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Design engineering guidelines for light weight suspension components

Application to a suspension component: Lower control arm

Master's thesis in Product development

NIKHITH VELLORE PRAMOD
DHANUSH SUGUNA RAMACHANDRA

Department of Industrial and Materials Science
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Supervisor: Ingemar Johansson, Senior Adviser - Wheel Suspension, CEVT AB
Supervisor: Thomas Hult, System Manager - Wheel Suspension, CEVT AB
Examiner: Magnus Evertsson, Chalmers University of Technology

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Design engineering guidelines for light weight suspension components
Division of Product development
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: Weight optimized structural design for suspension component 'Lower control arm' .

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Abstract

Affordable costs, fuel economy, driveability and overall vehicle performance are some of the main factors responsible for automakers to emphasize on developing weight optimization strategies. Optimization for weight has increased the necessity for developing robust structural design. With the advancements in the field of material science and manufacturing it is possible to have creative approach to automobile design engineering.

Wheel suspension components has been the area of focus for weight reduction since reduction in the vehicle unsprung mass proves to be most beneficial, as it would improve the fuel economy and vehicle's handling. In the case of hybrid and electric vehicles, range is of paramount importance, any weight reduction on the body and chassis can pave way for proportional weight addition for a larger capacity battery which would contribute to improving vehicle's range.

The aim of this thesis is to develop guidelines for light weight structural design for wheel suspension components. The process involves briefly studying the current development process and developing concept design for most efficient structure, finding suitable material and manufacturing techniques for the designed component. Thereby suggesting a process to develop weight optimized structural designs for suspension components. In view of the thesis time frame the suspension component chosen is a lower control arm of the rear wheel suspension of the Compact Modular Architecture (CMA), the existing component design is carefully investigated and a concept structural design for light weight is developed to meet the strength, stiffness and manufacturing constraints by assessing the performance of the concept design under the load cases available from the road load test data.

Keywords: Product development, Lightweight Structural design.

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Nikhith Vellore Pramod
Dhanush Suguna Ramachandra

Gothenburg, September 2018

Abbreviations

DPR	Design Pre-Requisite
RLD	Road Load Data
CEVT	China Euro Vehicle Technology
LCA	Lower Control Arm
RLCA	Rear Lower Control Arm
CMA	Compact Modular Architecture
CAD	Computer Aided Design
CAE	Computer Aided Engineering
FE	Finite Element
DBT	Design Build Test
DOC	Drive over Curb
ROC	Rearwards over Curb
SAC	Skid Against Curb
BIP	Braking in Pothole
OWT	Opposite wheel travel

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1 Introduction

This chapter provides a brief insight on the thesis problem formulation to the reader, it starts with a background about the Design Engineering group at CEVT in Gothenburg. It is followed by the aim, objectives and limitations of the thesis. Introduction concludes with the thesis outline.

1.1 Background

China Euro Vehicle Technology AB, CEVT, is a development centre for future platform of the Geely Group. CEVT covers all aspects of platform – from the total architecture, powertrain and driveline components.The company is located in Gothenburg.

The Design Engineering group is responsible for the development of wheel suspensions. The suspension systems in vehicles are fundamental components linking the vehicle to the wheels. The drivers for development of suspension systems include suspension geometry and structural design of suspension components. Salient features of a sound structural design are robustness and light weight. Thus, there is an increase in the need for developing structural design for light weight as it significantly contributes in developing fuel efficient vehicles for the competitive automotive industry.

In view of the scope of thesis the suspension component chosen is a lower control arm of the rear wheel suspension of CMA platform. The existing component design is investigated to learn the available design space, boundary conditions, material properties and understand the loads distributed on the component from the RLD. The RLD is the result of vehicle dynamics simulation where laods are calculated from different driving conditions, it is significant information required for CAE analysis of the component design as the measured values from RLD have higher reliability and repeatability.

1.2 Aim

The objective of the thesis work is to investigate how to develop light weight wheel suspension components for improved performance. The process is to be reviewed by working with 'Lower control arm' of the rear wheel suspension system of the CMA platform.

The thesis work aims to develop guidelines for light weight structural design for wheel suspension components. The process involves studying the current development process and developing concept design for most efficient structure, finding suitable material and manufacturing technique for the designed component. Thereby suggesting a process to develop weight optimized structural design for suspension components.

1.3 Limitations

A number of factors influenced the direction of the thesis work, they are as described below,

1. The thesis work has limited time frame. Considering the feasibility in the given time frame the new concept design was developed only for the LCA of the rear wheel suspension.

2. Computer resources are limited to CAD software available in personal laptops and FEA software available in University labs. The university labs are subject to availability.This limits the amount of CAD and FEA work done.

3. The process of structural design involves many attributes/requirements to be considered. In view of the duration and familiarity with the involved topics the attributes considered for design were limited to strength, stiffness, weight and geometry.

4. The other important attributes to be considered for more detailed process are durability, NVH, corrosion, crash testing, bushing press out forces and cost requirements.

5. Validation of the methodology may be limited to “proof of concept” rather than detailed process validation due time constraints.

6. Cost requirements is not factored as the thesis focuses more on developing concept design, but it is ensured that feasible material is chosen to develop optimum solutions.

1.4 Thesis outline

The whole project was divided into 3 phases.

PHASE 1: BASELINE STUDY
In this phase, literature studies relevant to thesis were identified and studied. The documents provided by CEVT relating to DPR, RLD and CAE were examined. The studies were necessary for formulation of requirements/specification and prerequisites for upcoming phases.

PHASE 2: CONCEPT DEVELOPMENT PROCESS
In this phase, a methodology which adheres to learning outcomes from Phase 1 is devised. Deliverable of this phase include a suitable process and selection of material for light weight structural design.

PHASE 3: PROCESS VALIDATION
Depending on the results from phase 2, the methodology is iterated in pursuit of further optimization.

2
Theory

The general concepts used to formulate the guidelines for light weight structural design necessary are explained in this chapter. A brief introduction to the baseline study and it's relevance for the process is explained, followed by the principles involved in optimizing structural design and lightweight materials for automotive applications is described.

2.1 Literature study

The thesis revolves around developing a methodology for lightweight structural components and validating the methodology by designing an LCA. The new design should be comparable or better performing than the existing design by CEVT. To accomplish this a broad literature review covering the aspects of product development, theory related to establishing baseline and light weight design has been studied.

Karl T Ulrich and Steven D Eppinger describe the product development process succinctly in the opening chapters of their book [4]. This lays the foundation to understand how products are generally developed. This is further supplemented by the work [3] of Steven C Wheelwright and Kim B Clark where they described the iterative approach to refine various designs. The summaries prepared by the lecture notes [5] of the course "Engineering Design and Optimization" shed light on the various product development principles used in this thesis work.

Guidelines for baseline studies [6] helped in establishing a baseline for the new design to compare against. The knowledge from that resource helped in narrowing down the information that is applicable from the Road Load data (RLD) obtained from CEVT.

The theory required for lightweight design can be split into design principles, materials and manufacturing. Principles of lightweight design used in the construction industry was studied from a journal [7]. These principles were identified to be relevant to this thesis as the loading conditions and environment were observed to be similar to what an LCA is designed to do. Other engineering resources explaining how I beams [1] and arches [8] were studied as they played a large role while developing the new LCA design.

