Tampereen yliopisto

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RESHORING OF BICYCLE FRAME MANUFACTURING THROUGH POSTPONEMENT

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ABSTRACT

METODI NETZEV: Reshoring of Bicycle Frame Manufacturing Through Postponement
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Bicycle manufacturers struggle to meet the seasonal demand of their products due to frame manufacturing lead times of upwards of 6 months. As such, design and testing through FEA is assessed in terms of labour hours for a proposed product development strategy. The current method of manufacturing bicycle frames within the custom geometry class is through brazing lugs and tubes. This manufacturing method requires 115 tools and 30 labour hours. By contrast, 3D printing the lugs and gluing them to carbon fibres tubes can bring the tools used to 31 and the labour hours to 9. The direct costs of the 3D printed frame method at 889.74 EUR are compared to the brazed frame technology and the market price of existing custom frames, being cheaper than the cheapest metal frame at 1315.14 EUR and a custom carbon fibre frame at 4624.90 EUR giving a perspective on the mark-ups possible.

It is important to note, however, that the overhead engineering costs have not been added to the investigation which is likely to greatly increase the price but also to add a quality component. The conclusion of the thesis points towards the technology being a promising candidate for domestic manufacturing within the European Union with the capability to reduce lead times to 3 or 4 months for 100 frames if finishing such as painting is not included. Further analysis and verification to this empirical study is needed before it can be implemented, particularly due to the novelty of the machines and materials used. The overhead engineering costs also needs further validation.

PREFACE

Primarily, I thank my mother Tatiana Ivanova Netzeva for keeping me going on my educational endeavours and for being a role model of excellence in research. For encouraging me and investing in my learning. For providing advice and reassurance during struggles and for the opportunity to study around Europe. I hope this prolonged learning leads to something you can be proud of.

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Tampere, 01.02.2019

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LIST OF SYMBOLS AND ABBREVIATIONS

ISO	International Organization for Standardization
ABC	Activity Based Costing
FEA	Finite Element Analysis
CAD	Computer Aided Design
HSL	Helsingin Seudun Liikenne – Helsinki Regional Transport Authority
FDM	Fused Deposition Modelling

h	Hour
TechLC	Technician Labour Costs per hour
TechS	Technician Salary
EngS	Engineer Salary
EngLC	Engineer Labour Costs per hour
USD	United States Dollar
EUR	Euro

1. INTRODUCTION

The subject of this thesis is the investigation of the possibility of bicycle frame production in Europe, and more specifically in Finland. It proposes a novel way to manufacture bicycle frames, posing the following questions: What are the development costs? What are the manufacturing costs? Do the high standards of living hamper the possibility to manufacture locally? As well as what are the advantages to be had in local production, will it be fast enough to satisfy seasonal demand?

Objective of the thesis is finding whether the market and legislative situation allow profitable frame manufacturing in Europe. It aims to discover what the product qualities should be to satisfy these market conditions. It also aims at analysing what business structure the frame development is best suited to and whether current bicycle or electric bicycle resellers can benefit from the process. The project proposes a design and manufacturing methodology to help the analysis of activity intricacies. Finally, cost of the frame is compared to other frames in the market. This should form an overview of the design and manufacturing process of setting up a 3D printed bicycle frame.

The background of the thesis are the current problems of global warming, rising fuel and transportation prices (Helsingin Seudun Liikenne, 2018) and high vehicle inefficiency leading to high taxation rates (Trafi, 2018). Adding to this, supply chains are complicated and ship through long distances while production and quality control knowhow for bicycle frames are becoming required in offshore countries such as Taiwan instead of Finland (Aittokoski, 2018). The newest technologies in design and manufacturing have not yet been applied to resolving this issue in a standardised way (Lin, et al., 2017). As the transport sector has one of the largest impacts on pollution, the design methodologies are applied to a vehicle likely to have impact on transport in the near future.

Scope of the literature review extends to a basic examination of the conditions under which bicycle frames are to be manufactured. What are the current demands of the market, what are the problems of manufacturing in 2018 and how should the 3D printing and simulation knowledge be disseminated within the manufacturing network. Issues around part supply are also briefly discussed where keeping inventories is expensive. Examples are provided describing how vehicle fleets can benefit from being able to manufacture diverse parts quickly.

Scope of the empirical study extends to proposing design and manufacturing methodologies, their ABC costing through the determination of the overhead and direct time utilisation and comparison with currently manufactured frames. An interview further elaborates the needs of small bicycle resellers in Finland. The study, does not detail the examination of the design or stress testing in detail. It also does not deal with the manufacturing optimisation or precise manufacturing parameters. These are topics are subject of a mechanical engineering study.

Structure of the thesis starts with an overview of recent developments in transportation in the Finnish market and legislative developments in the European Union. The “Knowledge Gap” elaborates on how legislation, trends, demand and manufacturing are related. Legislative and market situation describes where the current firms lose money with their manufacturing and inventory due to the requirements of the market. Current trends in manufacturing discusses the technology of how frames are currently manufactured, identifying areas for improvement. Difficulties in supply chain management discusses logistical problems in testing and fleet vehicle management. Condition and trends of global manufacturing describes economic development and how it can be leveraged. The knowledge transfer and congruency within manufacturing networks chapters cover the organisational structure needed to leverage knowledge-based process improvements. Finally, the effects of virtual and rapid prototyping are discussed as possible solutions

“Quantifying the effect of Postponement” describes the segments in which domestic and foreign manufacturing are compared through target costing and Activity Based Costing (ABC). The empirical study structure starts with calculations of the proposed manufacturing method and ends with a comparison between the target frame costs. Direct costs of both manufacturing technologies are calculated based on the activities they require. The engineering overhead costs of the 3D printed bicycle frame are estimated based on running test simulations and designs. Direct tooling costs are calculated based on their use within the activities. Similarly, labour usage is used in conjunction with data from Eurostat and Statistics Finland to calculate labour rates. The final costs of each technology are calculated and the overhead costs of frame testing using digital prototyping is determined. Finally, total frame structure manufacturing without finishing such as painting is compared and implementation recommendations suggest possible use cases. The discussion and conclusion discuss the validity of the study as a whole.

2. RELEVANCE

Bicycle frames and their electrification is relevant due to the developing market around electric vehicles. They are becoming increasingly cheaper to own and run in comparison to public transport. With a yearly adult travel card costing 1146.40EUR for the Helsinki region, an average e-bicycle is only 553.60EUR more expensive (Helsingin Seudun Liikenne, 2018) (Schaik, 2017). Danish and Swedish electric bicycle sales increase by 9% to 38,444 units and 50% to 67,500 units mark a significant average increase in market despite the low sales figures in Finland of around 7000 units (Schaik, 2017).

At the same time, the range of options and legislation is still developing rapidly. For example, September 13th saw the recognition of electric bicycles with and without a start-up aid as equal amongst minor changes in lighting legislation (Schaik, 2017). The change could potentially allow a large increase in brushless motor powered vehicles associated with better efficiency. The European Union (EU) is also attempting to restrict Chinese e-bike imports through anti-dumping duties for e-bikes and components which may include batteries and motors as well as anti-subsidies due to the manufacturers of Chinese e-bikes having received subsidies in their home country. (Oortwijn, 2017) It is expected that 750,000 electric bicycle imports are affected. (Oortwijn, 2019) This demand gap requires to be filled using diverse manufacturing adjustments from multiple European producers.

Constantly developing battery technologies and the newly scheduled Tesla battery factory in Nevada is supposed to increase the total volume of newly produced cells to more than twice as much as in the entire world in 2014, lowering battery pack price by 30% (Valdes-Dapena, 2016). These factors translate into a budding electric bicycle market in the Nordics. Open and developing legislation with a protectionist policy aimed at making the European Union self-sustained further increase the sales potential of these vehicles.

3. KNOWLEDGE GAP

3.1 Legislative and Market Situation of Bicycle Manufacturing

Self-sustainability legislation opens the possibility of manufacturing within the EU, requiring further investigation of what would be the best supply chain strategy to fulfil a possible newly found demand. The low labour costs associated with production in China are likely to be unavailable, encouraging a shift to local production for high volume companies. (Oortwijn, 2017) Since the availability of materials is regulated by the European Commission to ensure uniformity within the EU, the biggest remaining driving factor behind the identification of production sites is labour. (Ad hoc Working Group on defining critical raw materials, 2014) The newly joined EU members Romania and Bulgaria are hence prime targets for production centres as they have the lowest wages in the EU at 711USD and 537USD and have economies strongly structured around services. (National Statistical Institute: Bulgaria, 2018) (National Statistical Institute: Romania, 2018) At the same time, the expected overall increase in price of e-bicycles due to labour is likely to make custom solutions a viable choice for consumers with their capability to deliver better aligned value. Hence, efficient manufacturing of bicycles is beneficial for the EU community.

An analysis of the US bicycle industry done by Randall and Ulrich (2001) concludes that product variety is dependent on the type of supply chain and that success is dependent on correctly matching the two. Product variety, production mediation costs and market mediation costs as the three main variables when designing a domestic supply chain. The production mediation costs are dominant when a bicycle is highly customised and requires significant investment in direct materials, labour, manufacturing overhead and process technology investments. Market mediation costs occur when standardised size bicycles satisfy a large demographic. They incur high storage, mark down and lost sales costs.

Thus, when deciding on product offerings and manufacturing, it is important to establish whether increased product variety incurs dominatingly production or mediation costs. Frame assemblies are typically production dominant variety whereas trim colours are mediation dominant variety. For example, Cannondale with a production location in the USA and Specialised with production facilities in Asia. The first offers a large variety of steel frame geometries, the second offers a wide frame material range with only a few geometries. Both of the strategies are successful due to the ability to satisfy specific customer requirements in the first case mass users in the second. Translating to: the production dominant variety firm "Specialised" is associated with scale efficient /distant production while the market mediation dominant variety of "Cannondale" is positively associated with scale inefficient and quickly reacting local production. This research is important since it explores successful industry examples within an economy with more or less equal standards of living as the EU. (Randall & Ulrich, 2001)

The main point the investigation, however, is “there are no firms in this segment of the industry with sufficient scale to pursue the dominant strategy of centralizing within the home market and offering both production and mediation dominant variety” (Randall & Ulrich, 2001). The reason being, there are no bicycle manufacturing companies with the capacity to do so. Hence, it is impossible to investigate the efficiency or the advantages of a firm manufacturing in large quantities in its home market. Additionally, mass customisation strategies are not completely dismissed. During the 2001 study by Randall & Ulrich, the technology needed to achieve customisation strategies has been unavailable due to lower computational power used for prototyping as well as research on its applications and benefits as evidenced by Leino (2015). Recent developments in 3D technologies and increased availability of prosumer PC components such as high-core count CPUs have made this possible. For example on March 2nd 2017 AMD undercut the price of octa-core CPUs by 500USD providing better performance for computationally oriented tasks. (Alcorn, 2017) Enabling supply chain simulations, product development and demonstrations in virtual reality before the physical prototyping. In companies with low-volume production projects, lead and delivery times can thus be shorter with simulation. The same industrial gap of companies producing high volumes in their home markets is also present in the EU, with the additional benefit that its area is nearly half as big as the US which is expected to positively impact shipping costs through shorter delivery distances.

3.2 Current Trends in Manufacturing Related to Bicycles

Leading to current trends in manufacturing noted by Olhager, et al., 2017 where back shoring, albeit not as common as offshoring is gaining momentum in Europe, particularly with electrical equipment manufacturers. Fabricated metal products industries on the other hand have one of the biggest ratios of offshoring to back shoring. Meaning a loss of educated or skilled labour from the EU and particularly Finland as it is the country with highest number of respondents in the industry. The industry overview shows labour intensive jobs as the most offshored and technology intensive projects as the most back shored consistently. At the same time, technology intensive projects and back shoring are considered critical to the pursuit of manufacturing innovations, on which Nordic manufacturing is most dependent on (Heikkilä, et al., 2017). The specific case of Helkama Velox further illustrates the example, by deciding to offshore 90% of production of their most iconic bicycle model “Jopo” to Taiwan in 2007 for 2008 and 2009 and realising 32% of cost savings. Production was repatriated in 2010 with 11% higher cost savings afterwards, marking the significant benefits of offshoring and back shoring (Gylling, et al., 2013).

The study is focused on Small or Medium Enterprise (SME) and the period during which it was carried out has possibly not allowed the manufacturers or researchers to consider the newly joined EU members in late 2007. Bulgarian bicycle manufacturers do not TIG weld and make their own frames which was one of the requirements for Helkama Velox during the offshore decision. Financially speaking, however, the average salary in Taiwan is 1,505USD per month (National Statistics: Republic of China (Taiwan), 2017), compared to the aforementioned 537USD in Bulgaria. Compounded by the possibility to subcontract smaller engineering companies outside the industry makes the new EU members attractive. The following concerns still need to be answered to clarify the prospects of manufacturing within other EU countries:

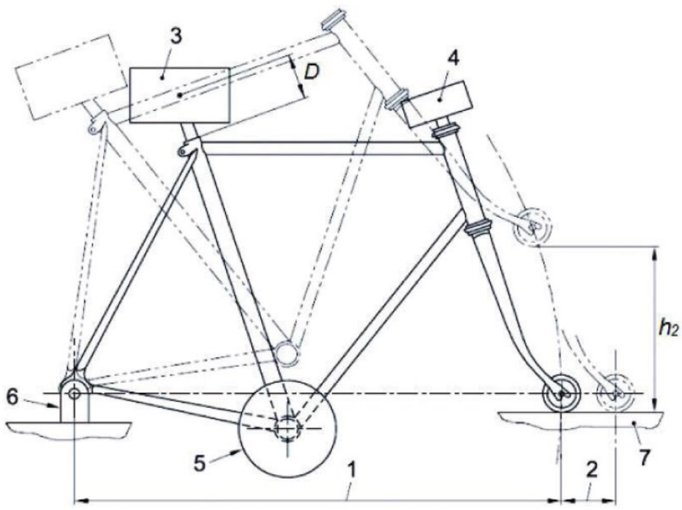
- What is the price of highly skilled TIG welders in both countries?
- What is the material availability in Eastern Europe?
- What are the shipping times and costs, especially considering the mileage by water?
- Manufacturing scale savings?
- Which manufacturing lead times are going to be most affected?
- Likelihood of the Lev or the Leu prices changing?

Another long term trend is modularity within the industry. (Galvin & Morkel, 2001) Bicycle producers are one of the first industries to standardise with a dominant design established in the 1890s. This owes to the limitation of human anatomy restricting the geometries of bicycles in urban or rural environments due to usability. Initial designs such as the Penny-Farthing bicycles are highly different in terms of frame geometries and power transmission due to unavailability of components and the complete manufacture of the bicycle. This allowed companies such as Peugeot Group to gain an almost exclusive market share. With the improvement of availability, standardisation of bicycle design occurred giving rise to local and then international standards. This owes to the realisation that manufacturing technologies began advancing too quickly for big companies to produce all sub-systems themselves. The cost savings from specialisation and a global supply chain outweigh vertical integration benefits. It follows when a company introduces a radical innovation, they should seek to maintain their intelligence through a closed system. As technology and other companies acquire the knowledge to manufacture, companies will profit by releasing their knowledge to establish their standards as the dominant ones in the industry with the potential to reap royalties.

Standardisation and modularity are investigated with Order Penetration Point when deciding on order versus make decisions when quality and quantity is concerned. OPP is defined as "the stage in the manufacturing value chain where is linked to a particular customer order" (Olhager, 2003). It defines how much of the product and value the factory creates when fulfilling a customer order. In products with high demand and seasonal volatility, the manufacturing decisions are taken closer to the engineering conception changes. At this point the products are also higher in price. For example, Norang, et al., 2010 perform an analysis of the supply chain of an Iranian bicycle manufacturer producing between 6,500 and 11,000 bicycles per year to establish where to place the Order Penetration Point. Concluding that with a bicycle constituting of 50% ordered parts, the delay in delivery is increased by a factor of 2 at least in comparison to 100% production at the brand factory. The articles use decision matrices and sensitivity analysis provide frameworks for the investigation of the OPP in regards to the supply chain and product characteristics

3.3 Difficulties in Supply Chain Management for Small Businesses and the Opportunities of Virtual Prototyping

Boutique manufacturing incurs high inventory holding costs due to the regulation, precision and technologies employed. For example, legislation based on ISO 4210 on bicycles details strength requirements such as static, dynamic and fatigue analyses which require high set-up costs to perform physically. The equipment manufacturers have not specified prices explicitly. Weight associated with the extra material to satisfy these criteria has a negative influence on the range of the bicycle and its ergonomics. (Roh, et al., 2018) Hence the precision with material addition requires more expensive technologies in construction. For example; cutting tubes can be done using a saw and grinder or using a laser cutter in which case the price difference between tooling and storage of equipment not in use can be more than 20,000USD (BossLaser, 2018).



Key

1	wheelbase	6	rigid mounting for rear-axle attachment point
2	permanent deformation	7	steel anvil
3	mass 1 (M_1)	D	distance to the centre of gravity (75 mm)
4	mass 2 (M_2)	h_2	drop height
5	mass 3 (M_3)		

Figure 1. *ISO Falling Frame Test Criteria. (International Standards Organisation, 2015)*

Illustrated is the falling frame criteria for bicycles. Due to the multiple bicycle standards for example regarding headsets, the mounting mechanism for the weights differs. The increased inventory of holding such mounts and weights of appropriate size so as not to interfere with frame geometries increases overhead for an SME. As a side note, the centre of gravity for the weights is unmarked. Meaning if the weights are optimised a frame can pass and fail with the same weight amounts.

Lead times for frame manufacturing can be more than six months with additional six to seven weeks at sea. (Oortwijn, 2015) The same problem exists in the aerospace industry where albeit aircraft being standardised, parts manufacturing remains difficult and expensive. The custom bicycle and aerospace industry are different only in scale in this sense. Reasons for this are the complexity of the machines where most parts are infrequently used and hence if they break, require fast shipping. Storing them also incurs high costs, since production for global availability means being left with expensive inventory once the current airplane models become outdated. (Walter, et al., 2004)

In industries dealing with custom design such as bicycles, require a high amount variation and engineering verification of safety. Preparing samples and testing them in a lab requires dedicated space and equipment and varying the design at this point is not cost effective. By employing virtual prototyping, it is possible to bring the product testing closer to or make it part of the development. (Cooper, 2006) The effect this is expected to have on the supply chain is limiting the material and part shipments to testing laboratories.

3.4 Ride and Logistics Sharing

Crowdsourced logistics experiments are being introduced operating similarly to ride sharing. There are legal challenges to introducing ride sharing within the Nordic markets such as legislation preventing low paying companies such as Uber to take over and protect taxi worker rights (Naumov, 2017). According to the minister of transport Paula Risikko in 2015, Uber is classified as a dispatch service and as such not illegal. To transport, however, a taxi licence is required for the driver (Ministry of Transport and Communications, 2015). Combined with the high vehicle ownership costs, the disincentive for using cars is effective in Finland. For a medium sized vehicle, the fuel costs and taxes can easily top 2000 Euro per year. (Trafi, 2018) (Trafi, 2018)

A Finnish company CoReorient for example is trying to push the technology forward by offsetting the negative social impact. It does so by working with the worker unions to promote and improve the technology. (CoReorient, 2017) In case this sort of technology becomes commonplace, it may allow for cheaper and less formal transportation of components. Maintaining a fleet of shared bicycles manufactured in the home country decreases the time needed for them to be fixed.

