surface texture.

Conventional metal-alloy frames are built out of mitred tubes that neatly fit together where the Hone is made out of the lugs and straight cut tubes. This straight cut saves time in the production process. After the sizing of the tubes, the bicycle can be assembled, almost like a jigsaw puzzle, into the welding jig. Here the final check happens to see if all of the tubes have been cut to the correct size.

After the check, the tubes and lugs are cleaned with an ultrasonic bath. This bath cleans all of the parts of any grease and filth. If the parts are not properly cleaned the welds that will be made in the next step will be of less quality due to chemical reactions between the heated titanium and grease and dirt. After the sonic bath, the parts are re-assembled into the jig an tagged together with small point welds.

when the frame is tagged together it is put on the measuring table to check the final alignment of the frame. After this is bent to be perfectly straight the frame is fully welded. After this step, the frame can be sent to the painter who can paint the bicycle in the correct colour scheme, after this step the bicycle is assembled and given to the new owner of the Hone bicycle.

6.4 Product Price

The Hone bicycle will not be a low-cost option for the consumer. The combination of the material titanium and the 3D printing technology makes it a high priced product. This sub-chapter will show an estimation of the price of the production of the bicycle, the estimated retail price and a rough estimation for the cost of further research on the bicycle and its technologies.

The production price
The production price of the Hone will not be low compared to the conventional titanium bicycle. The printing of the lugs will have a big impact on the total price as this process is very costly. It is no strange thing to assume that the 3D printing prices will drop in the near future. The development of faster printing machines and wider availability will have a big impact on the price of 3d printing. The price of the Hone bicycle as described below is based on the prices of materials and methods that are currently available.

The retail price
A retail price of €22.838,- euro for a frame is very high. There are cases where limited edition bicycle frames from big confection brands sell for as much as €25.000,- euro, but that is pretty much the limit. The average price of a complete custom titanium bicycle lies around €15.000 euro. The Hone bicycle is a totally new innovation in the market, is exclusive and custom made. This makes it no strange thing to price it in the highest range. The choice can be made to have a lower profit margin, which makes a lower price. This choice could decrease the feeling of exclusiveness and quality.

Further research of the product
With the current Hone design, the TO process must be re-created every time when the sizes of the frame change. This modelling process takes up almost one-third of the production price of the frame. There is an opportunity to create a parametric solver for the TO optimisation which automatically solves and calculated the new lug shapes for Braun. This will decrease the modelling costs drastically, as it could be done in house by Brauns own employers. Furthermore, there is the opportunity that the Hone, with more TO iterations, will give a higher performance result. The relocation of material can improve the weight and stiffness ratios. Both opportunities will require a seasoned TO and programming engineer. As the field of TO is still very young this will be very high-priced research. A very rough estimation of the situation is that it will take a seasoned engineer roughly 2 years of full-time work to write a program to realise these results. This will come down to at least € 100.000,- for the two years. This is based on the price of a topology expert and the degree of difficulty (PhD. level) of the case.

Materials:			
Titanium tubes (Dedacciai)			**€ 970,-**
- Down tube 44mm		€ 180,-	
- Seat tube 35mm		€ 160,-	
- Top tube 35mm		€ 160,-	
2x - Seat stays straight		€ 100,-	
2x - Chain stays tapered		€ 120,-	
3D prints (Set of 5) (OCEANZ)			**€ 5000,-**
- Head tube lug		set price	
- Seat tube lug		"	
- Bottom bracket lug		"	
- Drop out left		"	
- Drop out right		"	
Production materials			**€ 100,-**
-Welding rods		"	
-Argon		"	
	Total materials :		**€6070,- (ex vat)**
Labour:			
Engineering (Cad modelling)	**(€ 50,- p. hr.)**		**€3500,-**
- Remodelling frame	(6 hr.)	€ 300,-	
- TO optimisation new sizes	(24 hr.)	€1200,-	
- Design interpretation TO	(24 hr.)	€1200,-	
- Validation simulations	(16 hr.)	€ 800,-	
Production	**(€ 40,- p. hr.)**		**€ 680,-**
-Preparation	(3 hr.)	€ 120,-	
-Welding	(6 hr.)	€ 240,-	
-Buffing / polish	(8 hr.)	€ 320,-	
	Total labour :		**€4180,-**
	Total production cost		€10.250,-