The reporting [2] done by Mckinsey and company on lightweight material use provided a comparative overview of various metals used in the automotive industry. This helped us in narrowing down the materials to be investigated for this thesis work. Physical properties of materials for FEA work were derived from CES Edupack software.

The text book [9] authored by A.Y.Nee contained detailed information on various metal manufacturing processes. This proved to be a keen resource which helped in the choice of manufacturing process, design requirements for the chosen process as well as compatibility with material choice.

2.2 Baseline Study

To formulate guidelines for a process it is necessary to set up the information base with all the gathered data. Baseline data corresponds to the initial information/data available prior to project intervention. Examples of baseline data include technical specifications of the existing system such as the Design Pre-requisites (DPR), Road load data (RLD), material properties, operating parameters etc. A baseline study is necessary to establish the requirements for the course of the project and would serve as a benchmark against which the results and outcome of the project is to be compared with, this facilitates monitoring and evaluating the effectiveness of the project.

In the course of the study investigations are made to determine the best way to make use of the available data to arrive at the objective, in some cases simplification of the data is necessary to speed up the product development process and to ensure the deliverables are achievable with the constraints involved as mentioned in section 1.3. This ensures the best approach to measure the degree and quality of change during the implementation of the guidelines.

The thesis work mainly involved developing guidelines for light weight structural design. In order to achieve this goal the data available to formulate the process was assessed to establish a control suite of metrics to compare the end result. Data collection is an important part of the study as it helps in setting up basis for the given task. Primary source for data collection is information from the DPR report provided by CEVT [Appendix A]. Secondary source of data such as physical properties and material properties from various online material databases.

The learning outcomes of the baseline analysis is summarized as follows,

- Existing component is analysed to understand the stress levels from the selected load cases from RLD.
- Areas for improvement for the new design are identified using the baseline study.
- Appropriate simulation models to the concept design are understood prior to the design process.
- Based on project or product requirements suitable design principles are employed to the concept development.
- The software tools to be utilized are chosen based on the baseline study.

2.3 Lightweighting: Structural Design

In this section, we discuss the theory behind the processes and rules of thumb from a design engineers point of view, that were used for this thesis work.

Component design was conceptualized based on principles of lightweight design followed in civil engineering structural design. Construction relies on managing loads and often they are vertical loads. There are 5 principles for designing lightweight structure [7] of which 3 are relevant to this thesis. They are as follows,

Principle 1: The ratio between "live load" to dead load should be maximised. Live load refers to the amount of load a structure is designed to carry and dead load refers to the weight of the structure itself.

Principle 2: To develop light weight structures, elements which stress by bending should be avoided in favour elements stressed by tension or compression.

Principle 3: The ratio between tension strength and density of material should be maximized.

Arches and I beams adhere to these principles and hence are very popular structural elements in the construction industry. The other important area considered for this project is metal casting. Design engineers require fundamental knowledge in that manufacturing process to ensure the components designed can be manufactured.[10]

2.3.1 I Beam structures

As the name suggests, I beam is a beam with a cross section resembling the letter "I". The vertical element of the structure is called web and the horizontal element is called flange. When the I beam is subjected to vertical loads, flanges carry most of the bending effects whereas the web carries shearing effects. When an I beam is bent, it experiences tensile stress on one side and compressive stress on one side. The lesser the deflection, the lesser the stresses.[1]

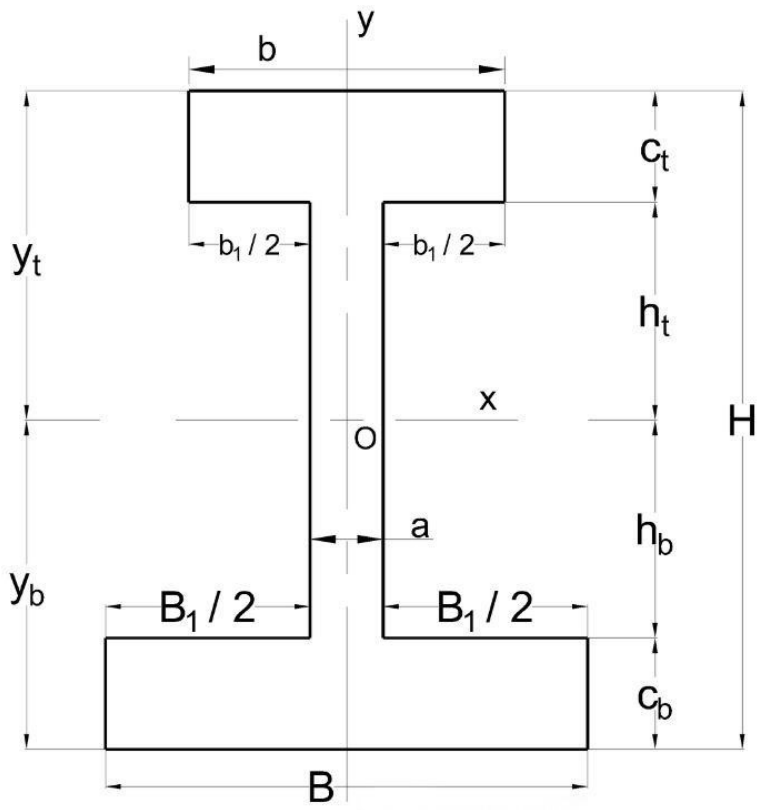

Figure 2.1: Cross section of I beam showing the flanges (horizontal) and web (vertical) [1]

To design an I beam for bending effects, one needs to be aware of the relations between various dimensions and how they effect deflection. From beam theory [11] we have deflection 'δ' defined as follows,

$$\delta = \frac{K * F}{E * I} \tag{2.1}$$

Where K is a constant which changes depending on the boundary conditions and the way load is applied, F is the magnitude of load applied, E is the young's modulus of the material used which is a constant and I is the area moment of inertia.

The moment of inertia 'I' for an I beam [1] is formulated as

$$I = \frac{1}{3}(By_b^3 - B_1h_b^3 + by_t^3 - b_1h_t^3) \tag{2.2}$$

From the equation, we can see that to minimize deflection for a given F, I should be maximum. To maximize I, we can increase flange dimensions.

2.3.2 Arch structure

Broadly defined, Arches are curving beams which are loaded at the boundaries. They carry vertical loads by resolving them to compressive loads which act along the arch structure and the boundaries. An important aspect of why arches are so effective in carrying loads is the phenomenon of arch action. It is caused by the horizontal loading of the boundaries which result in an upward thrust. This thrust naturally counteracts the vertical loads it is designed to carry [8].