3.5 Condition and Trends of Global Manufacturing

As noted by Ferdows (1997), manufacturing companies within developed economies such as the EU or USA can continue to manufacture competitively. Although, the Foreign Direct Investment ratios have shifted from developed economies towards the developing since 1997, the average investment still remains in favour of developed economies. The only year marking a difference is 2014 where European investment decreased by 20%. Globally, the difference in investment between developed and developing countries that year had been 125 Billion USD. With a close trend, likely to vary as labour becomes more efficient according to Ferdows, it is likely that the developing countries can overtake developed ones. (United Nations, 2017)

The most efficient way of retaining competitiveness is hence to focus on delivering customised solutions, respond faster to changing customer needs, append more services to products and employ new technologies, essentially making a large part of the physical product manufacturing intelligence based. (Ferdows, 1997) Companies centred on intangible product advantages are also capable of providing expertise in other areas of industry. The benefit of delivering customised solutions is constant learning that is useful during downtime. It is possible to use it for further learning or consulting. At the same time, manufacturing abroad remains an option, however, considering the attributes of custom solutions, there are knowledge based considerations in moving abroad. (Ferdows, 1997)

3.6 Knowledge Transfer for Foreign Factories

Since knowledge is the underpinning competitive advantage of modern manufacturing, it merits an investigation into what it is, how it should be created, transferred and used. Considering the importance of defining the new manufacturing methods for European-based production, the most important type of knowledge to establish is procedural. In other words, it is the specific familiarity gained while performing the task. Its presence makes the achievement of a task quick and efficient. In comparison to declarative knowledge, it is not as broad. Where one can understand the theoretical underpinnings, meaning a just as effective but slower performance and larger application area. This second type of knowledge is more suitable for research or learning of cross-industry manufacturing processes which is useful for the future development of a company. (Ferdows, 2006)

Tacitness describes the extent to which knowledge is non transferrable. In its absolute meaning, it is only available to the user who possesses it and is encountered when the processes in a field change quickly. In the absence of time needed to codify knowledge by creating manuals, much of the information remains innate. The best way to transfer it is through working with others in person. This happens frequently in cases when muscle memory is an essential part of the manufacturing process. In terms of classic virtual prototyping this is non-existent, however, Finite Element Analysis programs are yet unable to simulate the layered structure of fused depositing modelling and the internal honeycomb structures associated with them in rapid prototyping. Hence, it is up to the designer to invent alternative designs, suitable for re-importing into FEA analysis software. Once simulation software catches up it should be possible to automate this aspect of design.

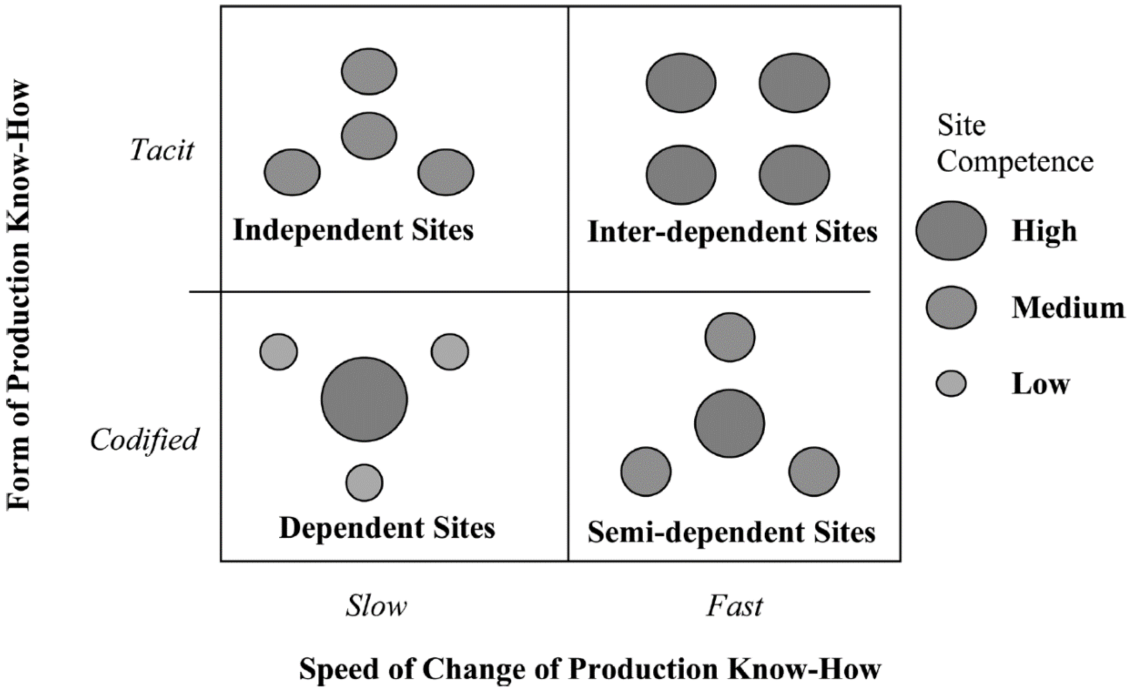


Figure 2. *Best organizational structure for knowledge absorption (Ferdows, 2006).*

Knowledge transfer mechanisms can be grouped in four types best representing the spectra of information available for company employees or consultancy customers. Moving people or rotating staff is best suited for situations where large amounts of information is based around understanding people and customs. Projects are suitable where fast implementation is key, even if the information is codified and transferrable it still requires the human interaction to polish the final product and speed-up implementation. Alternatively, it can also be useful when the knowledge is partially codified. For example, when using Open-Source software documentation is lacking, having the creator of the code or module hired as a consultant improves implementation speeds. Joint development is similarly capable of quickly transferring information between departments, however, it is most useful when operating at the forefront of technology and new methodologies are being adopted. Assistance with projects provides insight for the licensing company but it lacks the professional input from a dedicated team in joint development. Thus allowing the quick absorption or further development of information. Manuals and systems are useful when the information is heavily codified and the customer business is trying to compete with efficiency. (Ferdows, 2006)

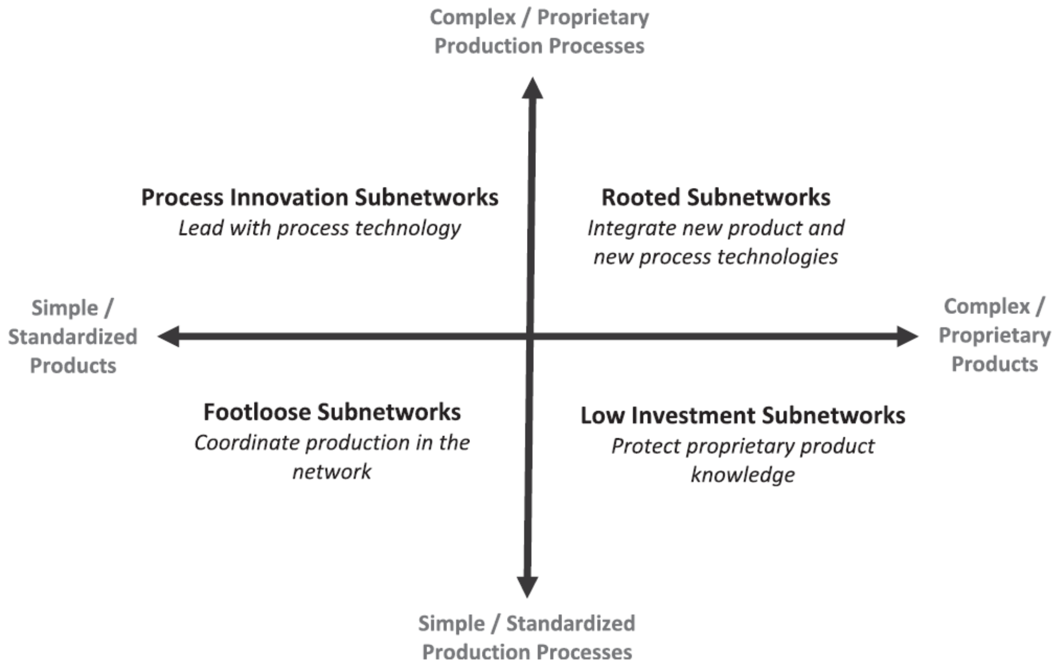


Figure 3. *Methods of knowledge transfer. (Ferdows, 2006)*

In the case of driving innovative bicycle design using digital prototyping, the knowledge initially falls into the joint development area. This requires direct feedback from bicycle shops to take into consideration their needs and those of the customer who is part of the technology development. Specifically, the bicycle shops through their direct contact with the customer are able to filter to the most important of frequent customer considerations. Establish which parts of the digital design should be left easiest to change. Digital parametric design is akin to coding through the arrangement of geometric constraints which are prone to failure in cases where the input parameters exceed geometric constraints of the model e.g. length too short from tip of middle finger to elbow.

3.7 Congruency of Manufacturing Networks

The concept refers to the ability of manufacturers to align themselves with the correct missions. In global supply networks, the multiple factories or industrial co-operators may be attempting to fulfil or improve in too many or diverse undertakings. The consequence is a difficult to manage overall process where the effectiveness of the product is less than the effort put in. A proposed solution by Ferdows is the periodic assessment of the manufacturer networks and comparison to their long-term strategic goals. The primary method of doing so is splitting into sub-networks and evaluating whether each one is congruent with the product it develops. Described are four categories of sub-networks. Of most interest are the bottom left and top right corner as they represent the two extremes plant capabilities.

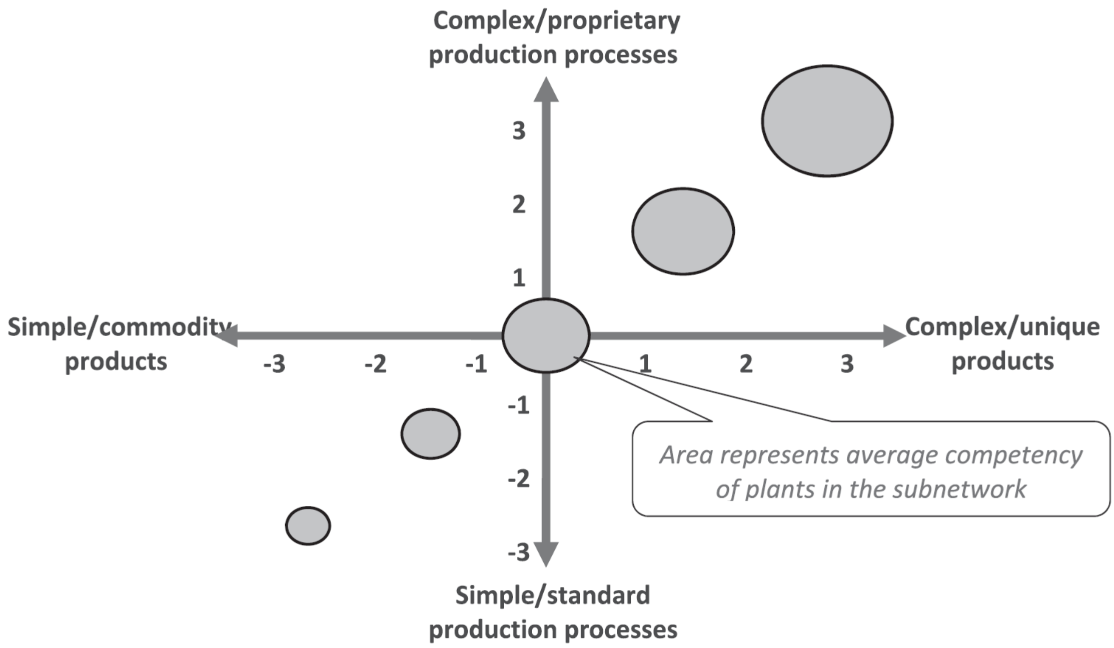


Figure 4. *Competency required for a certain level of product complexity. (Ferdows, et al., 2015)*

Rooted sub-networks producing the most high-end product using the most advanced knowledge which is often shared with other factories. They combine complex or proprietary products and manufacturing methods. These factories are thus innovative and prime targets for reshoring to industrialised countries, requiring stable working conditions for the formation of tacit knowledge between design and manufacturing divisions. On the other hand, "Footloose Subnetworks" are required to compete on price and use standardised processes. These require low-cost countries and continuous production improvement and automation. The diagonal forming between them can be considered as the gradual progress of a product from innovation to a staple. As such, Ferdows identifies the most congruent networks as being located there with some exceptions. A "red flag" is used to denote lack of congruency where the capability of the plant exceeds or falls behind the required to manufacture a product.

3.8 Effect of Virtual Prototyping on Bicycles

Due to the parametric nature of design, it is possible to introduce methodologies to decrease its labour intensiveness such as design automation. By leveraging the dimensional relation capabilities of computer programs such as SolidWorks, lengths can be automatically adjusted to match the dimensions of the user after an overall model is established. In combination with an experienced engineer, it is possible to establish the assembly tolerances and fitments and remove interferences. Following, is the automatic creation of 3D Models, engineering drawings to templates and other manufacturing data such as g-code which are sent to the manufacturer in minutes. This decreases the required human input and hence the need for specialised labour and repetition. On the other hand, it has the potential to complicate the initial design stage by requiring a robust model that does not break under reasonable parameters. (Javelin Technologies, 2010)

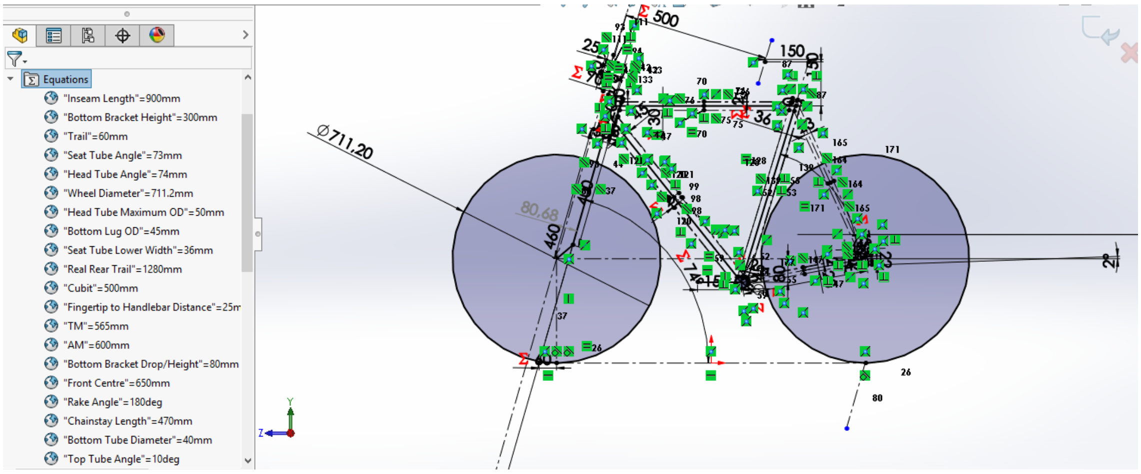


Figure 5. *Underlying geometric program.*

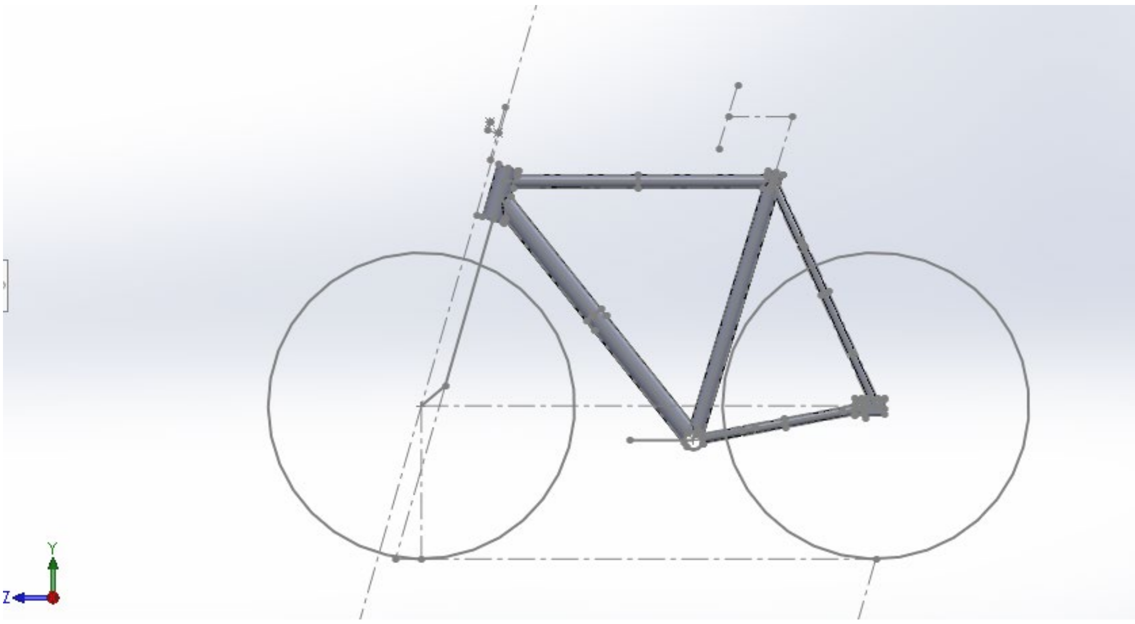


Figure 6. *Resultant solid model.*

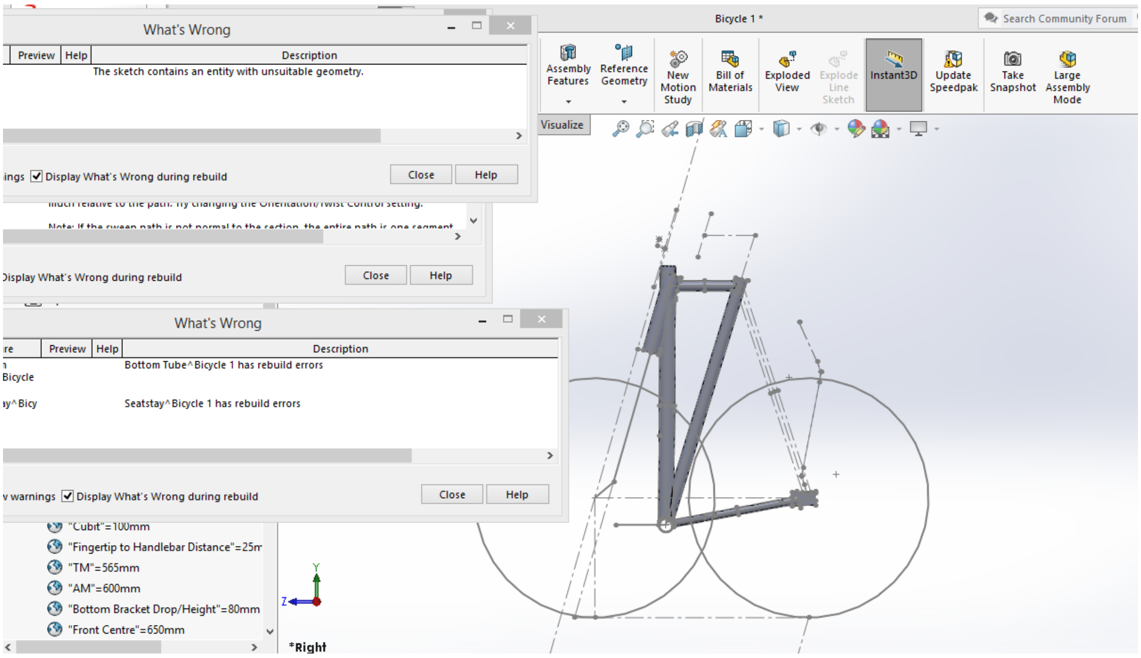


Figure 7. *Unrealistically exceeding parameters causes geometric conflicts under which the 3D or 2D model cannot be reconstructed.*

Going a step further, design and physical testing of the frame are sped up using simulation. The small quantity of boutique manufacturers, do not specify quality testing in terms of strength (Vagabonde Cycles, 2018) (Waterford Precision Cycles USA, 2016) (Saffron Frameworks, 2018) (SVEN Cycles, 2018). Unlike more widely known brands like Anvil Industries where handlebars undergo physical testing. This is possible because when focused on volume production, samples can be destruction tested, cut and measured. (Pinkbikes How it's Made: Anvil Industries Spank Handlebars, 2012). Doing so helps to increase the safety of customers and is useful for building brand loyalty, necessary to scale the business. When virtual prototyping is not employed on products they require a higher amount of physical test iterations. (Dascotte, 2004)

Bicycle manufacturers have not released their detailed design and testing processes as it will undermine their competitive advantage. Testing methodology information is collected in the form of documentaries collected by Pinkbike as they do not wonder in the technical details. In the case of boutique shops, a testing laboratory with the required jigs as specified by ISO standards require a high investment and floor space. (Graney, 2012) The jigs require electric motors to apply slowly ramping force and space for weights used in impact tests. Materials used in light-weight frame construction such as carbon fibre are also expensive and difficult to source due to source manufacturers dealing only with corporate resellers (Hexcel, 2018). Considering frame testing is a destructive procedure, multiple overload scenarios run computationally decrease jig, tooling and materials costs. Reducing the need for multiple finished products for every test. Since calculated results need to be verified, bicycle frames still need to be manufactured, however, the iterative design process is reduced. Experienced testing laboratories such as EFBE, however, do not explicitly state the price of tests making it difficult to gauge the exact cost savings. (EFBE, 2018)

3.9 Effect of Rapid Prototyping on Bicycle Manufacturing

Delayed manufacturing through the maintenance of undifferentiated material and rapid production through simplified production processes improve turnaround times. Traditionally material stocks can include bars for round components, slabs for milled parts, sheet metal for lighter support structures and others. With 3D printing, especially depending on the application, it is possible to reduce the heavy and differentiated materials needed for support structures. For example, Volvo trucks reduced the turnaround times for their engine building tooling from 36 to 2 days. (Stratasys, 2016) When the 3D printers are calibrated and set up correctly for the right material, part quality is accurate to 0.2mm and machine shop technician labour is reduced. Labour and inventory stock otherwise needed for subtractive manufacturing is also reduced through delayed differentiation. Inner design shapes can be made internally of structures introducing further capability to control part strength and functionality.