Bicycle fitting			€ 75,-
Custom Hone frame			€10.250,-
Custom paintjob			€ 550,-
Overhead +10%			€ 1.088,-
Profit +100%			€10.875,-
	Total retail price Hone		€22.838,-

6.5 Conclusion

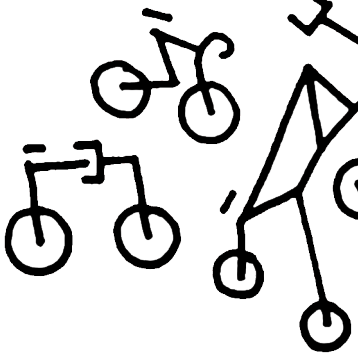
Project goal
The Hone bicycle is a unique and new product in the custom bicycle market. It combines new techniques and old production methods to make a bicycle that looks and feels lighter and innovative compared to the existing custom bicycles. In this way, it has succeeded in its goal to change the face of the conventional metal-alloy bicycle. Further tests need to be done to safely say if the shapes that are generated do evoke the same feelings that have been intended, but the reactions so far are positive.

Company
The Hone bicycle needs to be extensively tested in user tests before it can be safely sold to customers. Therefore a proposed user test will be included in the recommendations. Till the user tests are done Braun-cycling can use the bicycle as a promotional tool. The bicycle does show the craftsmanship and quality that the Braun-cycling company possesses. The product can be easily implemented into the regular production loop once the user tests are done. The downside to the product is that if it needs to be made in new sizes, the calculations need to be re-run by a third party. This because Braun-cycling does not possess the skills and equipment to work with CAD software.

Bicycle-industry
This product shows that, with further development, the tools of 3D printing and TO software can be valuable assets for the bicycle industry. TO has the potential to make bicycles out of metal-alloys that can get close to or outperform the performance of carbon bicycles. In a world where we need to live in a more sustainable manner can be of great value as metal-alloys are better recyclable than carbon material (so far).

Industrial-design
The combination of the use of TO as a practical tool and as an aesthetical tool is an interesting topic for further research. This marriage between performance and aesthetics can lead to improved performances, with less material usage. This has to potential to be one of the new design languages in the field of sustainability.

7.0 Recommendations



As of the short time span of the project not every facet is worked out as deeply as is needed to create a product that has reached its full potential. Furthermore, some subjects have surfaced during the course of the project that are relevant for further research or improvements.

7.1 Braun-cycling

Braun-cycling would like to keep on improving their products by giving graduation candidates of the TU-Delft opportunities for assignments within their company. The company sees the potential in the Hone project and wants to further research its potential. During the project, I gathered a deep insight into the way of working and strengths of the Braun-cycling company. Based on these insights I concluded the following recommendations for the company.

Testing the Hone bicycle

The Hone project is, in its core, based on and designed for the Braun-cycling company. Further user tests need to be done to guarantee that the bicycle (as is) is safe to use for the consumer. I would recommend to slowly build up the stresses on the frame. A step by step practical approach to validate the current design would be as followed:

(1)
Small cyclist (60Kg.) Sitting on the saddle.
Small cyclist (60Kg.) Bouncing on the saddle. (bump in road simulation)
Small cyclist (60Kg.) Standing on pedals.
Small cyclist (60Kg.) Jumping on pedals. (bump in road simulation)
Small cyclist (60Kg.) Slow start, cycling to 40 Km/h.
Small cyclist (60Kg.) Standing start to sprint.
Check if the frame is still straight