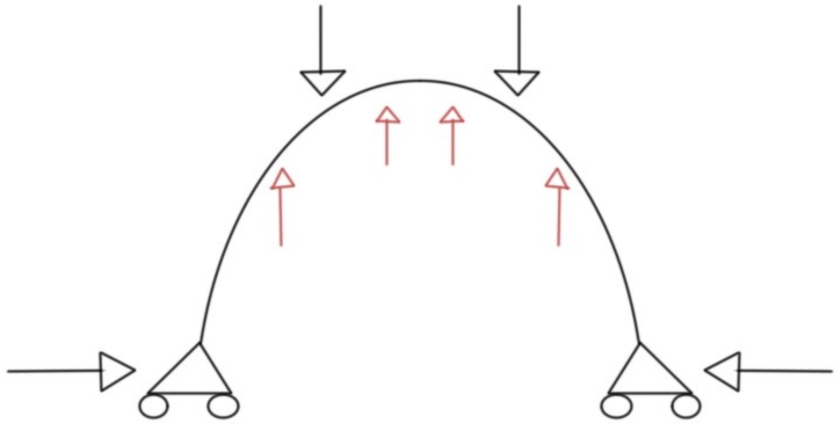

Figure 2.2: Arch section shown by red arrows, loads acting as shown by black arrows

2.4 Lightweighting: Materials

Lightweight materials and design have proved to be beneficial for various industries. Steel alloys, High-strength steel, aluminium (Al) alloys, magnesium (Mg) alloys, carbon fiber and polymer composites have replaced cast iron and traditional steel components across industries leading to more durable and robust solutions. Aviation industry in particular has seen significant development with use of advanced lightweight materials and innovative design approach to minimize material usage. For example the use of a onepiece carbon fiber car fender instead of a four-piece metal part, allowing for a 30 percent weight reduction and a 60 percent reduction in its tooling cost and the use of carbon fiber bearings for Airbus A340 horizontal tail have paved way for weight reduction by 50 % and cost by 30 % [2].

Achieving the targets of CO2 reductions is one of the important drivers for lightweight in automotive industry.Car manufacturers are required to adhere to the emission regulations, hence more emphasis is laid to increase the fuel economy as lighter cars would consume lesser fuel.

The advancements in the field of material science have lead to developing new materials composed of carbon-fiber composites, aluminium, magnesium and steel blends which have contributed to ensuring the vehicle to be made lighter in weight without compromise on strength and durability. Apart from fuel economy , overall vehicle performance is benefited from lightweight solutions owing to improved acceleration and driving dynamics.

The availability of various lightweight materials provide an opportunity for the automotive industry to select a particular material based on its characteristic properties and requirement for the applications. Based on material density weight saving potential varies, it is as shown in 2.1. Inherent properties such as stiffness, strength, malleability, ductility play important role in while selecting a material for a given purpose. Load conditions determine the material best suitable for the design process, for example stiffness of the material maybe the predominant property for required for a certain loads and for certain other load case it would be preferable if the material is more malleable.

Table 2.1: Lightweight materials and respective percentage of mass reduction relative to steel

LIGHWEIGHT MATERIAL	MASS REDUCTION
Magnesium	30-70 %
Carbon fibre composites	50-70 %
Aluminium and Al matrix composites	30-60 %
Titanium	40-55 %
Glass fiber composites	25-35 %
Advanced high strength steel	15-25 %
High strength steel	10-28 %

Apart from the load application, availability and ease of manufacturing plays a significant role to minimize the overall costs incurred during lightweighting approach. Materials used for lightweight solution offer immense weight reduction potential but come at higher costs. The major limiting factor for the use of advanced lightweight alloys and composites has been cost considerations. High-strength steel, for example, offers a weight advantage of 20 % over steel at an additional cost of 15 % per part, and aluminum is 40 % lighter but 30 % more expensive [2]. A comparison of different materials used for automotive application can be seen in 2.3

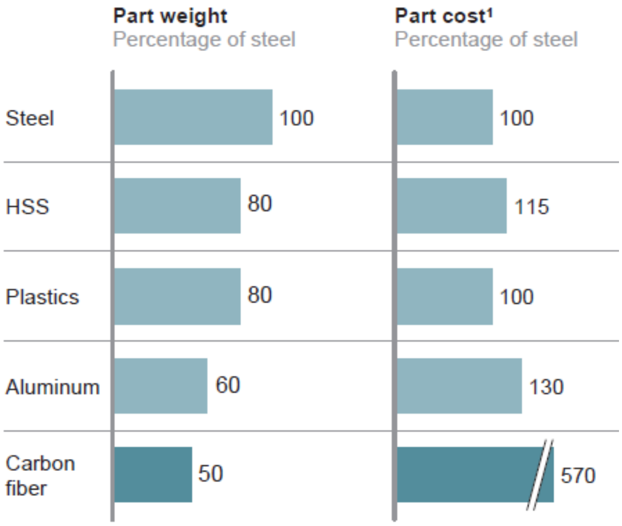

Figure 2.3: Cost comparison of commonly used materials [2]

The best strategy employed for lightweight solution aims to save material costs, increase material recyclability, easy integration into vehicle design and maximizing fuel efficiency. From this approach structural parts requiring strength and formability needed, e.g., side intrusion Beams use Steel components. Structural parts, but additional strength comes with increased difficulties in molding, e.g., B-pillar use High strength steel (HSS). Plastics are used for exterior and interior parts with no requirements for structural strength, e.g., fascias or covers. Aluminium is widely used for structural and functional parts, e.g., subframes or beams. For structural parts like frame, hood or tailgates requiring high strength Carbon fiber composites are used.

2.5 Design for Metal casting

Metal casting is a manufacturing process which involves pouring molten metal into a mold and letting it cool to form a solid part. It is a very cost-effective process to produce parts with complex geometrical features and it produces near net shape parts which require minimal post process machining. High volumes of production with very good tolerances are possible with metal casting which is an ideal fit for the automotive industry [9]. Various metals and alloys can be used in this process.

The process begins with melting the desired metals in large ovens. This molten metal is quickly transferred/poured to a mold. A mold is made up of a stationary cope and a mobile drag. The molten material settles in the cavity present between the cope and drag as shown in figure 2.4. The cavity is designed to be essentially the negative of the component to be produced. The molten metal is allowed to cool and solidify before it is removed. The removal takes place by removing the cope first and then either shaking the part out or ejecting the part with the help of ejector pins

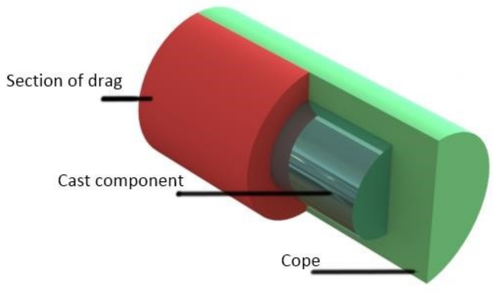

Figure 2.4: Casting process: Molten metal in centre

Designing for casting involves designing the mold and designing for cast component. For the scope of this thesis, only the principles involved for designing cast components are studied. The part to be designed should facilitate pouring of the molten metal, solidification and part removal. In order to facilitate pouring, the molten material should flow smoothly in the cavity. This implies that the part geometry contain uniform wall thickness and avoid sharp corners. To allow for solidification, shrinkage tolerances should be kept in mind as molten metal shrinks in volume when it solidifies.

To ensure proper part removal, proper parting lines and draft angles need to be considered. Parting line (2.5) refer to the boundary where the cope and drag meet and signifies the plane of separation.