Due the flexibility required for customisable bicycle frames, rapid manufacturing and prototyping are suitable technologies to fulfil this goal. Rapid manufacturing is different to typical machining due to the anisotropic product properties. Much like the vertically directional sclerenchyma cells supporting wood, 3D prints are made out of layered directional filament stuck together through heat. (Kent, 2000) Depending on the orientation of the part during manufacturing, they can assume positions longitudinally which in the case of a cantilever beam is the optimal position for carrying loads. For example, a layer with an applied load perpendicular to deposited filament direction to create tension, will break at much lower stress than if applied parallel. Part dimension affects the temperature at which previous layers are stuck and slicer variation introduces feature variability. There is no data or single methodology to calculate the strength of each individual part, only approximations. (Kalpakjan, 1992)

4. QUANTIFYING THE EFFECT OF POSTPONED BICYCLE FRAME MANUFACTURING

4.1 Research Methodology and the Empirical Problem

Since the problem is measurable in reference to real world finances of a business, the study employed is empirical. It uses questions that can be answered using real world experiences. (Blackstone, 2016) A combination of qualitative and quantitative research methodologies are used to avoid focusing on a problem too early. Qualitative interviews allow the outlining of problems through exploration of the personal views, in this case of bicycle shops. (Warren, 1988) The process allows for brainstorming and was used to build the hypothesis leading to this thesis. (UK Data Service, 2012) Quantitative interviews on the other hand help to determine the extent of problems or opportunities. For example, the amount of funds unused on leftover stock or the opportunity of additional sales which are essential to acquiring an idea of additional prospects during the peak sales season.

As part of the qualitative research, an unstructured interview with the main goal of probing the biggest problems in bicycle sales allowed the description of insufficient and expensive bicycle stock the sellers have to maintain. With unstructured interviews having a simplistic schedule to only encourage the conversation, the interviewee was allowed to express his own views and experience of selling in the electric bicycle market in Finland. The initial qualitative interview is made with Peltobikes owner Iiro Peltola.

The bicycle resellers Mr Iiro Peltola is representative of are the small, family owned shops. It allows him to concentrate on providing excellent customer service using expertise. Biltema on the other hand sells electric bicycles and competes on price with their most expensive model ending at 1299 Euro. (Biltema, 2018) Because the bicycles he sells are described as higher end, a locally manufactured frame must provide similar performance in terms of weight, manufacturing quality and propulsion if it is to replace the need for fully assembled bicycles. Carbon fibre-based tubing and lugs are expected to provide higher acceleration due to low weight. propulsion is sold in kits, providing the same resistance and ride dynamics while the rapidly prototyped parts can provide the holes, notches and hooks to secure and hide cables. The main take-away being:

> *Mr. Iiro Peltola - "I think the biggest problem is that retailers don't know exact demand beforehand and therefore they can't make enough pre-orders (or they don't have enough money for pre-orders). Therefore manufacturers can't reserve enough production capacity (and they don't have enough money to reserve production capacity without pre-orders or they are not willing to risk having unsold*

bikes sitting in warehouse). And when demand spikes during summer there is not enough bikes to sell."

Mr. Iiro Peltola hence describes the inability to source enough bicycles when needed. At the same time, even if money is available to reserve production they may risk staying unused. These are problems familiar to automotive manufacturers. Due to the expensive nature of cars, having them sit and lose value is detrimental to the dealerships. Fortunately, in Japan and Europe lean manufacturing and more specifically the Toyota Production system are implemented to decrease the price of holding inventory. Unlike the United States custom to buy a vehicle from a lot at the retailer, European society accepts a waiting period.

Mr. Iiro Peltola wanted big data to process information and provide a reliable demand forecast for large batches. A complication to changing the business model is larger orders of 50 or 100. These orders could complicate the situation because the 3D printers used for making the lugs would have to work at full capacity and prioritize a single customer.

Mr. Iiro Peltola - "I have been asked orders up to 50 bikes few times but I have never received actual orders of that size."

Mr. Iiro Peltola - "...those who buy up to 50 they need them for a good price also. And bigger suppliers can provide the same quality for a cheaper price since they have better margins."

The buyers look for discounts when buying bulk orders. Hence rapidly prototyped production is unlikely to satisfy major customers. It is most likely to remain as a way to relieve sellers from their uncertainty for normal purchases during the year.

Mr. Iiro Peltola - "Good quality bike is built from well known supplier parts as for electric part Bosch or Yamaha. For other parts Shimano, Sram, rock shock etc. And otherwise built quality is good. No hanging wires or something like that"

Mr. Iiro Peltola - "Most modern bikes have aluminium hydroformed frame. Some really high end bikes have carbon frame"

Mr. Iiro Peltola - "Well in some Chinese bikes, quality of welds can be bad and they can be a bit heavier."

Considering the expertise and customer service quality provided, it may be possible to solve the problem by refocusing the products he sells. In this case, small resellers could focus on introducing flexible manufacturing methods using small volume production equipment to provide higher value bicycles in comparison to bigger dealers. If the bottleneck is a distant frame origin location, it would be possible to reduce the problem by moving manufacturing locally and eliminating the welding labour.

4.2 Fully Manufactured Bicycle Frames as a Target Cost

Hand-made frame manufacturers do not reveal the time it takes to make individual parts of a custom frame. How long it takes to alter the designs, attach braze-ons and paint the frame. It is even less common to find hand-made electric bicycle frames. Hence a high-performance traditional frame design is used as the reference for price quotations. Overall prices for the frame and the fork assembly are quoted by the shops because they are designed for design continuity. Similar functionality can be expected from the 3D printed frame in terms of fitment. Designing a custom fork is a long process and they are a smaller part of the total cost hence price of a standard and accordingly priced fork is used. Prices are (will be) converted to Euro and bicycle manufacturers from Europe and the US are quoted since they work to a similar economic standard.

Table 1. *Frame styles and price comparison.*

Price	Custom and Defining Characteristics	Manufacturer	Location
1315.14EUR	Frame – made to Measure, steel	(Waterford Precision Cycles USA, 2016)	USA
3358.37-4632.24EUR	Complete Bicycle, steel	(SVEN Cycles, 2018) (Rossiter, 2017)	England
3000EUR	Complete Bicycle – made to measure, steel	(Vagabonde Cycles, 2018)	France
1713.93EUR	Frame – made to measure and finish, steel	(Saffron Frameworks, 2018)	England
4624.90EUR	Frame – made to measure, carbon fibre	(Divobike, 2018) (Road Bike Magazine, 2018)	Italy
3068.66EUR	Frame – Made to measure, steel	(Oswald, 2018)	USA
400EUR	Frameset – Commercial Grade Aluminium, no paint	(Felton, 2017)	Taiwan

This comparison detailed prices of frame features and materials expected from a bicycle. Divobike have approached the challenge of made to fit frames from carbon fibre using multiple and standard for their frame-type tubing. They join pre-made tubes by wrapping them in carbon fibre and infusing them with resin in a lug type fashion. This is a process similar to steel built frames where standard steel tubes are joined using MIG or TIG welding or brazed together with the help of lugs. Both of these techniques require craftsmanship to deliver a stiff, strong and light product. One case where both of these products fail is the ability to disassemble the frame and change parts, should a crack occur during riding or mishandling. If this happens, the entire structural integrity is compromised, and customers have to buy a new frame, having to wait for weeks to have it manufactured. In the process, potentially straying away from the supplier in the case availability is not present for the need. Most of the custom bicycle manufacturers are based in developed countries. This is potentially due to being close to a clientele that can afford hand-made bicycle frames.

Below is an example of large volume production quote for higher quality bicycles from Taiwan. Despite the Taiwanese bicycle industry having a catalogue of all the parts and frames produced in the country, prices are only quoted to individual customers. Quality, usually varies as well, due to the availability of equipment and expertise in the factories. Despite not being an academic source or business, Pinkbike, a magazine have acquired quote on a double suspension aluminium bicycle frame:

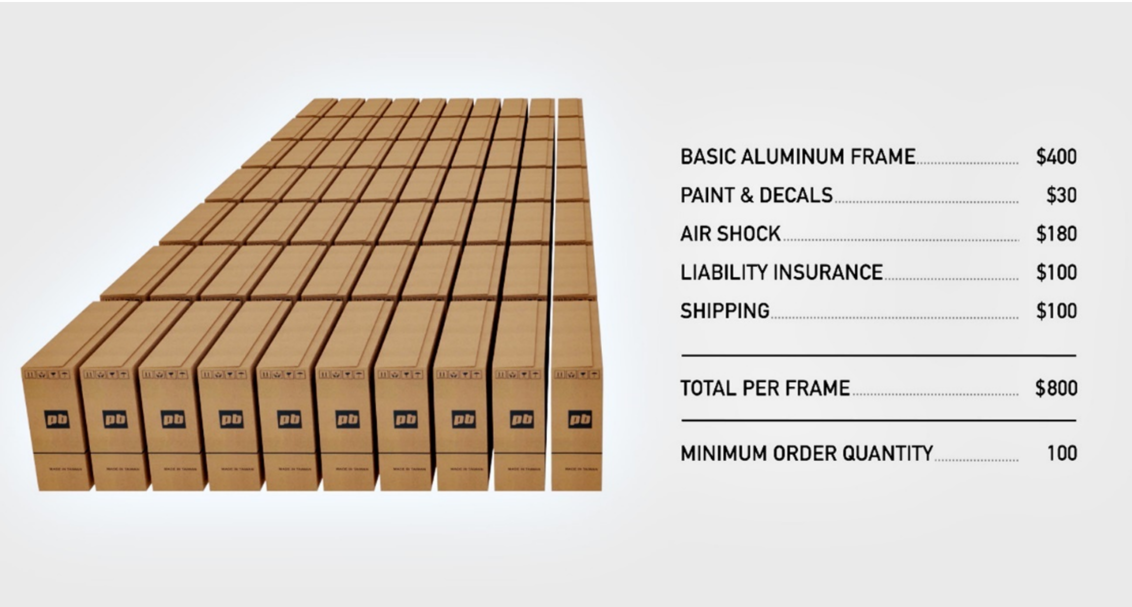


Figure 8. *Summary of a price quotation provided at the Taipei Cycle Show to Pinkbike. (Felton, 2017)*

Bicycle frame assembly activities remain highly manual due to the agility required for custom manufacturing. Despite robotised equipment, processes such as the application of flux before welding remains manual. For example, the largest conventional bicycle factory, "Fushida Group" producing 12 million bicycles per year as well as frames and components for brands such as Mongoose, Bianchi, Schwinn and Dunlop still utilise this method. (Tianjin Fujita, 2019) Triangle's, the largest bicycle frame manufacturer in Europe, Portugal has circumvented this problem through specialised aluminium treatment. (Oortwijn, 2016) High-volume production facilities are used where changing manufacturing settings on the automated machines is costly due to the high-volume models they produce, competing for fast turn-around times of around five minutes. (Agueda.tv, 2017) Smaller bicycle manufacturers which produce custom bicycles are assumed to use manual welding or brazing, requiring specialised welders. These activities are detailed in the Paterek Bicycle Frame building manual. (Paterek, 2004)

These traditional, necessary, complicated and demanding procedures for current bicycle manufacturing technologies are causing bottlenecks, increasing storage costs and delaying the delivery of frames to customers. The bicycle, as a product, is essentially mostly empty air. These are the main problems and the main design goals of a bicycle or a light electric bicycle or a motorbike. By utilising non-traditional technologies, it is possible to design around these limitations in a novel way. Thereby reducing the volume of goods shipped.

The market for low volume, custom bicycles is unlikely to disappear due to large variation between individuals and the differences their bodies undergo during growth and ageing. Traditionally, the flexibility in measurements and riding styles is provided by the lugged frame construction. It can be tailored to almost any size and requirements given the correct lug dimensions and angles are available for sourcing. And hence this traditional method is chosen as the benchmark and basis of the 3D printed, lugged construction.

4.3 Cost of Frame Building

4.3.1 Costing Methodology as a Design Driver

Using cost engineering in the design of the bicycle frame can ensure the most appropriate price to performance and quality are met. The starting point for this is target costing, however it only tells what the price should be. A complete digital prototyping and manufacturing process is able to identify the cost of a custom solution down to the minutes and provide price quotations and time estimates for the delivery, enabling Activity Based Costing (ABC). (Cooper & Slagmulder, 1997) After comparison to the target cost, value engineering can be used to optimise the design by balancing product life, specifications such as weight and price, providing accurate tuning characteristics for high performance products. (Mukhopadhyaya, 2009) (Kee & Matherly, 2006)The overall result of the process can be a Quality Function Deployment-like software whereby performance figures and costs similar to the real-world can be provided during the purchasing process. (Akao & Mazur, 2003) Target and ABC costing are the most important aspects of providing the service as they help determine the financial feasibility of the digitally prototyped frame and hence the focus in the development process.

Target costing determines the financial feasibility of a product. Through assessment of the competition, their relative performance and manufacturing technologies, it is possible to find whether the product fits within a market segment. In essence, it is checking whether a task can be done in-house cheaper. In the case sufficient performance can be provided with a lower cost and lower performance part, the product is cost-engineered to include it. By eliminating redundancies stemming from over-engineered components in this manner, the product package becomes balanced. (Cooper & Slagmulder, 1997)

Traditionally, ABC is used on products already in manufacturing because the activities need to be assigned to an existing process. With the digital prototyping and manufacturing process applied on bicycle frames, R&D overhead costs such as engineering for stress verification are quantified as methodologies. Analysing the methodologies on activity basis allows the prices to be determined for internal to the company purposes. (Johnson, 1991)

4.3.2 Direct Costs of Manufacturing a Brazed, Lugged Frame

The initial part-breakdown structure is characteristic of the types of components manufactured by specialist builders or available for purchase and order separately. In addition to buying those parts, the tools needed for assembly such as Oxy-Acetylene torches and compressed gas bottles require external storage areas equipped with the safety measures to keep the equipment in place, hence increasing overhead costs. (ISO, 2017) Due to highly custom frames being available from boutique manufacturers, only 30 hour approximation for the total work done is available from the Paterek Manual for Bicycle Frame

Builders (2004). Additionally, the manual provides detailed list of activities and machines for frame building. These are considered only to detail the differences in manufacturing and further describe the activities which are used to draw a better comparison between the 2 methods. Frame painting is not considered because it is a common activity after the frame assembly. Other overhead costs such as rent are not included because they are standard for both manufacturing methods. Manufacturing a brazed frame requires the following components:

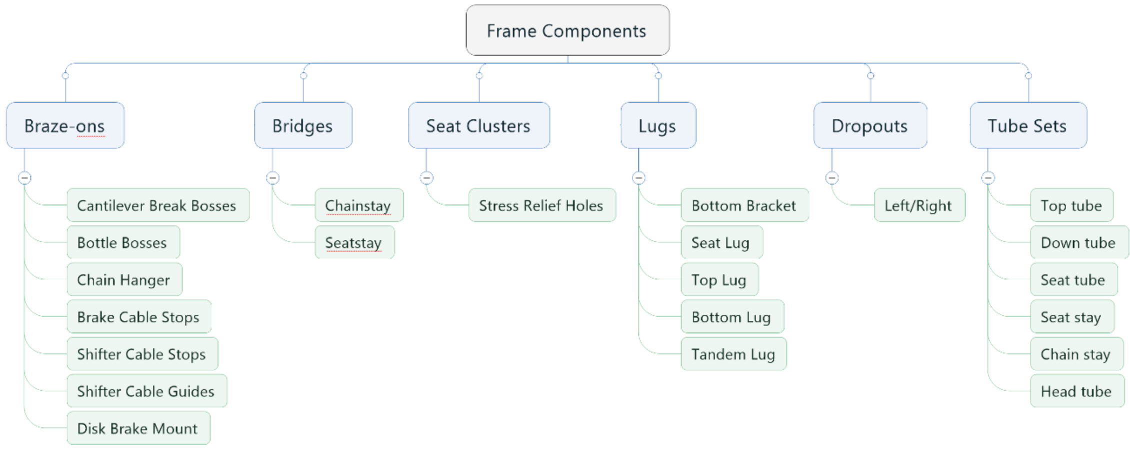


Figure 9. *Traditional custom frame assembly break-down structure with lugs.*

Individual activities for brazed frames have a high multiplicity. Although the bicycle frame building manual lists an activity as a single step, steps such as cleaning can entail multiple paraphernalia such as, compressed air, solvents, water and sand paper. Water rinsing process is tied to the shop water basin, hence parts need to travel to other parts of the workshop. Hence making the process unviable for scaling. Sand papering may require the proximity of extractor booths or tables.