(2)
Medium cyclist (80Kg.) Sitting on the saddle.
Medium cyclist (80Kg.) Bouncing on the saddle. (bump in road simulation)
Medium cyclist (80Kg.) Standing on pedals.
Medium cyclist (80Kg.) Jumping on pedals. (bump in road simulation)
Medium cyclist (80Kg.) Slow start, cycling to 40 Km/h.
Medium cyclist (80Kg.) Standing start to sprint.
Check if the frame is still straight

(3)
Heavy cyclist (100Kg.) Sitting on the saddle.
Heavy cyclist (100Kg.) Bouncing on the saddle. (bump in road simulation)
Heavy cyclist (100Kg.) Standing on pedals.
Heavy cyclist (100Kg.) Jumping on pedals. (bump in road simulation)
Heavy cyclist (100Kg.) Slow start, cycling to 40 Km/h.
Heavy cyclist (100Kg.) Standing start to sprint.
Check if the frame is still straight

After this short test, I would recommend to disassemble the bicycle and check on straightness by placing it into the welding jig. If the frame is still straight after the test the frame should suffice the Braun quality check.

Continuing the project

If Braun wants to continue the project, another recommendation would be to keep on researching the basis of the Hone project but to slim the technology down. The technology of the TO can only be made by a skilled CAD modeller and requires many hours to complete. This makes the price of the product very high, with a technique of which the company cannot check the final quality. A Braun product should always meet the Braun quality standards, which Braun should check themselves.

It would be interesting to make a 3D-printed lugged frame that is made out of steel. The modelling should be made so that it is parametric and could be used and controlled by the employees of Braun-cycling. Using a steel lugged frame without TO that can be created within the company itself should make for a lower priced- unique custom scalable bicycle design.

Simplification of choice

During the project, I noticed that Braun-cycling puts many hours of research, building and improving in implementing a lot of new parts and bicycle standard sizes. This because the company always wants to satisfy the needs and wishes of the customer. The offer all of these different parts on an already custom bicycle frame can be quite overwhelming for a potential customer. It also costs the company much time in research development.

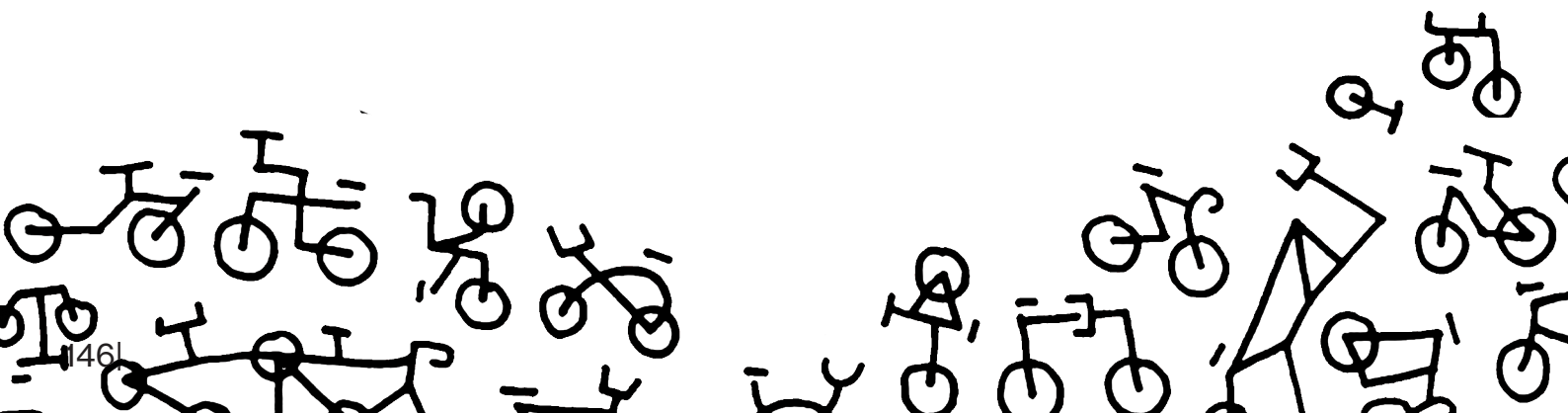
The interesting thing was that, during my interviews, I noticed that Braun cyclists love the fact that they learned so much about bicycles from Herman and Dave. The Braun-cycling company, with its 40 years of knowledge in building bicycles, has enough knowledge to pick out all of the pieces and bits that fit their bicycles best. A select choice of parts of which Braun-cycling knows that they complement their technology best, saves time spent on research and development and makes a new product more approachable for potential customers.