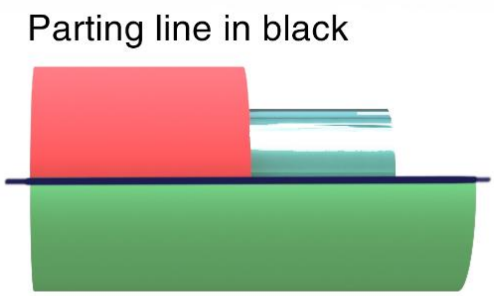

Figure 2.5: Casting process: Parting line indicated in black

Draft angle is the tapering given to a surface to ensure that the material avoids interfering with the drag when it is moved. The angle is measured along the parting lines from the surface of the component to the direction of pull of the drag as shown in the figure 2.6. Typically, a draft angle of 2 to 3 degrees is used for metal casting.

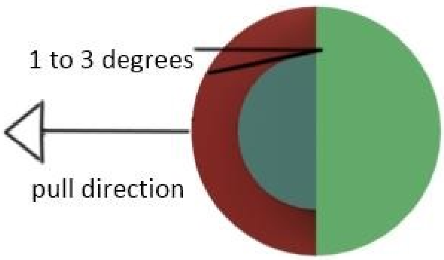

Figure 2.6: Metal casting process: Draft angle

3
Methodology

To understand how a component is developed, we need to understand the generic product development process, identify where individual components are developed, what the requirements of the components are and what the expectations of the component with respect to the generic product development process are. We also need to understand how a component is developed in the industry to identify opportunities to improve.

3.1 Generic product development process

The generic product development process as described by Ulrich and Eppinger is illustrated as shown in figure 3.2. Marketing, Design, Manufacturing and other functions like research, finance and general management are some of important aspects in the product development process [4]. For the scope of this thesis, only the design and manufacturing aspects of each phases shall be discussed.

Figure 3.1: Generic product development process

Phase 1 of the process is planning in which the need for a product or solution is established by activities like market research, business needs, road-maps of the company etc., the major outputs of this phase are the project approval and mission statement. The mission statement broadly directs the project and steer towards goals like profitability and performance.

Phase 2 is Concept development. As the name implies, this is where the products basic geometry begins to be developed. The needs and requirements the product needs to deliver are identified, based on which various concepts are generated, screened and selected. In general, it is encouraged to have an unconstrained approach while conceptualizing products to ensure that fresh, innovative and out of the box ideas are explored. The output of this phase is a feasible concept.

Phase 3 refers to the system level design. This is the phase where the concept is further explored in terms of its subsystems and their components. The functionalities of subsystems and their components are envisioned, and a general geometry is developed. The output of this phase is functional specifications or requirement specifications of the sub systems and by extension, for their components.

Phase 4 is detail design where the final designs for each of the components are developed. This includes final geometry, material, manufacturing and any other requirements that need to be satisfied by the requirement specification. The outputs of this phase will include CAD data, tooling information, manufacturing strategies etc.,

Phase 5 is testing and refinement where the individual components are integrated in to the system, tested for overall performance and gets approved by regulations. In general, System level tests and final refinements are made in this phase before being sent for manufacturing. So, it is expected that individual components perform nominally by this phase. Product prototypes with pre-production parts are produced and tested to identify for any potential engineering changes.

Phase 6 is the final phase, it is for Production ramp up. Here the manufacturing process begins, and initial full-scale products can be delivered to customers to be evaluated in their own environment to identify final issues and flaws like missing functionalities or conflicts between functions . A post launch review is conducted to capture knowledge of the entire project which can lead to improvements in future projects.

In the industry, components are usually developed by engineer's experience and their educated guesses. They are then designed and simulated to evaluate the performance. If it fails to perform, the process is restarted. If it fails at a manufacturability point of view, it is taken to the supplier or manufacturer to be rectified [10].

We can identify that the component development takes place in between system level design and testing & refining phases of the generic product development process as shown in the above figure orange area.

Figure 3.2: Concept design stages for the current scope shown in orange

The components are expected to meet the broad direction set by the mission statement, must be a part of the feasible concept, meet the functional specifications and requirements of the system they belong to, acquire final geometry, material and performance characteristics and perform nominally by the time they reach the testing phase. A dedicated concept development step is required for components which considers all the above-mentioned requirements. The design phase must account for "design for x", where x includes everything from mission statement to final manufacturing.

3.2 Proposed Methodology for concept design

In this chapter a generic methodology that can be applied to any component with a set objective is proposed accounting for the developmental environment identified above. It is a 6-phase methodology which starts with defining the system and ends with the final design while describing the requirements for each step. The proposed process is as shown in figure 3.4.

1. *System definition*

   The first step of the methodology is to define the system in which the component exists. The definition should include the general pre-requisites and direction of the product, the perquisites of the sub system it belongs to, the target specifications it needs to achieve for smooth integration to the system, the limitation present in developing the component and the boundary conditions.

   This definition is important in both new product development from scratch as well as development for improving upon existing components. In the former case, the definition might be relatively open to accommodate unknown factors but, in the latter, it should generally be tightly defined as a lot can be learnt from the existing components.

   Component requirements and prerequisites are set in this phase and together with testing methods form the outcomes of this phase.

2. *System analysis*

   In the second phase, the defined system is analysed to learn about the expected behaviour of the component in the defined system. This enables the engineers to design the component for expected behaviours and functions.

   In the case of new product development, theoretical studies and experimentation may be required to understand the system and predict the components behaviour. For improving a component, the existing one can be subjected to the prerequisites and test procedures established during step one to observe and learn from the results. The output of this step is functional requirements for the component.

3. *Concept development*

   The third phase is where the system/component starts to take shape. Based on the requirements from the previous phases, new concepts are developed, screened, selected and visualized. Contrary to how a product is developed, a component must be subjected within the constraints set by the system definition and analysis. The output of this step is a feasible concept.

4. *Manufacturability*

The visualised concepts need to be manufacturable. Hence, in this phase various manufacturing processes and materials are evaluated and the combination which is suitable for the concept is chosen. Design requirements for the chosen combo are identified. By the end of this stage all the important data that is needed to design, manufacture and test should be acquired. These together produces the output for this step which is a realizable concept.

5. *DBT cycle*

The realized concept needs to be validated against the test conditions established in the system definition. In general, multiple iterations of testing need to be done to ensure the best possible fit. One such iterative approach is the DBT cycle. [4]

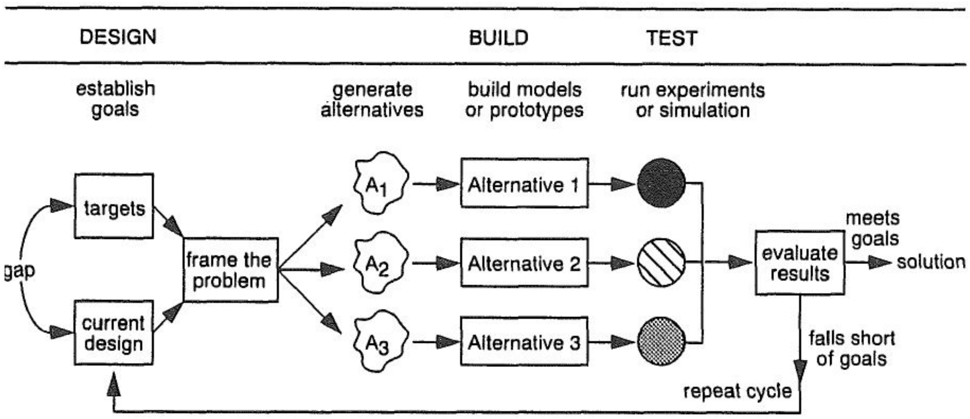

Figure 3.3: DBT Cycle [3]

DBT stands for Design-Build-test cycle. Based on the design requirements, the concept designed into a more representational model. Then it is built in either a digital or physical prototype and is tested with respect to the requirements set in the previous phases.