Precise assessment from the book is problematic because time estimation complexity is introduced by frequent change of tools during the manufacturing of a brazed frame. For example, activities 2 and 3, entailing filing the inside lug diameters and subsequent enlargement of the seat tube and down tube sockets on the bottom bracket shell are followed by activity 10. (Paterek, 2004) Activities 4 to 9 are performed on the: bottom lug, seat tube, downtube and head tube. Factory space and time is used to safely stow cleaning flammable solvents and mineral spirits before it is used again for cleaning the next item on the list, the top tube. At the same time, space should be allocated to the parts which are not worked on, in a clean condition safely without risking contamination.

The lugged and brazed custom frame direct costs are more numerous than the 3D printed one as evidenced by the higher number of parts. Due to the unforeseen complexity associated with analyzing the direct costs of the brazed frame in terms of labour and equipment in detail, the comparison includes only the overall suggested labour duration of 30 hours by the Paterek Manual for Bicycle Frame Builders (2004). The full activity list can be seen in the appendices. The activity types and their occurance instances, however, can be summarized as follows:

Table 2. *Activities used for building a traditional, custom bicycle with a brazed frame.*

#	Activity	Activity Instances	Total Assembly Time
1.	Flux Application	30	30 hours
2.	Brazing	29	
3.	Initial Clean	1	
4.	Final Clean	16	
5.	Attach Supporting Structure	2	
6.	Adjust/Measure	9	
7.	Tapping	3	
8.	Filing	5	
9.	Mitering	6	
	Total activities	101	

Table 3. *Traditional, brazed lugged frame lugs and braze on costs (Henry James Bicycles, 2018).*

#	Part Name	Catalogue name and Part Number	Cost	Cost in EUR
1.	Bottom lug	60° Oversize Stainless Steel Down Tube Lug – LUG-60DTOSS	15 USD	13.11
2.	Top lug	73° Oversize Head Tube Lug - Stainless Steel - LUG-73HTOSS	12 USD	10.49
3.	Seat Lug	73° Oversize Seat Tube Lug - Stainless Steel LUG-73STOSS	39 USD	34.09
4.	Bottom Bracket	Oversize Bottom Bracket 28x20mm Oval CS BB-OSFB	30 USD	26.23
5.	Rear Bridge Kit	Road Bridge Kit (Fastback) – USA B-BRKITUSA	19 USD	16.61
6.	Cable Stops	Cable Stop-Triple [Pair] Imported B-CS3IMP	6 USD	5.25
7.	Cantilever brake bosses (Pair)	Canti Brake Bosses - Rear Pair B-CANTIR	4.75 USD	4.15
8.	Seat stay caps/plugs	Seat Stay Caps, Cast Flute - 16mm [Pair] B-SSCAP16	20 USD	17.48
9.	Drop outs	Henry James Rear Horizontal Road Dropouts - DO-REARHZROAD	35 USD	30.6
	Total			158.01

Table 4. *Cost of high-performance stainless-steel tubes (Henry James Bicycles, 2018).*

#	Part Name	Explanation and Part Number	Cost in USD	Cost in EUR
1.	Chainstay Pair	24 mm Chain Stay - XCR114OV410001	136 USD	118.89
2.	Seatstay Pair	16 mm Seat Stays - XCR615560	86 USD	75.18
3.	Down tube	31.7 mm (1.25") Double Butted Tubes - XCRL11570	115 USD	100.53
4.	Top tube	31.7 mm (1.25") Double Butted Tubes - XCRL11570	115 USD	100.53
5.	Seat tube	31.7 mm (1.25") Single Butted Seat Tube - XCRM13635	124 USD	108.40
6.	Head tube	46.4 mm (1.827") STEERER DIAMETER 28.6 mm - XCRX18250	62 USD	54.20
	Total			751.8

4.3.3 3D Printed Frame Overhead Activities

When utilizing 3D printing, it is possible to lower the functional assemblies to 4 from 6. Due to the proximity of features such as chainstay or seatstay bridges, they can be integrated into the lugs. Fillets, resulting from the traditional brazing have to be polished and sanded. In the case of 3D printing, they are integrated into the structure and have the benefit of being consistently reproducible after material testing. As they are points of stress concentration, this is vital in ensuring the quality of multiple frames without testing them individually.

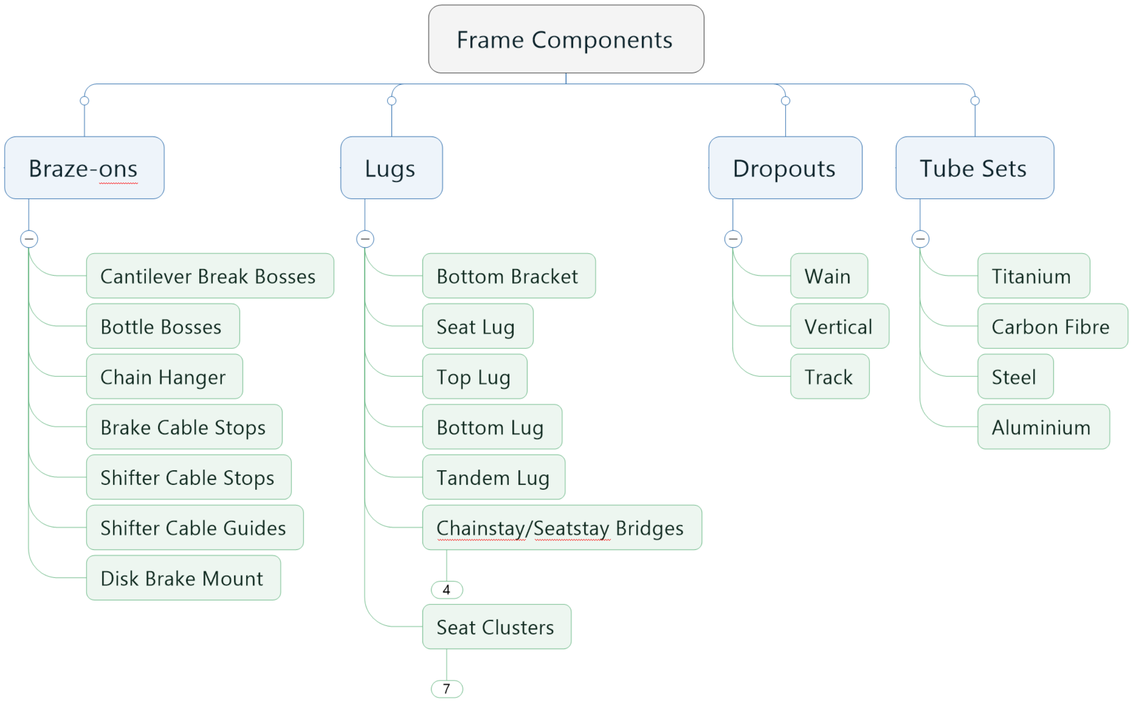


Figure 10. Custom bicycle frame assembly break-down structure with optional features from a 3D printing manufacturing perspective.

The braze-ons, lugs and drop-outs are the components which can be economically manufactured in-house using commercial 3D printing technologies. Before entering the assembly process, however, design, validation, and manufacturing engineering activities must be completed. They contain the bulk of overhead development costs associated with developing new products. Albeit being able to describe these activities, hourly time cost allocations are not accurate enough to be broken down to the hour. Development time can be broken down to 2 major cost pools. One being the new product development set-up costs, the second being the verification phase. The second phase can be done independently, whereas, doing the first phase usually requires the full process. The overhead engineering activities are briefly described in the following table:

Table 5. *Engineering Overhead Activities with descriptions and time estimations from testing demo tubular frames.*

#	Activity Name	Activity Description	Time Estimate
1.	Demand for a Light Vehicle requiring NPD	The type of product under investigation of this report. Investigation was carried out on a bicycle, that can be used as an electric vehicle.	
2.	Preliminary Feasibility Analysis	Engineers assess whether the client product is feasibly manufacturable. It would include checking whether there are resources, time, the skills and whether the machines can have the required flexibility.	2h
3.	ISO Criteria Review	Finding and reading manufacturing criteria. This step determines whether the product is legal for use in countries around the European Union. Despite the presence of small differences, Finland follows EU directives and standards.	10h
4.	Specific Customer Requirements and Design Flexibility Range	A Project Plan and/or Work Breakdown Structure is used to determine customer needs and is used as a reference document. These documents are used to help with the top-down design part of the product development process.	1h
5.	Preliminary Design Space	The maximum design space to comply with performance and features are established following from the project plan and WBS. CAD is used to determine the maximum size for the lugs for example and the preliminary relations between geometrical constraints.	120h
6.	Functionality and Cost Validation	The production tool path is simulated using slicer software. It provides the maximum time needed for manufacturing by the printers. The later list of activities required for assembling the frame can also be outlined at this stage.	4h

7.	FEA Analysis Set Up and Testing	The most arduous engineering task is setting up the FEA simulations, specifically defining contacts between and meshes, and ensuring only the most relevant data is recorded. Small set-up mistakes can cause a 100h simulation fail half-way. Additionally, making full use of the equipment requires being available to start the next step as soon as the last one finishes.	2249h
8.	Design Optimization	Redrafting the 3D model in the same design space without redundant material following the guidelines of the topology optimization. The resultant model is complicated and organic looking.	100h
9.	FEA Design Validation	The simulation has to be set up and ran again. This will ensure the thinned components work to the specified safety factor, that loading is spread evenly and that the fatigue and service lives are acceptable. The design optimization should also consider manufacturing constraints and the resultant anisotropy of the material.	779h
10.	Manufacturability Validation	Similarly to the functionality and cost validation step, the optimized lugs should be inserted back to the slicer software for final manufacturing adjustments, if part of the process cannot be completed by adjusting the slicer software, the CAD model itself has to be re-edited. For example, overhangs being too long is one of these problems. The assembly steps should be re-evaluated at this point if a design or a ge-	3h
11.	Parametric Design Adjustments	Edits should remain within the FEA design validation constraints. Material should not be removed from critical areas, but primarily added. Since the FEA topology design is redone using the parametric modeler, in the best case the modeler is push-pull based as with Spaceclaim.	8h

12.	Printing	This stage is completely automated and the time taken for completion is product specific. This stage requires periodically checking the printers to ensure it hasn't failed due to unsuitably small details if the designs need to have sharp or floating in supports details. Printing hours are machine hours, and not overhead costs.	
	Complete development time		3276h
	Scoping and set-up time		2386h
	Optimisation time		890h
	Optimisation - machine hours		641h
	Optimisation - labour hours		249h

Overhead machine hour rate is necessary to complete the design and analysis. Due to the lengthiest and most expensive process being that of FEA analysis and set-up, finding a way to reduce this bottleneck will make the process cheaper. The most impact can be achieved using a higher core count machine. The expected useful life of a processor is 2 years, due to an expected doubling of cores for commercial and home use computers scheduled for July 2019. The components for such a machine cost around 2000 Euro. As such the machine hour rate for such a machine if it were to run 24/7 is 0.11EUR/h.

The engineering activities are best represented as a flowchart. Similar to the stage-gate model, new product development goes through checkpoints before the parts are approved for manufacturing. Once the main product features are established, variations can be rolled out at a quicker pace. A benefit of using CAD packages such as SolidWorks versus open source ones such as FreeCAD is new variations having decreased long run costs. This owes to the increased robustness of connecting geometrical constraints and the ability to add configurations to an assembly. Commonly recurring features, resulting from topology optimisations are adjusted for production and saved as configuration of the existing assemblies. The result is reduced costs and a larger catalogue that can have features chosen based on situational suitability during the second runs. This second part, of the process is highlighted in black with white text.

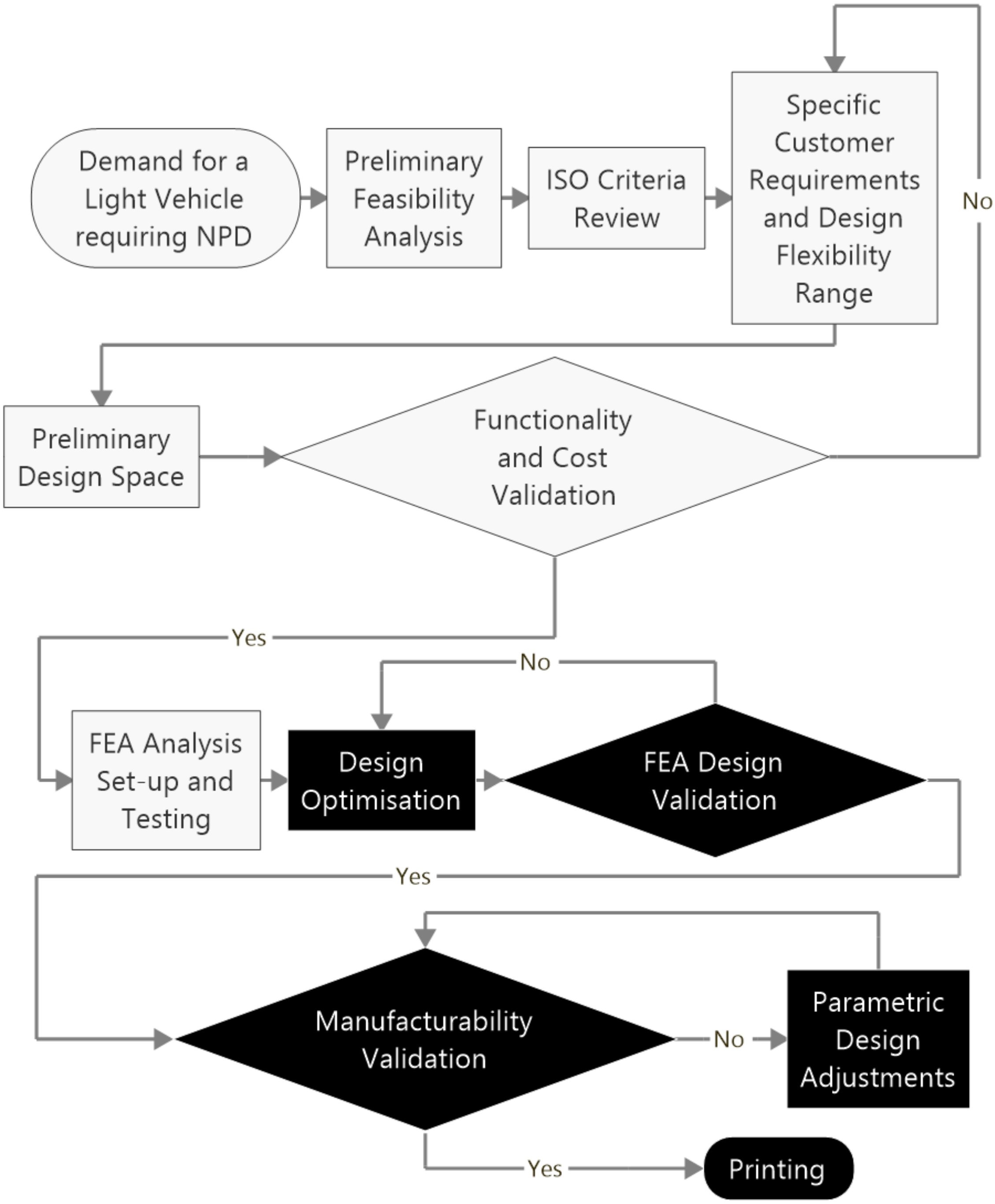


Figure 11. *Complete product development process for new bicycle frames.*

Because the most expensive part of the project in terms of hours is the initial set-up and FEA testing. It warrants a special breakdown of the activities required to complete it. Doing so identifies bottlenecks in the run times. Hence, if the method is to be adopted for other bicycle components such as stems and handlebars, the process will be cheaper as ISO does not specify dynamic tests for these other components. The largest part of the time spent comes from having to correct errors and re-run for results that yield errors.

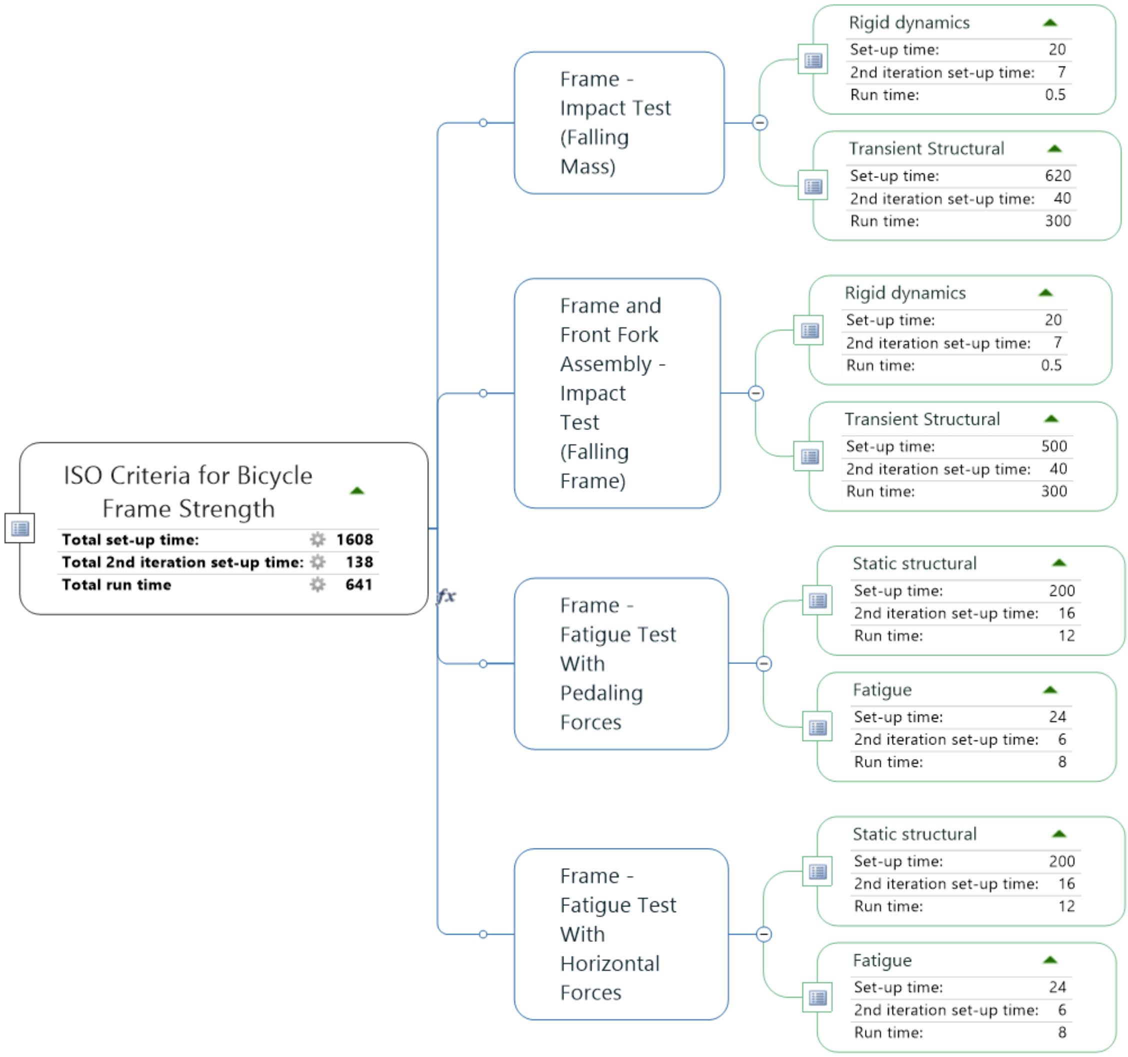


Figure 12. *Time cost break-down for the FEA testing and set-up time from testing the demo tubular frames.*

The biggest bottleneck during the engineering phase is the run times for the dynamic FEA tests. Due to the lack of personal experience in running FEA tests, it is currently impossible to produce a correctly running simulation on the first try. Test runs are therefore unavoidable and require attention to monitor for failures and resolve problems at a moment notice. When singularity errors occur, they can happen 50 hours into a test run. For this reason, personal notes from running of the FEA simulation studies are used to provide time estimates. Because defining the simulation parameters and detailing how the problem is decomposed is considered mechanical engineering, it is considered outside of the scope of this Master's thesis. Despite not providing real answers, the FEA analysis depicts how the problem is replicated in CAD and some of the results. The goal was figuring out how to mesh and model the interactions between multiple, thin structural members.