Custom road race E- bicycle

An unmentioned, but a very interesting product for Braun-cycling, is the market of the road race E-bicycle. As the average age of the road race cyclist is slowly rising, the market of the E-bicycle is steadily growing. Braun-cycling could be the first company to make a high-quality custom fitted E-bicycle for the consumer market. The 3D print lugs make for excellent parts to incorporate electronic components, batteries and motors.

7.2 The bicycle industry

It would be very interesting to look into using TO for the confection bicycle industry. This technology has the potential to improve the performance of bicycles, by saving weight and/or improving the strength of the frame. Furthermore, it is interesting to use TO in steel road race bicycles. Is it possible to make a fully topology optimised bicycle that can compete with a carbon bicycle but is recyclable? With an increasing demand for better recyclable products, the development of a recyclable road race bicycle that still performs on the top level would be very interesting.



7.3 Industrial design and the project

This project has scraped the surface of the use of TO as a practical and aesthetical tool in the world of bicycles. It would be very interesting if there would be more research into the use of topology and the effects of the shapes on the user. During the project, I noticed that the raw topology shapes seemed too fragile for most consumers and experts. Is it possible to define a golden ratio between the optimal performance of the shape given by the TO and the emotions that the shape evokes in the consumer? If this golden ratio is uncovered, where and in which field of production can it be used?

A
H
L
CE
Q/min
I
II
L
H
L
H
A
180
1000
365
2000
B
65
350
135
715
C
45
245
90
495
E-STOP
STOP
JOG BUTTON
SERIAL NO
X1000

8.0 Reflection

The assignment of designing a bicycle was not my first choice as a subject for my graduation. I started out with a desire to create a form language for sustainability. This was, of course, an assignment that was impossible to finish within 20 weeks. One of my biggest pitfalls is to make everything that I do too big. After a couple of months struggling with trying to define an assignment for my graduation, I came across this assignment. Designing a bicycle is a much more feasible assignment, compared to making a revolutionary new form language that is applicable to every product, so that was one step in the right direction.

The Braun-cycling company, with Herman and Dave, was really enjoyable to work with. In my learning goals, I described that I wanted to learn more about small business management. This assignment was the ultimate playground in which to do so. I observed Herman and Dave in how they ran their business. Asked questions about certain decisions and, sometimes, gave my opinion on what to do. During my time at the TU Delft, I worked at different part-time jobs, where I worked with a lot of people from different backgrounds and educational levels. This was something that helped me during this assignment. Herman and Dave, both really practical people, react with a different, more logical approach, than peers at the TU. Still, this sometimes cost a lot of energy as switching in between these abstraction levels is not easy.

During this assignment, I certainly learned a lot more about production methods and materials. I dove deep into the use of the topology tool, and how to optimise this for the bicycle industry. The final results are clean shapes that are new and unique in the bicycle industry. Now, looking back at the beginning of my graduation, where I wanted to come up with a new form-language for sustainability. Personally, I think that the result is a step towards such a solution. Topology makes clear defined shapes, which result in a certain form-language. This form-language not only makes the shape but can also save material, decrease stresses and eventually prolong the life of the product. So finally, maybe there is a future for topology in industrial design as a form language for sustainability.