Based on the test results, either design changes are identified, and the cycle is repeated or if the design is satisfactory, this phase concludes.The output of this step is a near system design.

6. *Final Concept*

The final step of the process involves refining the design to rectify any final issues and integrated to its parent sub system. System integration tests should be performed to ensure that the design leaving this stage is ready for the testing and refinement phase of the generic product development phase.

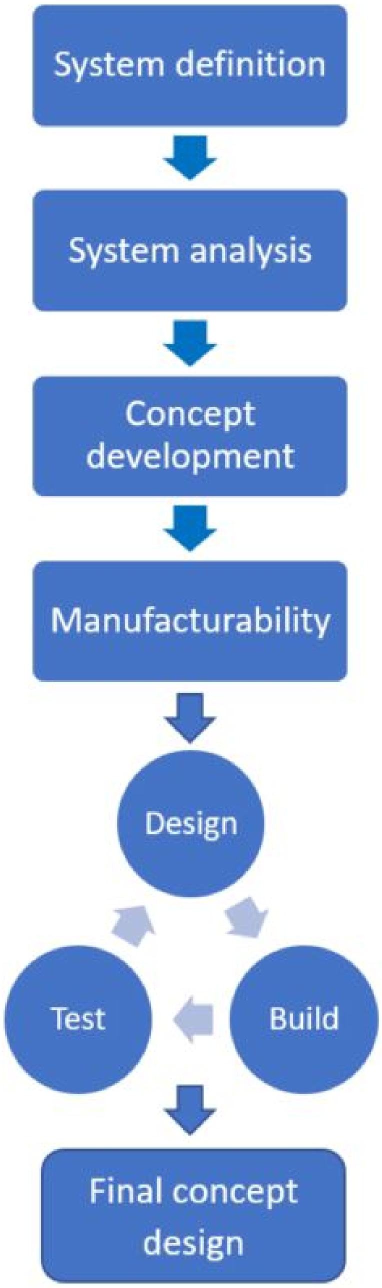

Figure 3.4: Concept design development process cycle

3.3 Tools used

Software tools utilized for the thesis are *Solidworks* for CAD modeling, *ANSYS* workbench for Finite Element Analysis, *CES Edupack* for evaluating different material properties.

4

Validation: Concept design for rear lower control arm (RLCA)

To demonstrate the methodology and to meet the purpose of the thesis, A Rear Lower Control Arm (RLCA) of Lynk and Co 01 is selected and a new RLCA lighter weight is designed. Along with ensuring the structural design of the component is lighter in weight the design is evaluated to meet the strengths and stiffness targets gathered from the DPR provided.

4.1 System definition

For this thesis, the task is to develop an LCA which is lighter than the existing design by CEVT. We can learn about geometrical, performance, testing requirements as well as identify opportunities for improvement by studying how the component was manufactured. Limitations for the validation work should be established as well.

4.1.1 Geometry

The component that is to be developed needs to be compatible with the existing Lynk and Co 01 rear wheel suspension system, which means all the hard points and interfaces the current component carries should be retained. This forms the basic design space definition.

The hard points of interest are the knuckle, damper, spring, bushing interfaces referred to as PT6, PT56, PT59, PT4 in the figure 4.1 respectively. For PT4, PT56 and PT6, dimensions like the diameter and positioning of the holes must be retained.

For PT56, the diameter of the pad as well as required dimensions for the spring should be retained. The design must also satisfy the packaging requirements as mentioned in [Appendix A.2].

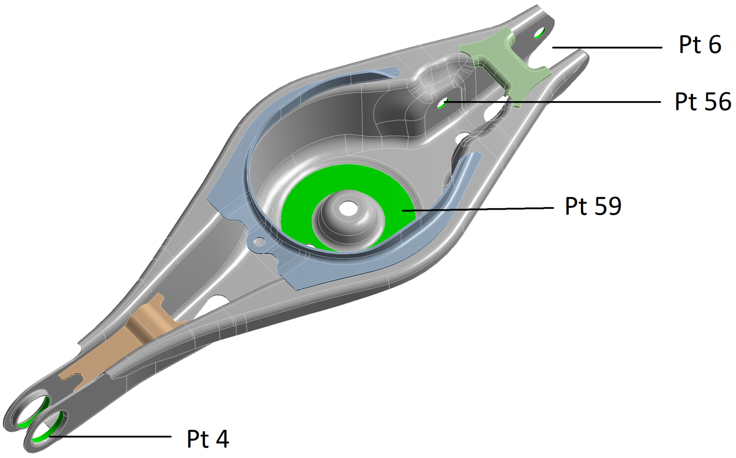

Figure 4.1: Geometrical Hard points

4.1.2 Objective and performance requirements

While the main objective is set for light weighting, the structural performance should be comparable or better. To achieve this, the component must satisfy key performance attributes like strength and stiffness to be applicable to the existing suspension system of CMA 1.5 platform.

Strength is a material property which implies, the materials yield strength is an important requirement to meet whereas stiffness is a property which depends on the material, load direction as well as geometry. Stiffness targets are set by CEVT guidelines which their design adhered to and hence, the new design should meet them too.

The performance attributes are set after gathering data from the DPR during baseline study,they are as tabulated in 4.1

Table 4.1: Concept Design Pre-requisites

Requirement	**Target**	**Justification**
Strength	0.2 offset of yield strength	A robust component needs to handle stresses without undergoing plastic deformation
Stiffness		
Axial stiffness pt 6	37KN/mm	CEVT DPR
Vertical stiffness pt 59	6KN/mm	CEVT DPR

4.1.3 Tests and boundary conditions

To validate the component, tests need to be conducted. For this thesis, strength and stiffness are chosen as performance attributes. CAE using ANSYS workbench is used in this thesis. Static structural analysis was performed to calculate for stress with non-linear effects enabled.

For strength, stresses need to be calculated when the component is subjected to loads derived from Road load data (RLD) A. RLD is required for CAE tools as the data gathered takes into account important vehicle and driving parameters, such as mass, inertia, air and rolling resistance, road characteristics, engine loads and vehicle speed. For CAE analysis they simulate specific events a vehicle undergoes such as,

- Drives Over Curb (DOC)
- Rearwards Over Curb (ROC)
- Brakes In Pothole (BIP)
- Opposite Wheel Travel (OWT)

The load cases derived from the from specific events during RLD Acquistion is chosen for the concept design development. The loads from RLD [Appendix A.4] simulate similar specific loading conditions in the CAE environment, this helps to understand the structural behaviour of the design under loading environment which is representative of the real life driving scenario. RLD proves to be beneficial here as the values obtained from the test data have higher reliability and would help in assessment of the new concept design under same exact loads the existing design was tested on.