Simulations use meshes to calculate forces at their nodes. The direct sparse solver of ANSYS is used which requires more time, than the The below figures represent how the falling frame problem is replicated in the CAD and FEA software, alongside with a close up of the mesh and results from the rear chainstays.

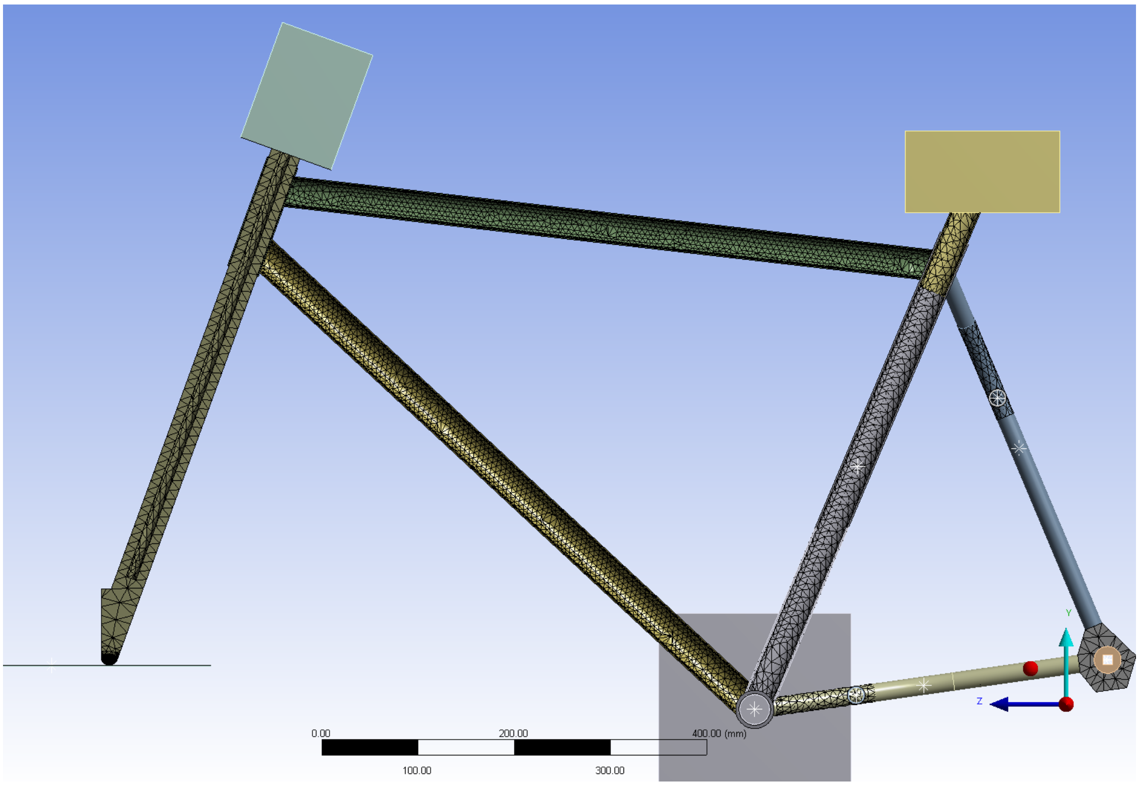


Figure 13. *Example falling frame test set up in ANSYS according to ISO criteria, meshed.*

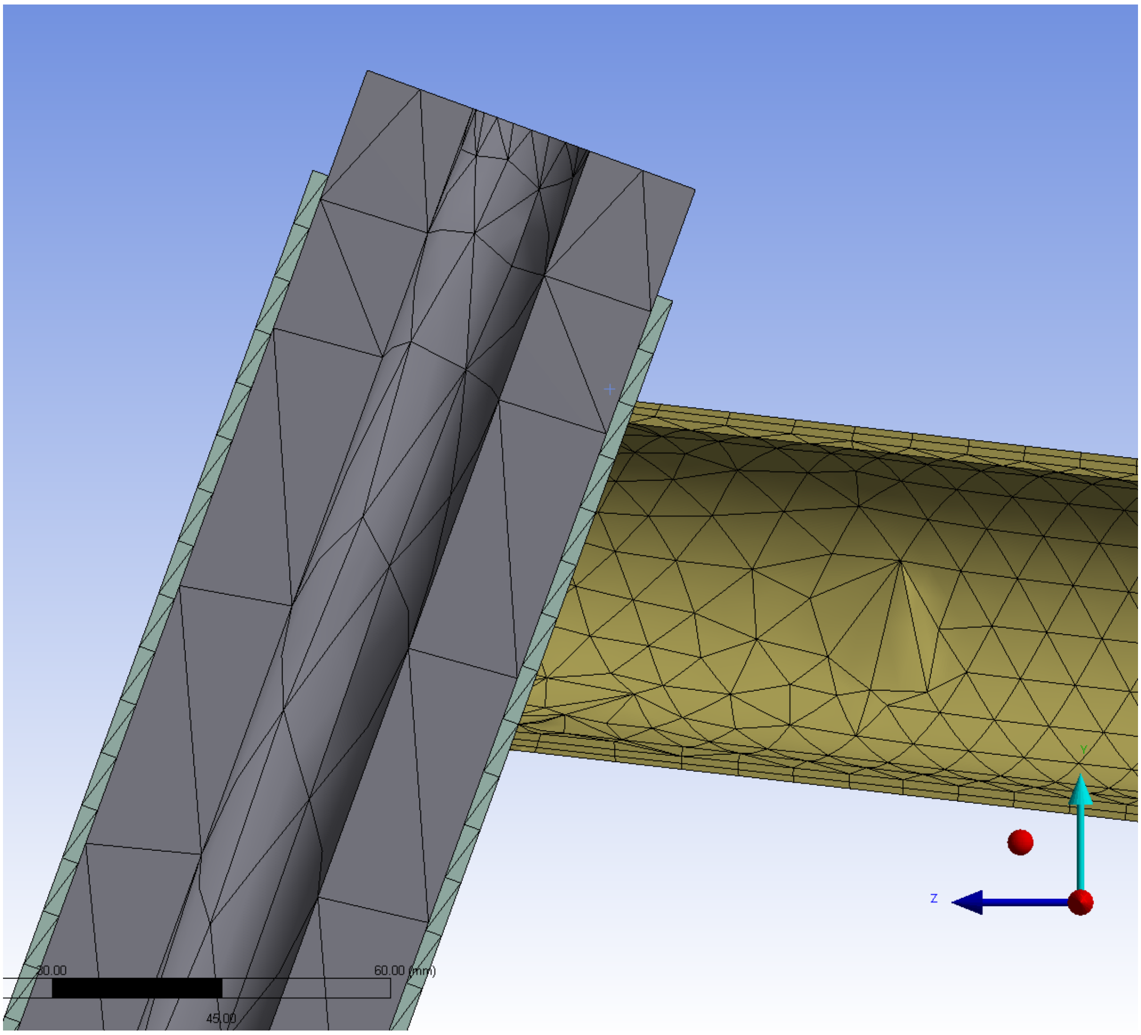


Figure 14. *Close up of the head tube and top tube mesh in the test set-up according to ISO criteria problem.*

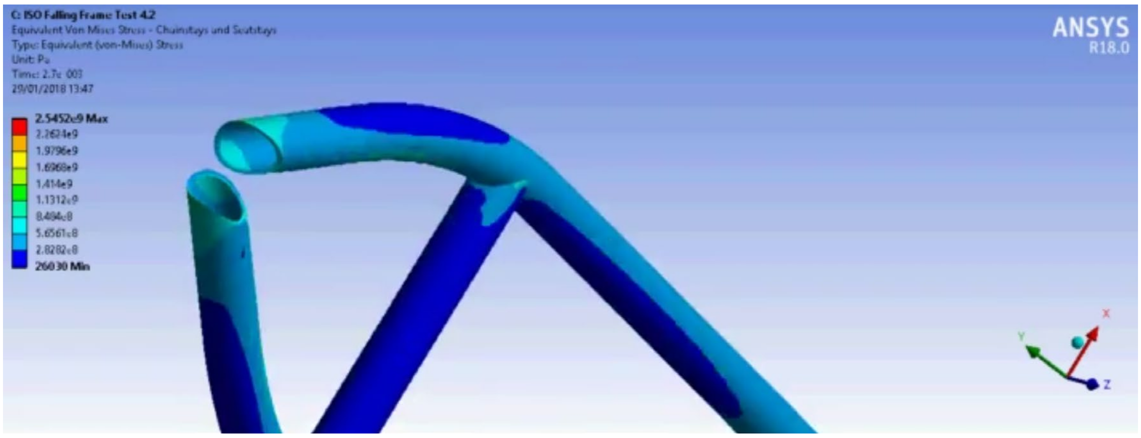


Figure 15. *Example result on the test frame, demonstrating Von Mises equivalent stress on the chainstays.*

The long duration needed for most of the simulations can be overcome with more computational power. Even in this case, where the mesh is reduced to barely having touching nodes between tube elements, a processor with more cores will yield an improvement in the simulation duration. The biggest bottleneck comes from the dynamic simulations having to be run at time steps of 0.0001s until 0.05. The computer configuration below is the one used to perform the stress analysis, it will yield the simulation run times achieved described in the time cost breakdown detailed above.

Table 6. *List of the computer configuration used to benchmark the stress analysis process. (PCPartpicker LLC, 2019)*

#	Part	Part Name (Configuration used)	Part Name (Recommended System)
1.	Central Processing unit	Ryzen 1700, Overclocked to 3.7Ghz	Threadripper 2990WX
2.	Motherboard	ASRock X370 Taichi	ASRock X399 Taichi
3.	Cooler	Raijintek Ereboss Core	CM Wraith Ripper
4.	Fans	4 x Noctua NF-A12x25 PWM	4 x Noctua NF-A12x25 PWM
5.	RAM	ADATA XPG FLame 16GB x 4	ADATA XPG FLame 16GB x 4
6.	SSD Storage	Samsung 960 M.2 500GB	Samsung 970 M.2 500GB
7.	Graphics Processing Unit	Radeon RX 580 8GB	Radeon RX 580 8GB
	System Cost	2000 EUR	3175.98 EUR

The recommended system is expected to perform at least twice as fast as the one used in this example simulations. This owes to the quadrupling of computational cores. More than double the performance is difficult to achieve because of the speed and latency associated with transferring information from RAM to the CPU and as well as the latency in communication between CPU cores which need to schedule, share and transfer between cache. Because the overhead time are mostly dependent on the engineering labour, the recommended system is expected to save more than half the initial set-up time, especially in the hands of an experienced engineer.

4.3.4 Direct Costs of Manufacturing a 3D Printed Frame

Despite the technology being highly individual, assembly labour costs can be summarized easily on the basis of activities. Following previous experience with 3D printing, the activity time estimates are established. It is important to note, however, that this is the best-case scenario where the correct slicer is set-up to provide the easiest to remove supports. Activity costs are grouped by type so as to make presentation easier. The full list of activities and their associated labour hours can be found in the appendix.

Table 7. *List of activities required to manufacture a 3D printed lugged frame using the same number of components as a brazed frame grouped by type.*

#	Activity	Activity Instances	Total Labour Hours for a 3D Printed Frame
1.	Separate 3D printed parts from Build plate	1	10 hours, 15 minutes
2.	Remove support material	7	
3.	Smoothing	7	
4.	Gluing	12	
5.	Mitering	6	
6.	Sanding/roughing	6	

Table 8. *List of activities required to manufacture a 3D printed lugged frame using a joined and decreased number of components, grouped by type with occurrence.*

#	Activity	Activity Instances	Total Labour Hours for a 3D Printed Frame
1.	Separate 3D printed parts from build plate	1	9 hours
2.	Remove support material	4	
3.	Smoothing	4	
4.	Gluing	10	
5.	Mitering	5	
6.	Sanding/roughing	5	
	Total Activities	29	

The resultant comparisons information demonstrates how design decisions can further improve shop-floor activities. By organizing the frame assembly activity-based tracking process through categories to include the activity number, an explanation of the activity, and the activity category the effect of adding or removing features can be tracked during the design phase. For example, radial geometries and constraints such as the head tube hole are likely to require finishing operations such as sanding due to housing rotating components.

The manufacturing stage of the custom frame can be completed using laser sintering and fused deposition modelling. All of these are viable commercial processes; however, the price of these procedures makes them prohibitive for low value frames. Metal, titanium laser sintering technologies are primarily used for high value products, primarily in surgically dependent goods such as hips. This owes to long service life and durability requirements. (General Electric, 2018) Comparing the direct costs, a sample part is taken from the CAD program and sliced, accounting for material usage and time to manufacture. The large discrepancy in the prices between printing technologies is assumed to owe to the more difficult servicing of the laser printer.

Material properties data is unavailable for the reinforced polymer materials. As these are novel materials their constituents are being adjusted according to manufacturer capability. There are currently no standardized filaments for particular tasks even if they comply to RoHS and REACH directives. Performance with age is also unknown, which means they might be unsuitable for certain, high performance and risk heavy tasks. The same is true for the 3D printer where part durability is unknown. For example, the quality of the metal rails can affect the longevity due to fatigue and creep. Bearings, however, can be replaced with Schaeffler ones for example where Materials for 3D printing are primarily sourced from European and US manufacturers. Hence the European Economic Area benefits from retaining manufacturing and competitive advantages within the Union. Should staple global technological products become vetoed as in the case of Huawei, companies may continue to manufacture in locally. (Reuters, 2018)

To give an idea of the manufacturing scale available within the manufacturing process and the prices associated with a certain size, the head tube assembly is analyzed using different 3D printing technologies. The comparison is done through price, printing time and an explanation of the benefits of each technology. The head tube is a prime example of the benefits of 3D printing whereby the assembly costs for 3 different pieces are reduced by unifying them in a single part to reduce changeover times. With larger parts, however, the cost for printing is higher due to the increased time spent in the printer and in cases where larger printers are used, accuracy is lower. Overall dimensions for the model are provided below.

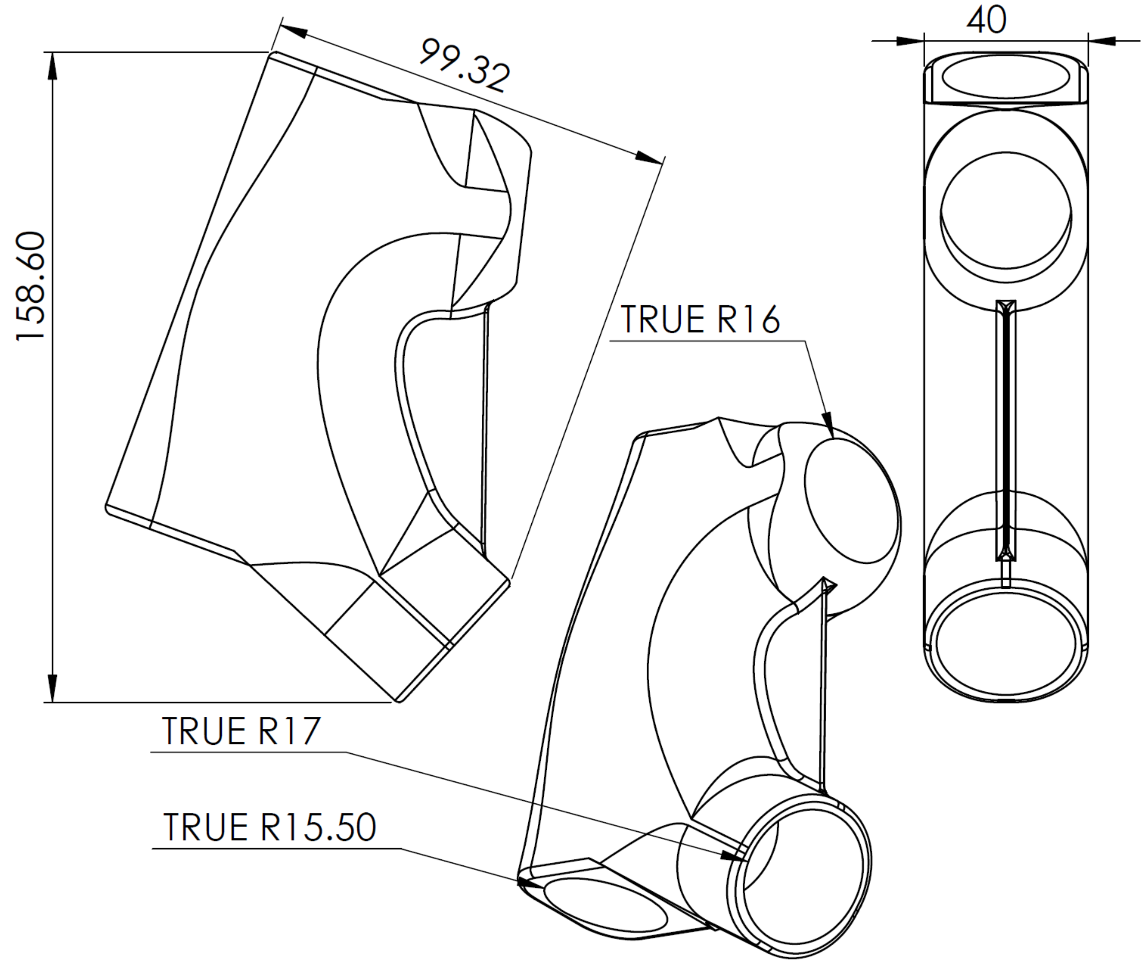


Figure 16. *Head tube with integrated lugs schematic, showing the overall dimensions of a demo head tube and lugs combined piece.*

Table 9. *Comparison of printing costs for the head tube with integrated lugs for four 3D printers with estimated printing time.*

#	Manufacturing Method	Explanation	Cost	Time Estimate
1.	Markforged MK2	Uses Fused Deposition Modelling. By melting material off a spool, held in a dry box, it lays the material slowly. The increased rigidity from continuous carbon fibres make the print dimensionally accurate. (Carbon Fibre – Polyamide [ONYX])	59 USD	40h
2.	Markforged Metal X	Uses slow Fused Deposition Modelling with metal fillers. Once the material is laid, some of the plastic binder is washed and the rest burned away as the metal filler is fused together in the sintering furnace. (17-4 Stainless Steel)	200 USD	121h
3.	M2 Cusing Multi-laser	High-speed laser sintering process with a price premium. Large print bed, high accuracy, and difficult material handling make this process viable for only the most valuable bicycles. (17-4PH H900 Stainless Steel)	4891 USD	N/A
4.	Prusa i3 MK3	Slow, fused deposition modelling. The technology is the same as the Markforged MK2 albeit less accurate. This printer allows customization and adaptation of the materials, not tying the process to a single material manufacturer.	23 EUR	62h

Assumptions made in this table are, that the object is printed as a solidly infilled piece. Support structures are not directly relevant to the costing and so are taken into account into the cost of the product coming out of the printer before clean-up. The rest of the demo pieces are sliced for printing on the Prusa i3 MK 3. The materials used are either the only option as part of a proprietary technology in the case of Markforged, or can be purchased and swapped separately for the Prusa and similar types of printers, the traditional options being Colorfabb and Formfutura. This is because the print bed is large enough to accommodate them and because it is the economically cheapest option for production. At the same time there is currently no quantified data about the maintenance costs of that particular printer.