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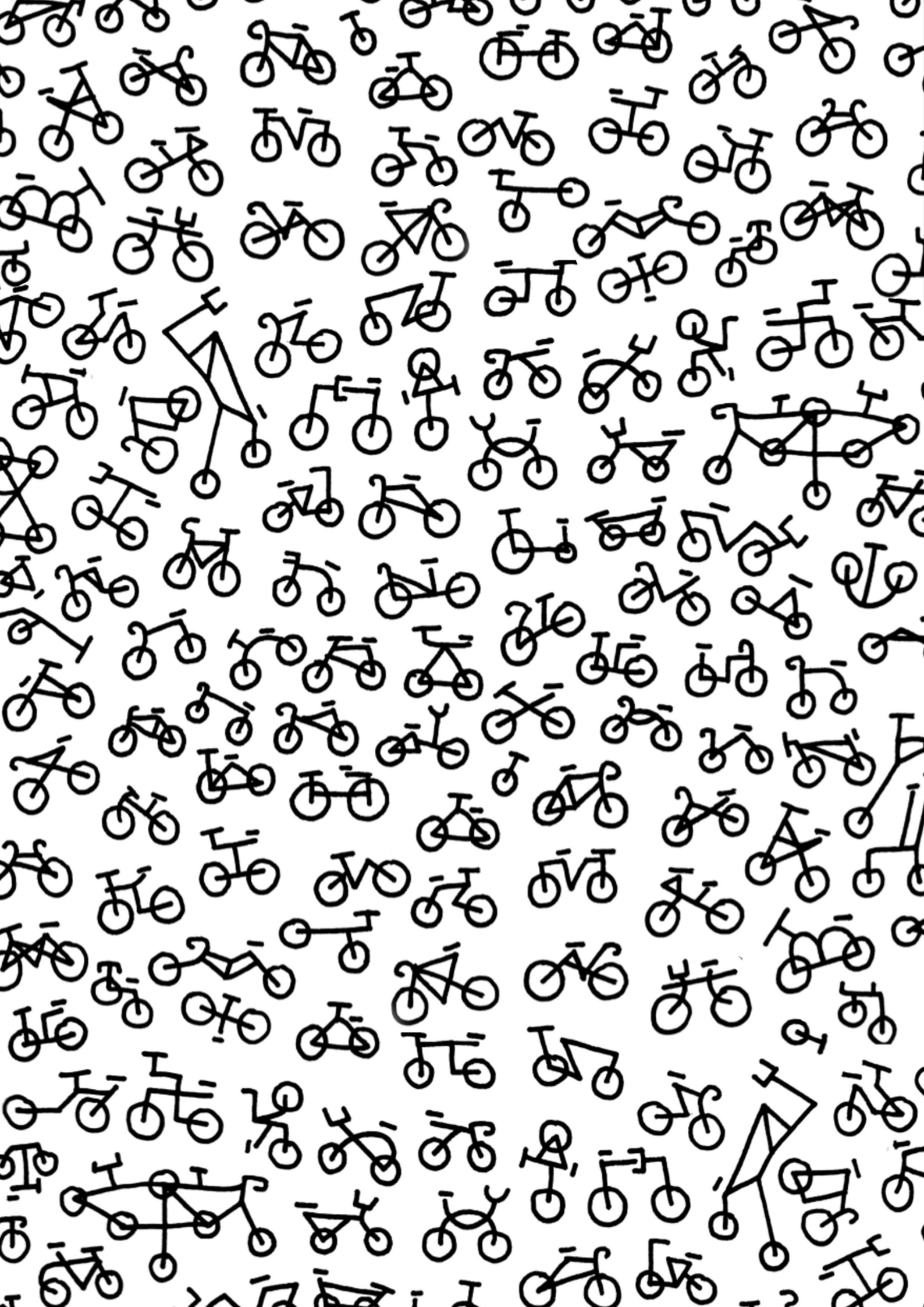
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