For stiffness calculation, unit loads (10 KN) are applied at PT6 along the axis of the component and at PT59 along the vertical axis. The resultant displacements are calculated via CAE and hence stiffness is obtained by using the formula.

$$S = \frac{F}{x} \tag{4.1}$$

Where S is the stiffness, F is the force applied and x is the displacement or deflection.

4.1.4 Material and Manufacturing

From CEVT documentation, it is known that their component was made from steel (YS420 alloy) and manufactured by metal stamping process. The process involves pressing a die onto a malleable metal to form the desirable shape. Observing the design, features like additional brackets are apparent which are welded to form the component.

An important thing to note is that CEVT designed the component with a particular assembly in mind. It requires a spring insertion tool to assemble the spring and LCA as shown in the figure. To make the new design compatible with this assembly process, the geometry highlighted in the figure should be retained. The geometry to be retained is shown in red and the spring insertion tool is shown in blue in the figure 4.2

Figure 4.2: Geometry to be retained in red

There is an opportunity to improve manufacturing time as the process employed by CEVT has at least two major steps (stamping and welding). Any manufacturing process which reduces the number of steps or post processing is an opportunity.

4.1.5 Limitations for the component development

- Ideally, a full suite of performance requirements like NVH, Crash worthiness and fatigue are to be met. But they are not considered for this thesis due to the limited time and resources.
- For FEA, analysis was done with non linear effects turned on but with linear material models due to the software and computer limitations. To circumvent this limitation, the design aims to develop a component where stress never exceeds yield limit.
- Additional requirements like clamping forces for pt6 and pt4 are not considered as the scope of thesis is limited to developing a sound structure and not a final design.
- Concept development is limited to developing a single concept owing to time limitations. Ideally the full process of concept development including screening and selecting should be performed.
- The DBT cycle proposed in the methodology is open to multiple variations of the same concept. However, this thesis only considers a single variation after each iteration as exploring all variations requires more than the available time.

4.2 System analysis

By carefully analyzing how the existing LCA behaves under the loading conditions, an understanding of the load path for the new component was visualized. In this phase, the existing LCA is subjected to strength testing to observe how it behaves.

The load data primarily consists of vertical loads (Z direction here) at PT59 and PT56 which result in bending of the suspended structure and axial forces at PT6 which result in either tension or compression along the entire component axis.

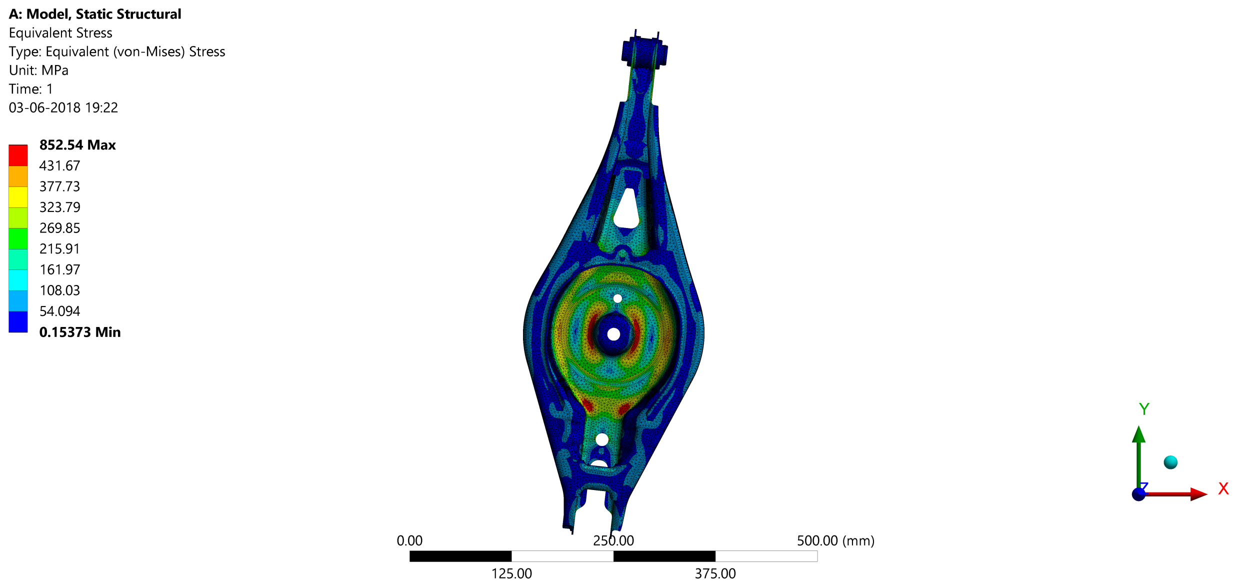

Figure 4.3: FEA of existing design under LC3 (top view)

The analysis shows that the load is primarily carried by pt 59 as shown by the stress distribution and the presence of sharply cornered walls result in high levels of stress concentration as shown in red figure 4.3.

Figure 4.4: Brackets used for existing design in blue

The stress distribution on each of the three brackets is uneven, where material closer to PT 59 experiences more stress than material further away. It infers that the purpose of the brackets is to provide tensile stiffness along the length and to prevent the structure from opening as shown figure 4.4

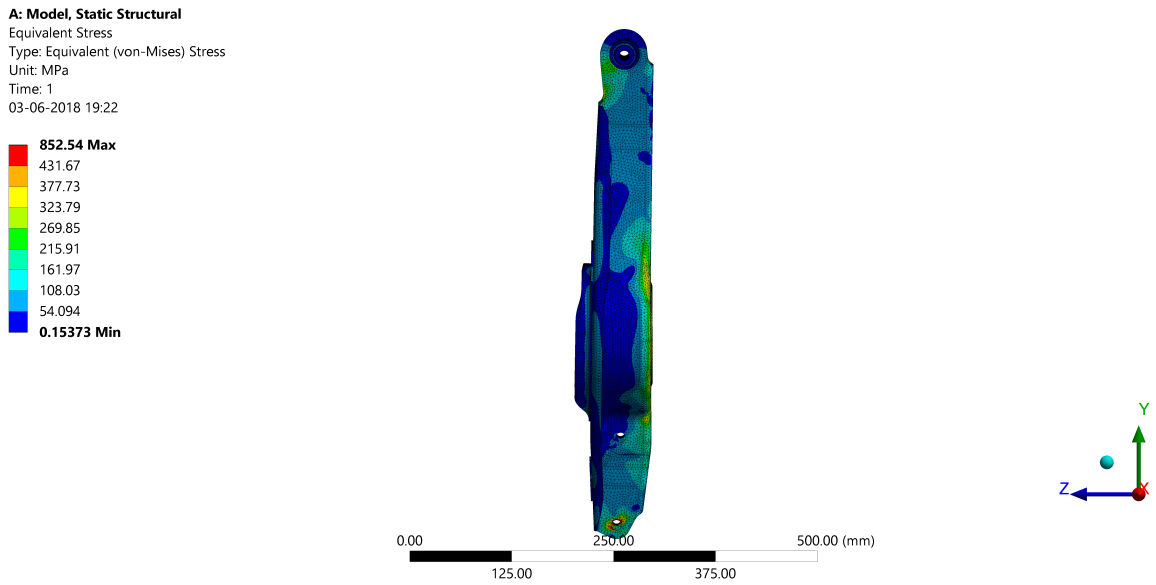

Figure 4.5: FEA of existing design under LC3 (front view)

Although the side walls carry some of the loads as shown in figure 4.5, a considerable amount of material is relatively stress free with the span of the wall being unstressed and the anchor points being stressed. This indicates potential for either material removal or better geometry to distribute stresses.