Another issue are the support structures which add eight hours to the print time. Given the importance of rigidity, they are a necessary for a structurally sound part. It is difficult to put an exact price on them because printer maintenance and hence depreciation costs are unavailable. The difference, however, between using them for this part is 8h. Manufacturers should assign a cost to this particular feature and consider the cost of designing around it. To do so, the price of the machine, its space savings, and the cost of removing the supports should be considered. Here is an example of what the part should look like, with and without the supports to give an idea of how difficult it is to remove them. The long tunnel that must be cleared of the support structure is used for the fork steerer tube.

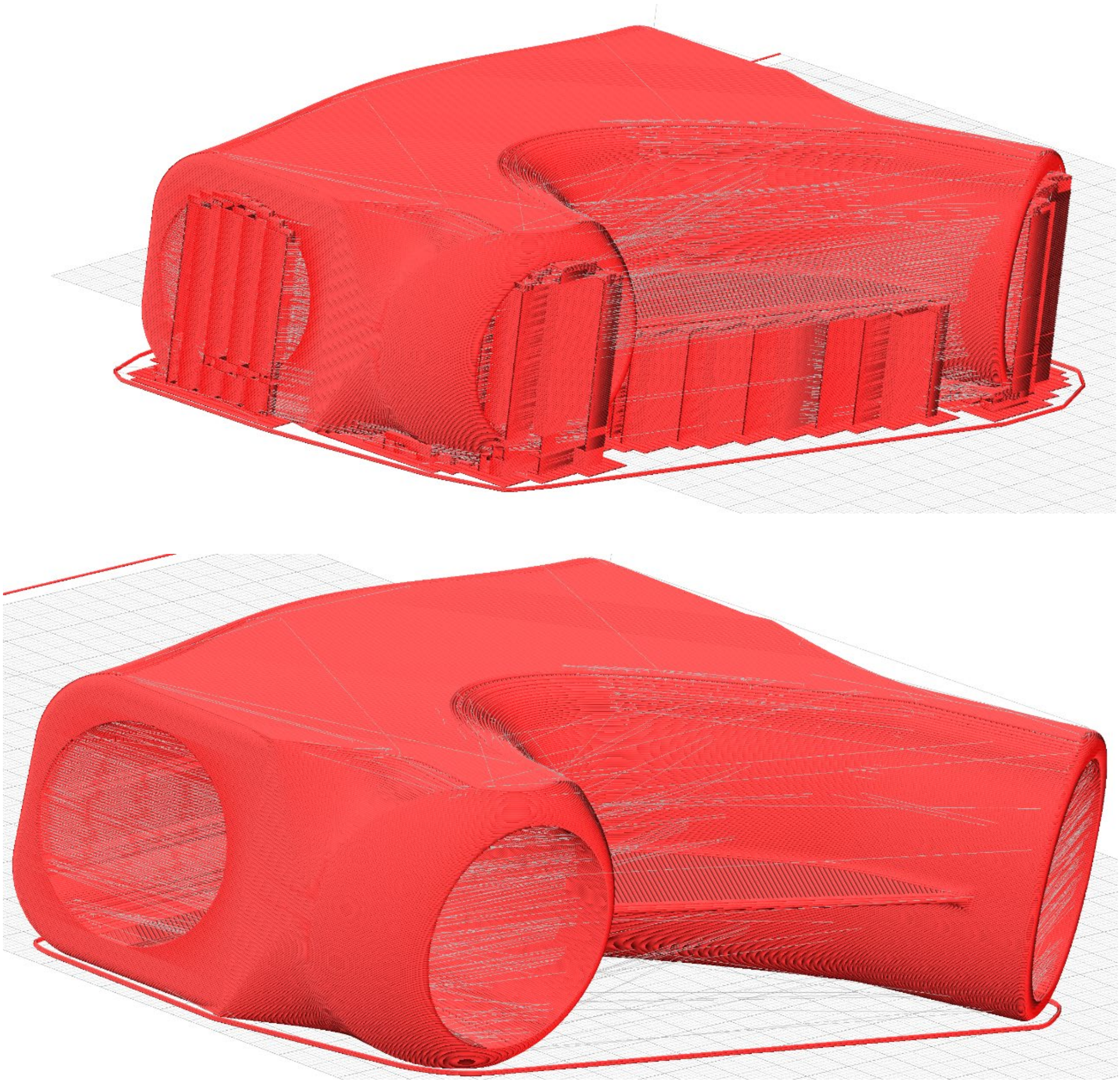


Figure 17. *Head tube with and without support material.*

Prices of the other 3D printed lugs, part of the assembly are determined using the Prusa Slic3r slicer software. With the modularity of the printer and its associated software, the production costs are expected to only fall from this point onwards. Additionally, the Prusa printer as of currently has the most suitable bed for quick part changeovers through the use of spring steel and Polyetherimide allowing release of the part through simple bending. In the case of Markforged, the print bed must have glue applied to it and parts need to be chiseled off, potentially damaging the bed or part and increasing changeover.

Table 10. *Demo frame lugs manufactured on a Prusa i3 MK3 using CarbonFil - Black.*

#	Part Name	Explanation	Cost	Time Estimate
1.	Head Tube/Lugs	Fused lugs and head tube, reducing labour costs	23 EUR	62h
2.	Bottom Bracket	Uses a more or less traditional bottom bracket design with lengthened lugs for additional support needed because of the anisotropic qualities of the part.	25 EUR	71h
3.	Seat Lug/Seatstay Plugs	Seatstay plugs are integrated into the seat lug, further reducing brazing or welding. Manufacturing them as one piece also decreases chances of warping.	39 EUR	104h
4.	Dropouts	The 2 piece drop outs for the left and right side of the frame all fit on the same print bed due to their small size. The demo pieces used do not have the required adjustment for the actual frame but nevertheless are representative of the dimensions.	9 EUR	23h
	Total		96 EUR	260h

Individual costs of the carbon fibre tubes are calculated from the economic order quantity of RockWest Composites. Despite being a US based supplier, they have a comprehensive order system, clear explanation of the manufacturing process and use carbon fibre from Mitsubishi Chemical, Carbon fibre and Composites. The order quantity chosen is chosen as the minimum available to complete a single bicycle. This way, inventory holding costs will not be burdened, however, in case of demand, this raw bulk material can be ordered at discounted prices.

Table 11. *Demo frame bicycle tube cost from RockWell Composites (Rockwell Composites, 2019).*

#	Part Name	Part Characteristics	Cost
1.	Seatstay/Chainstay 2 Pairs	The unidirectional tubes can be used interchangeably between seat stay and chain stays. As such 4 of them are in a single order.	207 EUR
2.	Down /Top Tube pair	Unidirectional tubes, available for use interchangeably between Top tubes and Down tubes. As such, 2 of them are in a single order.	122 EUR
3.	Seat Tube	A single unidirectional tube	95 EUR
	Total tube cost		424 EUR

4.3.5 Cost of Tooling

The tooling required for the manufacture of the metal frames highly affects the overall cost for the expected short production runs of custom frames. It takes 115 unique tools to braze together a frame, whereas gluing a frame takes 31 tools. Additionally, the number of changeovers required between the tools, and workshop organization to be learned means workers have more to learn, remaining more valuable for the company. A popular Finnish workshop tools importer offers milling machines for circa 3000 Euro and lathes for circa 2000 EUR. (Koneita.com, 2019) Contrasting with this, a good quality 3D printer costs 1000 EUR fully assembled. (Prusa Research, 2019) The large size of these machines and respective weight of 350kg and 180kg makes shop floor retooling impossible by hand, requiring a commitment from frame manufacturers to their floor layout. To help calculate the cost of machine hours, an estimation of the depreciation period of major equipment is given, considering full time operation. Equipment for the brazed frames can be summarized as such:

Table 12. *Major tools list used in making a brazed frame.*

#	Tool Type	Description	Depreciation Period	Cost
1.	Milling machine	A versatile metal working machine for cutting metal at a wide variety of angles with high accuracy – 350kg	5 years	3000 EUR
2.	Henry James Universal Jig	A jig used to hold most of the table – 30kg. (Henry James Bicycles, 2018)	4 years	3595 EUR
3.	Rear triangle Fixture	A jig used to align the rear triangle tubing and gear tab. (File and Torch, 2018)	4 years	346 EUR
4.	Bench grinder	Used for sharpening tools and grinding away small parts of the tubes –	3 years	145EUR
5.	Air compressor	It has a compressed air tank and an electric pump motor, can be wheeled around - 140kg	2 years	595EUR
6.	Angle clamp	Used for holding tubes and mitering them or welding.	1 years	99EUR
7.	Welding/brazing gas equipment	Oxygen and Acetylene fuel tanks with nozzles. Each 44kg, total 88kg	3 years	3000EUR

By contrast, the 3D printer weighs circa 11kg and can be carried by hand to a new location. When production is low, machines can be stored, making way for other activities on the shop floor. In case production needs to be increased, the printers can be stacked above each other. The most expensive, heavy and important tools for each production method are summarised to provide information on depreciation and amortization costs. The price of the Prusa printer has the added aftermarket option for a high resistance 3D printing nozzle, particularly suited for abrasive materials, this is a necessary as it prolongs the maintenance period of the machine and the reproducibility of the prints.

Table 13. *Tooling options for the 3D printing process.*

#	Printer Make and Model	Printer Description	Depreciation Period	Cost
1.	Markforged MK2	Traditional FDM, with high quality components and structure optimized for accuracy rather than low price. It uses high quality materials for its nozzle, flat linear rails and belts, guaranteeing wear is minimal and the printer reliable. Can be carried by hand around the workshop.		20000 EUR
2.	Markforged Metal X	A system comprised of a traditional-based FDM printer, washer and a sintering furnace. All stages require moving equipment.		200000 EUR
3.	Prusa i3 MK3	One of the most popular 3D printers, well documented and fully featured with feedback sensors and open source design make it an excellent production option if it is well maintained. Multiple of these can be bought and manufactured in-house to concurrently manufacture frame lugs.	1 year	1200 EUR

The chosen tool for the manufacturing of lugs is the Prusa i3 MK3 or a derivative of it, thereof. Its advantages include, low price, serviceability, documentation and expandability. Multiple of these printers can be bought to speed up production, however, the flexibility of 3D printing means a single one is needed to set up a production run. To manufacture the frame concurrently, five or six of these printers will complete all the pieces within 104 hours, the time it takes to print the bottom bracket. Smaller and less expensive tools of the tools are lumped together. Their price is expected to be around 15 euro per piece.

Printing all the parts simultaneously on a larger bed printer is possible, however, dimensional accuracy is lower due to the rail flex during rapid extruder movements. As production increases and errors and maintenance schedules are determined, a printer of larger proportions such as the Prusa i3 Hephestos can be used. The difference between multiple smaller printers and a large one, is the larger loss of parts should a single print fail. Additionally, the single extruder on a large bed means hot plastic will be extruded over cooler previous layers. Due to leaving porosities between layers. There are, however, slicers that can print single parts at a time on a large printer, however, space between the parts needs to be larger, and parts short to avoid collisions.

Table 14. *Small tool count needed for the manufacture of a traditional brazed, lugged frame and a 3D printed, lugged frame.*

#	Frame Design Type	Tool Amount	Average Estimated Tool Cost	Depre-ciation Period	Total Small Tool Cost
1.	Brazed Lugged	108	15EUR	2 years	1620EUR
2.	3D Printed Lugged	30	15EUR	2 years	450EUR

The depreciation periods, machine costs and tooling costs are used to calculate the cost of machine hours which are then applied equally amongst the machine hours required to manufacture each frame. Expensive machine hour costs are added to the simple tool costs per hour. In the case of the brazed frame, this figure is not fully accurate as the machine hours vary from machine to machine and the individual activity times is estimated. It is also assumed the machines are ran 24 hours in a day, every day, for a year.

Table 15. *Cost rates for the tooling during the labour hours for the creation of a brazed lugged frame and a 3D printed lugged frame.*

#	Frame Design Type	Machine Hour Cost
1.	Brazed Lugged	0.44 EUR/h
2.	3D printed Lugged	0.16 EUR/h

4.3.6 Labour Required and Cost Rates

The assembly labour defines the best candidates for frame building activities through their skills, experience and hence salaries for the two methodologies. The knowledge profile is defined through the activities as detailed in the Paterek Manual or personal previous experiences with 3D printing and part preparations for the assembly. In traditional frame building, considerations include the ability to operate machines and resolve problems as well as manipulate material with limited capability to redo mistakes without assistance. In the second, familiarity with the technology is likely to be more important.

A problem with the recommended time suggestions for each activity of brazed frame building is the unspecified changeover times. Due to the complexity of applying flux, heating and cooling the frame in the order of seat tube, downtube, head tube, and top tube before adjustment and then repeating the process for the rear triangle, the amount of, clean up, set-up and start-up for a single frame builder is higher than it would be for a 3D printed lugged frame. Specifically, this can be a problem for high tensile steels where rusting occurs when their protective oils are washed off. This can be circumvented with stainless steels; however, they are softer and weaker, compromising the product performance.

Working with heated metals requires experienced frame builder and rider. This owes to the accurate execution of hand welding to reduce frame warping. Due to the custom geometries expected from a custom-building service and changing catalogues of lug providers, the precise amount of heat needed for a joint to suck silver in is determined through observation as detailed in the Paterek Manual for Bicycle Framebuilders (2004). Experience is also required in riding and building bike frames specifically, because the misalignment errors occurring during the heat treatment can only be seen felt by an experienced rider and builder. Additionally, weak points can be identified early on to have the frame only partially disassembled for adjustment.

Despite the large variety of machining operations of a brazed frame, the knowledge required for completing them is encoded. Machinists can follow guidelines reproducibly as lathes and mills possess the mechanisms such as feed and speed controls to cut materials consistently. The manufacturing formula provide approximate enough parameter to set the machines up with. At the same time, the volume of information needed to set the machines up is high and requires problem solving skills. By comparison, the skills required to assemble a 3D printed lugged frame are fully limited to being able to follow encoded knowledge. There should not be a need to bend tubes beyond their elastic limit to correct them or be able to see the exact colour of a heated joint. In cases where bending of the tubes has to occur, there is no consideration how many times a joint has been reheated.

Unfortunately, lack of personal experience with traditionally manufactured frames makes detailed labour costing inaccurate enough not to include it into the analysis. Fortunately, Eurostat (2018) have a collection of the labour per hour costs covering major activity sectors. The average salary in "Industry" being 2910 EUR per month. This is assumed to be the technician salary due to the much lower value compared to the TEK freshly graduated engineer recommendations. The analysis and comparison easier as the costs are determined using the same statistics for every country. An important factor for the location of production of a knowledge intensive process is the percentage of educated personnel. Luxembourg is included as the highest educated in stem country to provide perspective.

Table 16. *Industry salaries in three countries of interest as potential manufacturing locations. (Eurostat, 2018)*

#	Country	Industry Labour Hourly Cost	R&D Personnel % of Workforce
1.	Finland	36.30 EUR	29
2.	Bulgaria	4.70 EUR	19.4
3.	Luxemburg	32.50 EUR	34.3

Overhead cost rates for engineering labour cannot be found in Eurostat. As such, the Finnish society of Academic Engineers and Architects salary recommendation of 3780 Euro per month is used in combination with the average salary in the public sector and ordinary contracts. (TEK, 2019) (Statistics Finland, 2018) These figures are used in conjunction with the labour hourly cost to find the ratio of taxes to salaries covered by the employer and hence the cost rate for the engineering labour:

$$\frac{\left(\frac{TechLC - \frac{TechS}{160}}{\frac{TechS}{160}}\right) * EngS + EngS}{160} = EngLC$$

Where:

$$TechS = Technician\ Salary$$

$$TechLC = Technician\ labour\ costs\ per\ hour$$

$$EngS = Engineer\ salary$$

$$EngLC = Engineer\ labour\ costs\ per\ hour$$

$$Conversion\ Factor\ from\ Monthly\ to\ Hourly\ Wage = 160\ work\ hours\ in\ a\ month$$

Substituting with the values produces:

$$\frac{\left(\frac{32.72-\frac{2910}{160}}{\frac{2910}{160}}\right)*3780+3780}{160}=42.50EUR/h$$

To calculate the machine cost rates, expected depreciation by year is taken into account. Large equipment depreciation is calculated separately, while tools and smaller equipment is grouped together and acquires a group depreciation cost. These are used together with the expected use hours the machines see.

4.3.7 Total Estimated Cost of a 3D Printed Lugged Bicycle Frame

The estimated cost of the 3D printed lugged frame is calculated at stages. This should provide information on how much a frame should cost depending on the specification required by the customer. By assigning costs throughout the development stage and the manufacturing stage, prices for newly developed products can be calculated based on how much novelty is included in the product. This helps to identify the amount of performance for an amount of cost depending on whether new features are included.

Table 17. *Major cost pools and final costs in major interest cost groups.*

#	Cost Pool	Cost	Cost Rate (EUR/h)	Final Cost in EUR
1.	Scoping and set-up engineering labour	2386h	42.50	101405.00
2.	Optimisation Machine Hours	641h	0.11	70.51
3.	Optimisation Engineering Labour	249h	42.50	10582
4.	Direct materials – Printing Filament			96
5.	Tubes			424
6.	Printing time machine hours	260h	0.16	41.6
7.	Assembly Technician Salary	9h	36.30	326.7
8.	Tool usage depreciation	9h	0.16	1.44
	Total manufacturing direct costs			889.74
	Material costs for a single frame			563.04
	Total Engineering Overhead cost			112057.51

The price difference between the composite, 3D printed lugged frame and a mass produced one illustrates the higher performance requirement these frames can achieve. The total cost for manufacturing and assembling a single frame is 889.74 EUR. This is higher than having a high-quality aluminium frame manufactured in Taiwan by 489.74 EUR. The price before overhead allocation is too high to compete with conventional frames from Taiwan or China. These costs do not provide a complete picture of the competitive landscape because they are less than 20% of the total cost of the similarly featured carbon fibre tubed bicycle at 4625 EUR. It is possible to deliver a competitively priced product in the case where the frame provides enough functional features in relation to the other frames on the market.

4.4 Product Analysis and Implementation Recommendations

4.4.1 Competitive Comparison

Investigating the sales potential of the new frame requires it to be compared against the other competitors, with their features and in terms of manufacturing costs. Because there is no time allocation of the activity costs of a brazed frame, only the direct material costs can be compared. It is possible to extrapolate that the method is more expensive than with the 3D printing assembly method because it uses more activities, 101 versus 29. With this in mind, the material cost for a single brazed frame is 909.81 EUR. Compared to the material costs of 563.04 EUR for a 3D printed frame. Part of the reason the brazed frame is so expensive is the highest quality of stainless-steel tubing chosen. It is possible to manufacture it out of tubes only for 751.80 EUR and to spend less on materials to decrease the material costs into the 500 EUR zone. Because labour remains the most expensive part of the assembly, it does not make sense to skimp on the materials.