It is inferred from the nature of loads and resulting stresses that a newly developed component is required to carry bending and axial loads. The geometry should have the capacity to use most of its structure to distribute these loads for efficient use of material.

4.3 Concept development

For developing a structural concept to address the requirements from system analysis, inspiration can be drawn from civil engineering structures already in use. Reflecting back on the principles 1 and 2 of lightweight structure from theory from section 2.3, there is an opportunity to improve the ratio of live load to dead load.

There is an opportunity to integrate elements which resist loads by tension or compression instead of bending as well. I beams and Arches are excellent construction elements for this purpose.

I beams have an excellent live load to dead load ratio as most of the load carrying is done by the flanges requiring less material as can be observed by the cross section of an I beam fig 4.6 and 4.7 . When the I beam is subjected to vertical loads, flanges carry most of the bending effects whereas the web carries shearing effects. They are also excellent at carrying tensile or compression forces which is relevant as the LCA experiences those along the axis of the component from PT4 to PT6

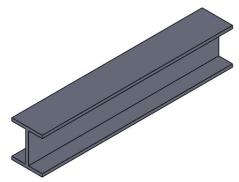

Figure 4.6: I beam concept

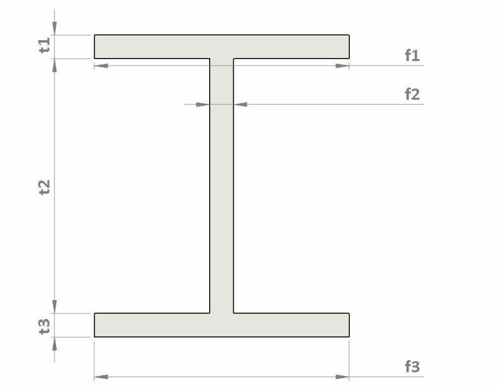

Figure 4.7: I beam concept Cross-section

Arches can transfer vertical loads to compressive loads along their geometry making use of material efficiently to carry large vertical loads without significant deflection. The geometry is used in constructing bridges which need to carry vertical loads exerted on their spans. Arch action helps with managing overall stress levels as well across the span of the component. This is relevant to this thesis where the component is required to handle vertical loads at pt56 and pt59 and experiences horizontal loads at pt4 and pt6 for arch action.

For the concept to incorporate the above arch, I beam and geometrical features retained from CEVT component, a manufacturing process which can produce complex features and preferably a near net shape product is suitable. The material should be manufacturable for the selected process as well as have a good strength to weight ratio.

4.4 Manufacturability

This phase explores the material/manufacturing process combination which enables the concept to be manufacturable.

4.4.1 Manufacturing Process

Metal casting is a common manufacturing process used in the automotive industry to produce a wide range of products. The key strength of the process is its ability to produce parts with complex features and high volumes of production. Both advantages are ideal for this case. Design for casting however requires some key points to be considered, they are as follows [9]

- Uniform thickness: Uniform wall thickness is ideal for casting as it results in uniform shrinkage and consistent physical properties.

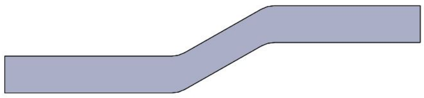

Figure 4.8: Example: Uniform wall thickness

- Minimizing hot spots: Hot spots are generally the areas where walls intersect or join. Hot spots result in porosity issues while the molten metal is shrinking which leads to weak points in the structure. Reducing the number of hotspots and providing ample radius at necessary spots would address this concern.

- Avoid sharp corners: Sharp corners prevent fluid flow of molten metal in the pouring stage and creates inconsistencies when solidified. Use smooth corners to avoid weak design.

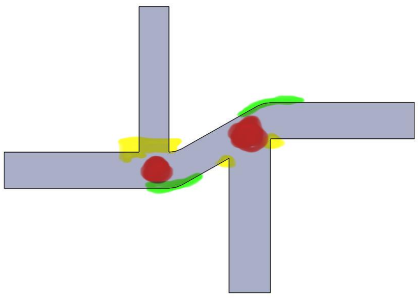

Figure 4.9: Example: Hotspots shaded in red, sharp corners in yellow and smooth corners in green

- Parting lines: A parting line is where the cope meets the drag and which denotes the direction of ejection. Having a good idea of where the parting line(s) while designing ensures the castability of the component. It is as shown in figure 2.5

- Draft angle: To safely eject the casted produce, the geometry should have appropriate draft angle along the parting line.It is as shown in figure 2.6

4.4.2 Material Selection

Material choice plays a big role in developing lightweight components. Common lightweight materials used in general are Aluminium, Magnesium, titanium, Carbon fibre composites, fibre glass composites etc., Carbon fibre and glass fibre cannot be used in casting and titanium is very expensive.

Magnesium is a very good metal to cast with a good strength to weight ratio, but offers lesser corrosion resistance compared to Aluminium. Hence it is not advisable to be used in components like LCA which are exposed to the environment.

Aluminium is a widely used metal in the automotive industry owing to its high strength to weight ratio. [9]. Reflecting on principle 3 of light weight structures from theory 2.3, the Al alloy which offers the best yield strength to density characteristics is an ideal choice for this project. Plotting castable aluminium alloys with yield strength vs weight gives us figure 4.10