Assembly labour is the biggest cost driver in in the manufacturing process. A country with a low average wage such as Bulgaria will yield a 3D printed frame direct manufacturing cost of 605.34EUR due to a total assembly cost of 42.3 EUR. This demonstrates the competitiveness of Bulgaria as a reshoring country. If production is also done in Finland, due to the possibility of allocating a worker to work part time, design has to be used reduce the assembly costs. In the case separate lugs need to be used on the head tube assembly and assembly the time a worker needs to spend on it is increased to 10 hours. The implication is that a 85.3% of a full frame can be assembled for this price in Bulgaria.

Table 18. *Summary of bicycle frame prices and the cost of a 3D printed lugged frame for consideration when establishing mark-up costs.*

#	Frame Description	Direct Manufacturing Costs
1.	Brazed, lugged frame (Paterek Manual)	1998.81 EUR
2.	Imported frame from Taiwan	400 EUR
3.	Waterford Precision Cycles USA	1315.14 EUR
4.	Saffron Frame-works	1713.93 EUR
5.	Oswald Cycle Works	3068.66 EUR
6.	Divo Bike	4624.90 EUR
7.	3D Printed frame	889.74 EUR

Despite the price of the 3D printed frame not taking into account the overhead costs required to engineer it, the bar chart provides an idea of how much extra can be charged for it in order to cover said development costs. These prices are not conclusive, however, because the exact features such as finish and steel alloy types used in the manufacturing are not specified. Lead times can be considered other less tangible benefits. With Saffron Frameworks (2018) citing a six-month lead time for a custom frame, it may be possible to win market share through prompt provision of a product, limited mostly by the 260h or circa 11 days needed for printing.

Despite the lead time being around 11 days, the process is bottlenecked by the printing speed. In case a printer is used for each of the demo pieces, the bottleneck becomes the slowest part to print. In the demo case, the Seat Lug/Seatstay at 104 hours or four days before assembly can begin. To further increase the speed, this part can be broken into smaller features such as the seat lug and the seatstay plugs, allocating a printer for each part is likely to reduce the total printing time to 71 hours or three days before assembly starts. As the parts are increased, however, the assembly labour increases. On the other hand, production can be juggled in this manner to satisfy slow sales periods and fast sales periods. Should the frame be manufactured in four days, 100 frames can be manufactured in a little more than 13 months by a single builder. The process can hence be sped up by hiring four builders to satisfy a lead time of a little more than three months in the case the raw material and spare part supply chain for the 3D printers can keep up with the manufacturing demand.

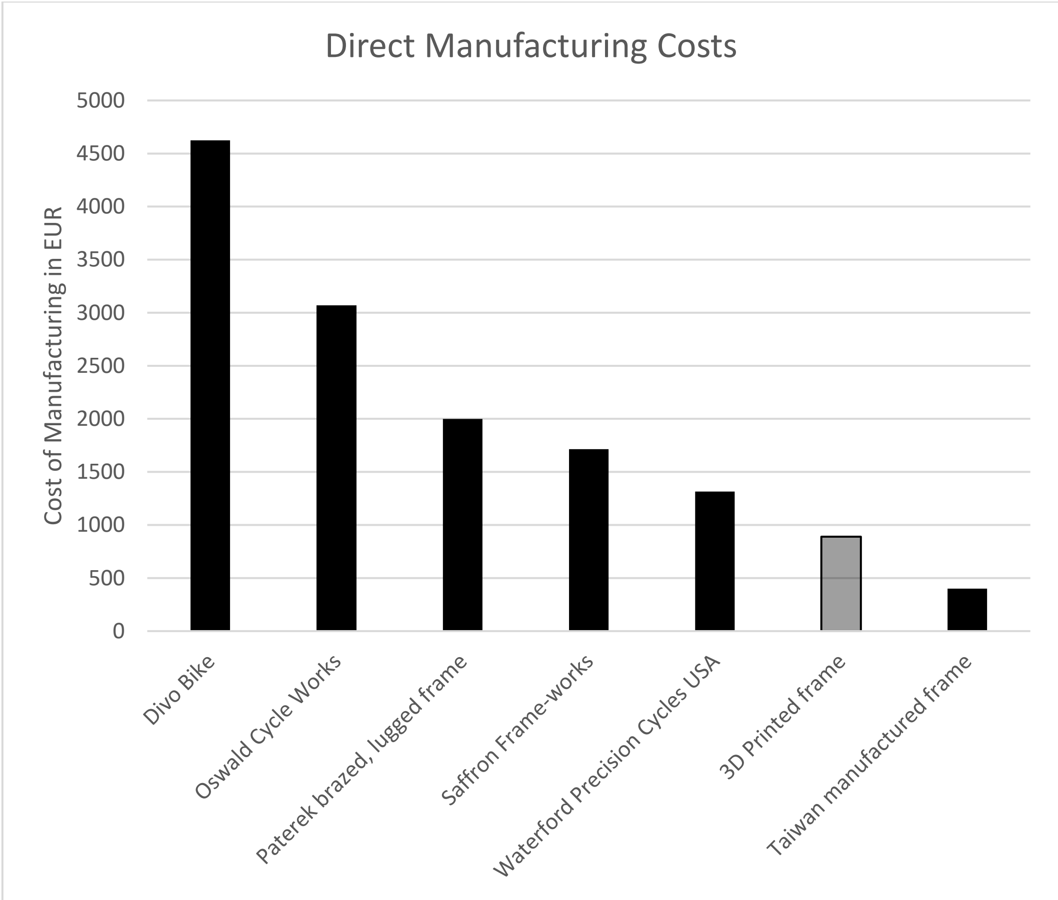


Figure 18. *Comparison between frame set prices and the cost of manufacturing a 3D printed frame.*

4.4.2 Implementation Recommendations

Retaining only the most common features and geometries and by changing parameters within them results in unique shapes through the method of topology optimisation. Current technology allows reinsertion of the hard points into the result of the optimisation to provide an easier to manage 3D model. It would be possible to make specifically tailored bicycles for loads in the cases where

Further cost reductions can be achieved if expensive for the building process part orders are consolidated. For example, if the frame tubing is standard and used in other industries it can be ordered together at a bulk discount. Storing the tubes as a raw material decreases inventory holding costs by also decreasing the space requirement.

2

It is difficult to pin down the exact costs of manufacturing due to the large flexibility in the way machines are used. As suggested by Tim Paterek, the custom frame shop runs as a machine shop during downtime. The same is true of a manufacturing laboratory equipped with 3D printers that can produce replacement parts for other vehicles or customised medical supports for wrists. These sorts of laboratories are likely to catch on, with increasing environmental consciousness. Parts can be made using bio degradable polymers locally if they are to serve only a temporary role. For bio-degradability to occur, coatings preventing UV light to degrade polymers must be used. Such polymers are already produced in Finland by Arctic Biomaterials (2019). Using reinforced polymers would prolong the life of a frame as well. The downside is, the reinforcement fibre fillers such as glass require a different recycling strategy.

A completely integrated digital prototyping and rapid manufacturing is likely to be the technology to invest into for the future. Once the process is established, it becomes dependent on the quality of the designs to produce the frame needed with incredibly short lead times. With recent breakthroughs in semi-conductor and technology strategies enabling smaller manufacturing processes on 10nm and 7nm, the way is paved for even smaller processors translating into a near-instantaneous digital prototyping process moving the largest bottleneck in production. Combined with artificial intelligence, product features can be introduced

Delivering a lugged bicycle as a kit for developed countries is likely to reduce the assembly costs by circa 200 EUR, making the frame as affordable as if it would be built in Bulgaria. In the case customers choose this option, there needs to be a disclaimer that the manufacturer is not responsible for injuries owing to the lack of quality control supervision. Delivering kits will likely save space during shipping, reducing costs and greenhouse gas emissions.

Small batch runs and complementary bicycles for example, pulling bicycles for stuck cyclists can justify a high development cost. With the advancement of CAD and its ability to handle multi-body assemblies it may be possible to input group parameters where light vehicles are designed to operate with each other. For example, the parameters and use case scenario is taken into account for a location with large amount of gravel, the optimised complementary vehicles then both have strengthened hooks and frames with higher fatigue life.

5. DISCUSSION

The main goal of this thesis was investigating the possibility of reshoring bicycle frame manufacturing to Finland. The literature review finds there are current efforts by the European Commission to reduce Chinese bicycle imports. (Oortwijn, 2017) Additionally, this problem is accelerated by increasing taxation on fossil fuels (Trafi, 2018). This is set to increase local demand of bicycles and frames in Finland in conjunction with requiring shorter lead times. (Gylling, et al., 2013) On the other hand, even with the being highly suggestive of a protectionist policy, the laws do not rule out the possibility of circumvention through partial completion of bicycle manufacturing within Europe. The low prices of bicycles set to be affected by the laws mean increased taxes are going to merely lower the profit margins of the importers.

Despite the news sources originating from a professional magazine, exactitude of these news is not properly investigated. Additionally, most of the sources for the investigation are based on market research and hence not academic.

The production know-how transfer acceleration as suggested due to inter-dependent production sites is possible in the manufacturing methodology suggested. (Ferdows, 2006) this is made possible by the cheapness and availability of high-performance consumer CPUs and 3D printers that can be held at local and small manufacturing sites without a heavy storage investment. Unfortunately, the biggest hindrance in developing this business model is the required availability of engineers and technicians. This would be possible in the case of larger manufacturing sites, however, the temporary demand for bicycles makes permanent employment at these sites impractical.

Quantifying the effect of bicycle frame manufacturing postponement reveals a possible reduction in manufacturing costs for highly custom frames, however, the price remains higher in comparison to high-quality imported aluminium frames from Taiwan. Despite completing all the activities required for the design and manufacture of the 3D printed bicycle frame with carbon-fibre tubes, there is no physical prototype to show. Time estimates remain based on previous experience with 3D printing.

The complexity associated with FEA simulation meant the direct manufacturing costs and simulation activity costing will be different on different frames. The complexity of having an increased amount of parts would increase simulation time beyond what was available for the development time of non-linear dynamic studies. The resulting inconsistency is likely to impact actual frame development time, however, the development costs are likely to remain similar with increased experience. The analysis, and in particular the FEA testing time allocation should be considered for internal company use. It can also be used for giving a price quotation but in that case, the estimate may be too short.

6. CONCLUSION

The investigation revealed how a possibly high-end 3D printed and glued bicycle frame can compare in two major market segments in terms of direct manufacturing costs. The 3D printed frame was 1109.07 EUR cheaper compared to high-end custom steel brazed frame manufactured according to Paterek guidelines and 489 EUR more expensive than the mass-produced Taiwan imported aluminum frames. Additionally, the activity investigation revealed the majority of the production costs will come from the materials.

It is possible to make manufacturing in developed countries such as Finland with a labour rate of 36.30 EUR attractive. This can be done by lowering the complexity of the frame assembly. Parts can be unified such as in the case of the head tube-top lug-bottom lug and the frame does not have to be heated to be joined. The activities decrease from 101 to 39 and the number of tools used decreases from 115 to 31. This makes the process flexible, and possible to be started and stopped, whenever there is demand.

The possibility to manufacture intricate shapes provides the opportunity to create a large amount of proprietary information. Together with the requirement that manufacturing needs to be close to the source of demand to reduce inventory holding costs and increase response speed creates the manufacturing site structure to be highly competent. Through cooperation with other manufacturing sites of the same capabilities, they should be able to respond quickly to demand. Despite the availability of lower cost metal lugs and tubes, the process for manufacturing a traditional lugged frame remains more complicated, demanding 108 unique hand tools, contrasting with the 30 required for the 3D printed frame. Production can hence be changed quickly from bicycles to something else too. The major pitfall to being able to engineer such frames are the overhead costs of 112 057.51 EUR.

In short, constructing a frame within the European Union utilizing 3D printing, glue and composite tubes has profitability potential. It is reported there is demand of 750,000 electric bicycle frames in particular. The extent it is possible to compete to is with products with high profit margins and with a high potential for customization. The mass production high quality aluminum frame market remains too cheap for 3D printing to be able to compete in with current materials. The proposed design and manufacturing methodology is largely easy to allocate utilization costs to. Unfortunately, this is hindered by personal capability to break down the simulation problem and set it up for testing quickly.

Future research into the topic should take into account the upper and lower limits of quality and price when choosing component parts for the bicycle frame. Additionally, multiple mechanical engineers should be consulted for the estimation of the time durations. Building physical prototypes should also be done as there is no replacement for this testing methodology. It is expected that the time taken to complete a frame will decrease. Future research topics can include, defining the sort of modularity needed for being able to provide frames in batches of around 50, very quickly. Should the reseller maintain a stock of semi-differentiated parts. Another topic to investigate is at what point do customers want to change their bicycles, especially for fleet vehicles, at what point is it better to recycle the bicycle and buy a new one. Coatings to maintain the required longevity while guaranteeing recyclability are also an area for improvement. This will allow commercial 3D printing using bio-degradable polymers, making composting the frames better for the environment.

REFERENCES

[1] Ad hoc Working Group on defining critical raw materials, 2014. *Report on Critical Raw Materials for the EU.* [Online]
Available at:
https://ec.europa.eu/docsroom/documents/10010/attachments/1/translations/en/renditions/native
[Accessed 11 January 2018].

[2] Agueda.tv, 2017. *Inauguração da Triangle´s (empresa instalada no PEC).* [Online]
Available at:
http://agueda.tv/archive.ud121?trigger_pre_event_0=return_results&search=Triangle%27s&oid=13444885
[Accessed 5 January 2019].

[3] Aittokoski, H., 2018. *"Räjäytetty" Jopo-fillari on kouriintuntuva esimerkki globalisaation vaikutuksista suomalaiseen työhön – palaavatko yritykset Suomeen, kun Aasian palkkataso nousee?.* [Online]
Available at: https://www.hs.fi/blogi/maailmanselittaja/art-2000005514488.html
[Accessed 24 January 2019].

[4] Akao, Y. & Mazur, G., 2003. The Leading Edge in QFD: Past, Present and Future. *International Journal of Quality & Reliability Management,* 20(1), pp. 20-35.

[5] Alcorn, P., 2017. *Results: Scientific & Engineering Computations And HPC.* [Online]
Available at: https://www.tomshardware.com/reviews/amd-ryzen-7-1800x-cpu,4951-10.html
[Accessed 20 April 2018].

[6] Arctic Biomaterials, 2019. *ABM Technical.* [Online]
Available at: https://abmcomposite.com/#technical
[Accessed 31 January 2019].

[7] Biltema, 2018. *Sähköpolkupyörä.* [Online]
Available at: http://www.biltema.fi/fi/Vapaa-aika/Polkupyorat/Polkupyorat/Sahkopolkupyora-/
[Accessed 14 April 2018].

[8] Blackstone, A., 2016. *Open Textbook Library: Principles of Sociological Inquiry – Qualitative and Quantitative Methods.* [Online]
Available at: https://open.umn.edu/opentextbooks/BookDetail.aspx?bookId=139
[Accessed 15 April 2018].

[9] BossLaser, 2018. *Industrial CO2 Lasers.* [Online]
Available at: https://www.bosslaser.com/boss-ls-2436.html
[Accessed 3 February 2018].

[10] Cooper, R., 2006. *The seven principles of the latest Stage-Gate method add up to a streamlined, new-product idea-to-launch process..* [Online]
Available at: https://www.stage-gate.net/downloads/working_papers/wp_23.pdf
[Accessed 6 February 2018].

[11] Cooper, R. & Slagmulder, R., 1997. *Target Costing and Value Engineering.* 1st ed. New York: Productivity Press.

[12] CoReorient, 2017. *AIKO Smart City Robot Logistics project in Otaniemi.* [Online]
Available at: http://coreorient.com/developmentpilots/
[Accessed 6 February 2018].

[13] Dascotte, E., 2004. Linking FEA with Test. *Sound and Vibration*, 1 April, pp. 12-17.

[14] Divobike, 2018. *Design and Tech.* [Online]
Available at: https://www.divobike.com/design-and-tech/
[Accessed 3 January 2018].

[15] EFBE, 2018. *EFBE. The benchmark for safety and quality for bicycles and e-bikes..* [Online]
Available at: http://www.efbe.de/#vier
[Accessed 10 May 2018].

[16] Eurostat, 2018. *Hourly labour costs.* [Online]
Available at: https://ec.europa.eu/eurostat/statistics-explained/index.php/Hourly_labour_costs#Labour_costs_per_hour_highest_in_industry
[Accessed 25 January 2019].

[17] Felton, V., 2017. *Building Bikes in Asia - An Inside Look.* [Online]
Available at: https://www.pinkbike.com/news/we-went-to-taiwan-and-started-a-bike-company.html
[Accessed 24 January 2019].

[18] Ferdows, K., 1997. Made in the World: The Global Spread of Production. *Production and Operations Management,* VI(2), pp. 102-109.

[19] Ferdows, K., 1997. Making the Most of Foreign Factories. *Harvard Business Review*, 1 April, pp. 73-88.

[20] Ferdows, K., 2006. Transfer of Changing Production Know-How. *Production and Operations Management,* 15(1), pp. 1-9.

[21] Ferdows, K., Vereecke, A. & Meyer, A. d., 2015. Delayering the Global Production Network into Congruent Subnetworks. *Journal of Operations Management,* I(41), pp. 63-74.

[22] File and Torch, 2018. *GEAR TAB ALIGN SILVA no. 892.* [Online]
Available at: https://www.torchandfile.com/GEAR-TAB-ALIGN-SILVA-no-892_p_310.html
[Accessed 24 January 2019].

[23] Galvin, P. & Morkel, A., 2001. The Effect of Product Modularity on Industry Structure: The Case of the World Bicycle Industry. *Industry and Innovation,* 8(1), pp. 31-47.

[24] General Electric, 2018. *100,000 patients later: The 3D-printed hip is a decade old and going strong.* [Online]
Available at: https://www.ge.com/additive/case-study/100000-patients-later-3d-printed-hip-decade-old-and-going-strong
[Accessed 20 January 2019].

[25] Graney, J., 2012. *Santa Cruz Bicycles - Test Lab* [Interview] (23 February 2012).

[26] Gylling, M., Jussi Heikkilä, K. J. & Saarinen, M., 2013. Making Decisions on Offshore Outsourcing and Backshoring: A Case Study in the Bicycle Industry. *International Journal of Production Economics,* 162(1), pp. 92-100.

[27] Heikkilä, J., Olhager, J., Martinsuo, M. & Laine, T., 2017. *Relocation of Nordic Manufacturing: Policy Implications Derived from the Research,* Tampere: Tampere University of Technology. Industrial and Information Management.

[28] Helsingin Seudun Liikenne, 2018. *Tickets and Fares.* [Online]
Available at: https://www.hsl.fi/en/tickets-and-fares
[Accessed 9 January 2018].

[29] Henry James Bicycles, 2018. *Henry James Jig Comparison Chart.* [Online]
Available at: http://www.henryjames.com/about-henry-james/hj-jig-comparison-chart.html
[Accessed 24 January 2019].

[30] Hexcel, 2018. *Hexcel Official Distributors.* [Online]
Available at: http://www.hexcel.com/About/Official-Distributors
[Accessed 11 May 2018].

[31] International Standards Organisation, 2015. *Cycles. Safety requirements for bicycles. Part 6: Frame.* Helsinki: Suomen StandardiIsoimisliitto SFS.

[32] ISO, 2017. *ISO 15614-1:2017 - Specification and qualification of welding procedures for metallic materials,* Geneva: ISO.

[33] Javelin Technologies, 2010. *Using Design Automation to Reduce Costs & Increase Profitability.* [Online]
Available at:
http://www.solidworks.com/sw/docs/Design_Automation_2010_ENG_FINAL.pdf
[Accessed 10 May 2018].

[34] Johnson, H., 1991. Activity-Based Management: Past, Present, and Future. *Engineering Economist,* 36(3), pp. 219-238.

[35] Kalpakjan, S., 1992. *Manufacturing Engineering and Technology.* 2nd ed. Reading Massachusetts: Addison Wesley Publishing Company.

[36] Kee, R. & Matherly, M., 2006. Decision Control of Products Developed Using Target Costing. *Advances in Management Accounting,* 15(1), pp. 267-292.

[37] Kent, M., 2000. *Advanced Biology.* 1st ed. Oxford: Oxford University Press.

[38] Koneita.com, 2019. *Milling Machines.* [Online]
Available at: https://shop.koneita.com/en/2080-jyrsinkoneet
[Accessed 16 January 2019].

[39] Leino, S.-P., 2015. *Reframing the Value of Virtual Prototyping.* 1st ed. Espoo: Teknologian tutkimuskeskus VTT Oy.

[40] Lin, C., Huang, S. & Liu, C., 2017. Structural analysis and optimization of bicycle frame designs. *Advances in Mechanical Engineering,* 9(12), pp. 1-9.

[41] Ministry of Transport and Communications, 2015. *Minister Risikko: Provision of Uber rides is legal, but driving requires taxi licence.* [Online] Available at: https://www.lvm.fi/en/-/minister-risikko-provision-of-uber-rides-is-legal-but-driving-requires-taxi-licence-796955
[Accessed 6 February 2018].

[42] Mukhopadhyaya, A., 2009. *Value Engineering Mastermind: From Concept to Value Engineering Certification.* 1st ed. Electronic Book: Response.

[43] National Statistical Institute: Bulgaria, 2018. *Average Monthly Wages and Salaries of the Employees Under Labour Contract in 2017.* [Online] Available at: http://www.nsi.bg/en/content/6410/total
[Accessed 21 April 2018].

[44] National Statistical Institute: Romania, 2018. *Gross Average Earning.* [Online]
Available at:
http://www.insse.ro/cms/sites/default/files/com_presa/com_pdf/cs12r17.pdf
[Accessed 21 April 2018].

[45] National Statistics: Republic of China (Taiwan), 2017. *Earnings and Productivity Statistical Analysis.* [Online]
Available at: https://eng.stat.gov.tw/public/Data/712221616527RLXRM7Z.pdf
[Accessed 18 January 2018].

[46] Naumov, D., 2017. *Finnish law puts Uber in a choke-hold, so this new local challenger plays by the book to capitalize.* [Online]
Available at: http://nordic.businessinsider.com/uber-will-not-be-welcome-in-finland-anytime-soon-so-this-new-local-challenger-is-playing-by-the-book-to-capitalise-2017-3/
[Accessed 6 February 2018].

[47] Norang, A., Eghbali, M. & Hajian, A., 2010. *Supply Chain Analysis Model Based on System Dynamics Approach: A Case of Iranian Bicycle Manufacturer.* Herbin, IEEE.

[48] Olhager, J., 2003. Strategic Positioning of the Order Penetration Point. *Production Economics,* 1(85), pp. 319-329.

[49] Oortwijn, J., 2015. *Lead Time Is Our Biggest Problem.* [Online]
Available at: https://www.bike-eu.com/shows-events/nieuws/2014/08/lead-time-is-our-biggest-problem-1011496
[Accessed 31 January 2019].

[50] Oortwijn, J., 2016. *Portuguese Triangles Makes Alloy Frames in Five Minutes.* [Online]
Available at: https://www.bike-eu.com/home/nieuws/2016/01/portuguese-triangles-makes-alloy-frames-in-five-minutes-10125444
[Accessed 4 January 2018].

[51] Oortwijn, J., 2017. *News Article: E-Bike Dumping Duty Could Already Be In Place by July 2018.* [Online]
Available at: http://www.bike-eu.com/laws-regulations/nieuws/2017/10/e-bike-dumping-duty-could-already-be-in-place-by-july-2018-10131652
[Accessed 8th january 2018].

[52] Oortwijn, J., 2017. *News Article: EU Announces Start of Anti-Subsidy Proceeding on E-Bike Imports from China.* [Online]
Available at: http://www.bike-eu.com/laws-regulations/nieuws/2017/12/eu-announces-start-anti-subsidy-proceeding-e-bike-imports-china-10132458
[Accessed 8 January 2018].

[53] Oortwijn, J., 2019. *Switching from Imports to E-Bike Production in EU Raises Questions on Local Frame Making.* [Online]
Available at: https://www.bike-eu.com/home/nieuws/2019/01/switching-from-imports-to-e-bike-production-in-eu-raises-questions-on-local-frame-making-10135193
[Accessed 30 January 2019].

[54] Oswald, T., 2018. *Oswald Cycle Works.* [Online]
Available at: http://www.oswaldcycleworks.com/oswald-bikes
[Accessed 4 January 2019].

[55] Paterek, T., 2004. *The Paterek Manual for Bicycle Framebuilders.* 3rd ed. Philadelphia: Kermesse Distributors Inc..

[56] PCPartpicker LLC, 2019. *Current Part List.* [Online]
Available at: https://de.pcpartpicker.com/list/PqsZ7W
[Accessed 28 01 2019].

[57] *Pinkbikes How it's Made: Anvil Industries Spank Handlebars.* 2012. [Film] Directed by Mike Levy, Aaron LaRocque. United States of America: PinkBikes.

[58] Prusa Research, 2019. *Original Prusa i3 MK3 3D printer.* [Online]
Available at: https://shop.prusa3d.com/en/3d-printers/181-original-prusa-i3-mk3-3d-printer.html#
[Accessed 16 January 2019].

[59] Randall, T. & Ulrich, K., 2001. Product Variety, Supply Chain Structure, and Firm Performance: Analysis of the U.S. Bicycle Industry. *Management Science,* 47(12), pp. 1588 - 1604 .

[60] Reuters, 2018. *EU's tech commissioner says Europe should be worried about Huawei.* [Online]
Available at: https://www.reuters.com/article/eu-china-huawei/eus-tech-commissioner-says-europe-should-be-worried-about-huawei-idUSB5N1VQ026
[Accessed 20 January 2019].

[61] Road Bike Magazine, 2018. *Bike Test: Divo ST Italian Carbon Road Bike.* [Online]
Available at: https://roadbikeaction.com/bike-test-divo-st-italian-carbon-road-bike/
[Accessed 18 April 2018].

[62] Rockwell Composites, 2019. *Bicycle Carbon Frame Tubing.* [Online]
Available at: https://www.rockwestcomposites.com/round-tubing/round-carbon-fiber-tubing/bicycle-carbon-frame-tubing
[Accessed 24 January 2019].

[63] Roh, J., Hyeong, J. & Kim, S., 2018. Influence of Folding Mechanism of Bicycles on their Useability. *Applied Ergonomics,* 69(1), pp. 58-65.

[64] Rossiter, W., 2017. *Sven Cycles Pathfinder first ride review £4,000.00.* [Online]
Available at:
https://www.bikeradar.com/road/gear/category/bikes/road/product/sven-cycles-pathfinder-review-51552/
[Accessed 4 January 2019].

[65] Saffron Frameworks, 2018. *Ordering and Pricing.* [Online]
Available at: http://www.saffronframeworks.com/ordering/
[Accessed 18 April 2018].

[66] Schaik, J.-W. v., 2017. *News Article: Germany Adopts New Regulations for Bicycles and E-Bikes.* [Online]
Available at: http://www.bike-eu.com/laws-regulations/nieuws/2017/3/germany-adopts-new-regulations-for-bicycles-and-e-bikes-10129378
[Accessed 9 January 2018].

[67] Schaik, J.-W. V., 2017. *News Article:Nordic's E-Bike Sales Increase, But Markets Tend to Differentiate.* [Online]
Available at: http://www.bike-eu.com/sales-trends/nieuws/2017/11/nordics-e-

bike-sales-increase-but-markets-tend-to-differentiate-10132130
[Accessed 8 january 2018].

[68] Statistics Finland, 2018. *Official Statistics of Finland (OSF): Structure of Earnings.* [Online]
Available at: http://www.stat.fi/til/pra/index_en.html
[Accessed 24 January 2019].

[69] Stratasys, 2016. *Stratasys: Resources.* [Online]
Available at: http://www.stratasys.com/-/media/files/case-studies/automotive/cs_fdm_au_volvo.pdf
[Accessed 13 April 2018].

[70] SVEN Cycles, 2018. *Pathfinder Light Road and Gravel Bike.* [Online]
Available at: https://www.svencycles.com/products/pathfinder-light-gravel-bike/?departmentID=39&page=1&q=
[Accessed 18 April 2018].

[71] TEK, 2019. *Salary recommendations.* [Online]
Available at: https://www.tek.fi/en/services/salaries/salary-recommendations-0
[Accessed 24 January 2019].

[72] Tianjin Fujita, 2019. *Fujita Battle: Company History.* [Online]
Available at: http://www.fuji-ta.com/company-story
[Accessed 4 January 2019].

[73] Trafi, 2018. *Car Comparison Service.* [Online]
Available at: http://autovertaamo.trafi.fi/trafienergiamerkki/oto-214
[Accessed 22 April 2018].

[74] Trafi, 2018. *Structure and amount of tax.* [Online]
Available at:
https://www.trafi.fi/en/road/taxation/vehicle_tax/structure_and_amount_of_tax#base
[Accessed 22 April 2018].

[75] UK Data Service, 2012. *Introduction to qualitative interviews.* [Online]
Available at: https://www.ukdataservice.ac.uk/teaching-resources/interview/qualitative
[Accessed 14 April 2018].

[76] United Nations, 2017. *World Investment Report,* Geneva: United Nations.

[77] Vagabonde Cycles, 2018. *Grand Raid.* [Online]
Available at: http://vagabondecycles.com/voyage/grand-raid.html
[Accessed 18 April 2018].

[78] Valdes-Dapena, P., 2016. *Inside Tesla's ginormous Gigafactory.* [Online]
Available at: http://money.cnn.com/2016/07/26/technology/tesla-gigafactory/index.html
[Accessed 9 January 2018].

[79] Walter, M., Holmström, J. & Yrjölä, H., 2004. *Rapid Manufacturing and its Impact on Supply Chain.* Dublin, Helsinki University of Technology.

[80] Warren, C., 1988. *Gender Issues in Field Research.* 1st ed. Newbury Park: Sage.

[81] Waterford Precision Cycles USA, 2016. *Gunnar Fastlane Pricing.* [Online]
Available at: http://gunnarbikes.com/site/bikes/fast-lane/
[Accessed 18 April 2018].

APPENDIX A: LIST OF ACTIVITIES AND THEIR ORDER FOR A BRAZED LUGGED FRAME

The following activities are summarised from literature and numbered by hand. So there may be errors during the calculation in Microsoft Excel. (Paterek, 2004)

Braze-ons

Cantilever Break Bosses

82. Apply flux to underside of seatstay x2
83. Braze shifter cable guides onto the top tube

Brake Cable Stops

80. Apply flux to underside of seatstay x2
81. Braze rear brake cable stop onto the top tube x2

Shifter Cable Stops

75. Apply flux to seatstay x2
76. Apply flux to top tube x4
76. Apply flux to seat tube for front derailleur cable x2
77. Braze shifter cable stops onto the seatstay x2
78. Braze shifter cable stop onto the top tube x4
79. Braze front shifter cable stop on seat tube x2

Shifter Cable Guides

73. Apply flux to seatstay bridge and surrounding area
74. Braze shifter cable guides onto the top tube

Brake Cable Guides

71. Apply flux to top tube 5cm away from the front
72. Braze brake cable guides onto the top tube

Bridges

Chainstay

63. Drill 1/16" air expansion holes
64. Final clean the chainstay bridge and chainstays from oil
65. Apply flux to seatstay bridge and surrounding area
66. Install temporary supports
67. Silver braze the chainstay bridge to both chainstays

Seatstay

59. Adjust the seatstay bridge length
60. Final clean seatstay bridge from oil
61. Apply flux to seatstay bridge and surrounding area
62. Silver braze the seatstay bridge to both seatstays

58. Install a framebuilding wheel in the rear dropouts

Seat Clusters

Stress Relief Holes

Lugs

Bottom Bracket
3. Enlarge seat tube and down tube sockets in the bottom bracket shell
10. Final degreasing of the bottom bracket
2. File inside lug diameters
14. Apply flux to seat tube socket in bb
24. Assemble bottom bracket seat tube
26. Braze the seat tube into its socket on the bottom bracket
30. Tapping of the bb threads
31. Alignment check of bb
35. Tapping of the bb threads
36. Alignment check of bb
49. Check Rear Triangle Fixture Adjustments for the bottom bracket and chainstays
51. Apply flux to chainstay openings on the bottom bracket
53. Tack the chainstays to the bottom bracket shell
68. Tapping of the bb threads
69. Alignment check of bb
70. Serial number stamping
Seat Lug
50. Check rear triangle fixture adjustments for the seat lug stays
52. Apply flux to chainstay openings on the bottom bracket
54. Tack and braze the seatstays into the seat lug
56. Braze the seatstay plugs to the ends of the seat lug
3/32"-7/64" Drill
Top Lug
Bottom Lug
21. Final Clean bottom lug from oil.
22. Apply flux to head tube and down tube interface
23. Assemble bottom lug to head tube and down tube
29. Braze the bottom lug to the down tube and the head tube
32. Alignment check of bottom lug joint
2. File inside lug diameters
4. File and sand down outside edges of lugs and bottom bracket shell
24. Set up welding/brazing equipment according to instructions for brazing
44. Level the rear triangle fixture

Dropouts

Left
13. Final clean left dropout from oil
16. Apply flux to the chainstay interface of the dropouts
27. Braze left drop out to left chainstay
56. Silver braze the left seatstay into its dropout
Right
13. Final clean right dropout from oil

17. Apply flux to the chainstay interface of the dropouts
28. Braze right drop out to right chainstay
55. Silver braze the right seatstay into its dropout

Tube Sets

Top tube

37. Mitering the front part of the top tube for interfacing with the head tube
38. Mitering the front part of the top tube for interfacing with the head tube
39. Final clean top tube from oils
40. Tack and braze the top tube to the head tube, top lug
41. Tacking and braze the top tube to the seat tube lug,

Down tube

7. Mitering the Down Tube for Head Tube fit
12. Final clean down tube from oil
20. Apply flux to the top end, the head tube lug interface
33. Mitering the down tube lower end for bottom bracket fit
34. Tack and braze the down tube into the bottom bracket joint

Seat tube

6. Mitering the seat tube for bottom bracket fit
9. Final clean Seat Tube from oil
5. File inside lug diameters
15. Apply flux to the bottom bracket end of the seat tube

Seat stays

45. Fitting the seatstays
46. Final clean seatstays from oil
47. Apply flux to the top seatstay interface to accept the plugs (x2)
48. Braze seatstay caps to top end of the seatstay tubes
55. Braze the seatstays to the dropouts

Chain stays

14. Final clean chainstay from oil
18. Apply flux to the chainstay interface of the dropouts (x2)
44. Fitting the chainstays
57. Braze the chainstays into the bottom bracket shell sockets.

Head tube

8. Drill air expansion hole
11. Final clean head tube from oil
19. Apply flux to the lower end of the head tube where the bottom lug tube interfaces
43. Finish threading the head tube ends

1. Primary clean tubes from oil
42. Front triangle joints must be cleaned

APPENDIX B: 3D PRINTED LUGGED FRAME CONSTRUCTION, SEPARATE LUGS AND HEAD TUBE ACTIVITIES

1. Separate 3D printed parts from the printing plate

Printing table

Assuming the print surface cannot be removed from the print bed.

Braze-ons

Brake Cable Stops

6. Remove support material of Brake Cable Stops
13. Smoothing of Brake Cable Stops

Shifter Cable Stops

7. Remove support material of Shifter Cable Stops
14. Smoothing

Lugs

Bottom Bracket

2. Remove support material
9. Smoothing of the bottom bracket
26. Glue Seat Tube into the Bottom Bracket
30. Glue Down Tube into the Bottom Bracket
37. Glue Chainstays into the Bottom Bracket

Seat Lug

3. Remove support material from Seat Lug
10. Smoothing of Seat Lug
33. Glue the Seat Lug onto the Seat Tube
34. Glue the Top Tube into the Seat Lug
37. Glue the Seatstays into the Seat Lug sockets

Top Lug

4. Remove support material from top lug
11. Smoothing of Top Lug
31. Glue Top Tube into the Top Lug
32. Glue Head Tube into the Top Lug

Bottom Lug

5. Remove support material
12. Smoothing
27. Glue Down Tube into Bottom Lug
28. Glue Head Tube into Bottom Lug

Dropouts

Seatstay and chainstay plugs

8. Remove support material
15. Smoothing
35. Glue the top part of the Dropouts onto the Seatstays
36. Glue the bottom part of the Dropouts onto the Chainstays

Tube Sets

Carbon Fibre

Top Tube

16. Mitre both ends of the top tube
20. Roughen the plug interface areas

Head Tube

17. Mitre both ends of the head tube
21. Roughen the plug interface areas

Down Tube

18. Mitre both ends of the Down Tube
22. Roughen the plug interface areas

Seat Tube

19. Mitre both ends of the Seat Tube
23. Roughen the plug interface areas

Seatstays

20. Mitre both ends of the Seatstays
24. Roughen the plug interface areas

Chainstays

21. Mitre both ends of the Chainstays
25. Roughen the plug interface areas

APPENDIX C: 3D PRINTED LUGGED FRAME CONSTRUCTION, JOINED LUGS AND HEAD TUBE ACTIVITIES

1. Separate 3D printed parts from the printing plate

Lugs

Bottom Bracket

2. Remove support material
6. Smoothing of the bottom bracket
20. Glue Seat Tube into the Bottom Bracket
21. Glue Down Tube into the Bottom Bracket
37. Glue Chainstays into the Bottom Bracket

Seat Lug

3. Remove support material from Seat Lug
7. Smoothing of Seat Lug
24. Glue the Seat Lug onto the Seat Tube
25. Glue the Top Tube into the Seat Lug
26. Glue the Seatstay tubes into the Seat Lug sockets

Head Lug

4. Remove support material from top lug
8. Smoothing of Top Lug
22. Glue Down tube into the Head Lug
23. Glue Top Tube into the Top Lug

Dropouts

Subtopic

5. Remove support material
9. Smoothing
27. Glue the top part of the Dropouts onto the Seatstays
28. Glue the bottom part of the Dropouts onto the Chainstays

Tubes

Top tube

10. Mitre both ends of the top tube
15. Roughen the plug interface areas

Down Tube

11. Mitre both ends of the Down Tube
16. Roughen the plug interface areas

Seat Tube

12. Mitre both ends of the Seat Tube
17. Roughen the plug interface areas

Seatstays

13. Mitre both ends of the Seatstays
18. Roughen the plug interface areas

Chainstays

14. Mitre both ends of the Chainstays
19. Roughen the plug interface areas