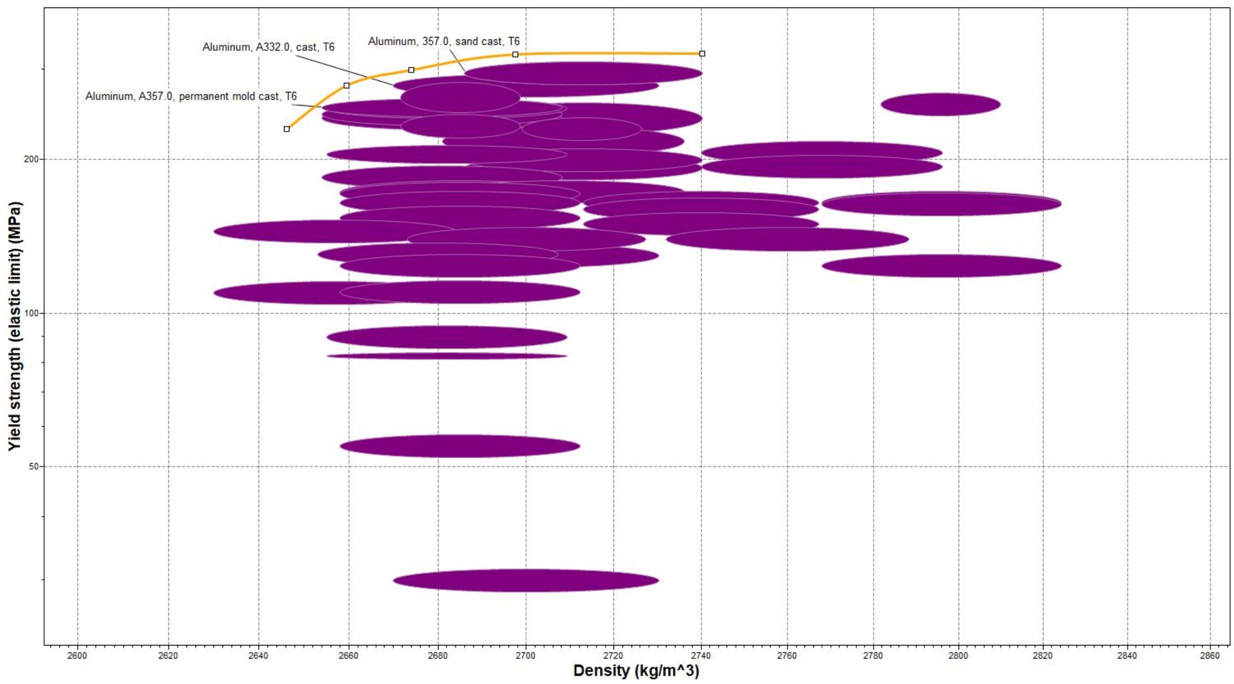

Figure 4.10: Graph generated using *CES Edupack* for material selection

Drawing a pareto curve to maximise yield strength and minimise density reveals a choice among A357 optimised for sand casting and for permanent mold casting and A332. Looking at the key physical properties in the context of this thesis as shown in the table 4.2, We see that Sand cast Al has higher Yield strength with comparable density. But permanent cast Al has better elongation characteristics. A332 alloy also has better strength characteristics compared to A357 permanent cast but has the poorest elongation.

In comparison, YS420 steel used in CEVT component is stronger, elongates more but is vastly denser. The full physical properties of all these materials can be found in the Appendix C.

Table 4.2: Comparison of material properties considered for the concept design

Material	**Yield Strength (MPa)**	**Density (Kg/m^3)**	**Elongation (strain)**
	Aluminum		
A357 Sand cast	281-311	2690-2740	2-2.4
A357 Permanent cast	244-263	2650-2710	3.8-4.6
A332	266-294	2670-2730	1.0-2.0
	Steel		
YS420	420-520	7800-7900	17-26

Better elongation implies better ductility which means that in the event of a fracture, this material stretches more before failing catastrophically. This factor gives the edge to A357 Permanent cast, as its important for suspension components to resist fracture as much as possible. Hence, this material is chosen for the component and all subsequent phases.

4.5 DBT cycle

Designing and validating the component takes place in this phase. It is an iterative process where the design is modelled in sequence addressing the areas with high stress concentration and design changes to reduce the stresses.

Then the design is tested and validated under the most critical load case which is BIP, the cycle is repeated until the component is stable in this load case. Then it is tested with all the load cases to verify it’s stability and performance.

4.5.1 Cycle 1

The first cycle starts with fixing the hard points as shown in figure 4.11 in the CAD software followed by defining the bounding box, the design space is realized. Once the design space is visualized, the geometry required for the pt 59 is developed along with the curvature that defines the overall arch from the concept as shown in figure 4.12.

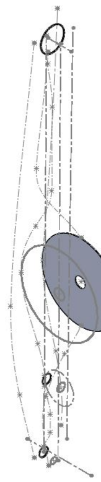

Figure 4.11: Concept design Step1: Cycle 1

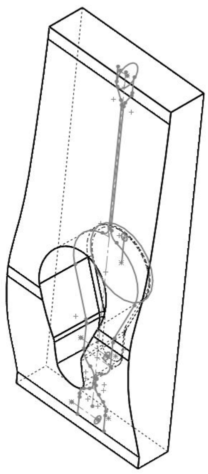

Figure 4.12: Concept design Step2: Cycle 1

Design principles applied for concept design

Referring back to concept development phase 4.4, the figure 4.13 illustrates how the concept of an I beam is integrated into the design.

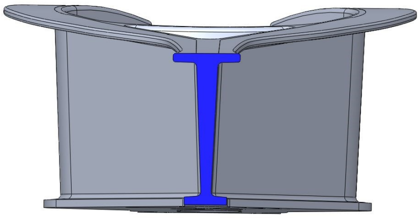

Figure 4.13: 'I' beam in Concept design

In the figure 4.14 the arch structure is incoporated in the regions shaded in blue.

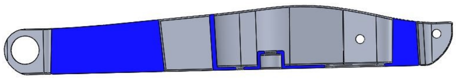

Figure 4.14: 'Arch' shape in Concept design

Referring back to the manufacturability phase 4.4, Design for casting should ideally start early in the design phase. The pull directions for casting, draft angles are implemented early on as is illustrated in the cross section below figure 4.15

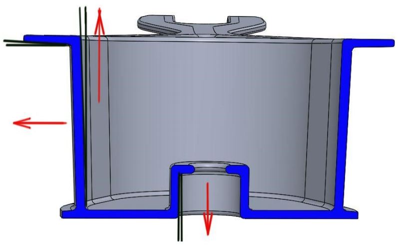

Figure 4.15: Cross section showing pull directions in red and draft angles in black for the concept

Care should be taken to design the component with uniformly thick walls as much as possible and keeping as illustrated in figure 4.16

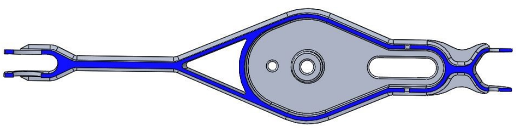

Figure 4.16: Uniform wall thickness in Concept design

Wall intersections are inevitable and hot spot formations are unavoidable. However, the number of hotspots can be reduced, and adverse effects of sharp corners can be mitigated by using proper radii at corners as illustrated figure 4.17.

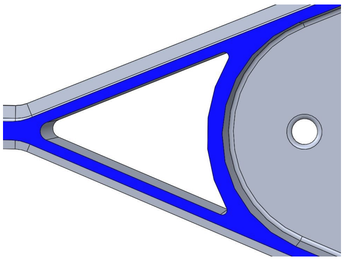

Figure 4.17: Radii provided to avoid sharp corners in Concept design

The overall profile of the concept is then constructed in CAD with minimal wall thickness maintaining uniform wall thickness as much as possible and accounting for draft angle.

The reason for starting the first designs with minimal thickness is to ensure that weak points are easily identified during tests as shown in figure 4.18. Finally, top and bottom flanges are added to realize the I beam concept figure 4.19.

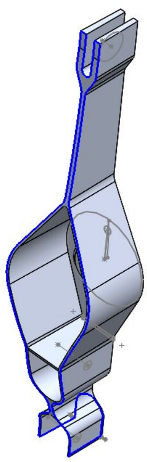

Figure 4.18: Concept design Step3:Cycle 1

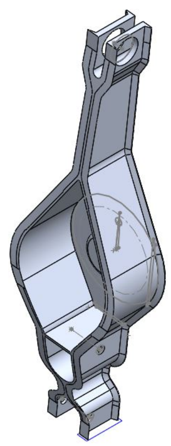

Figure 4.19: Concept design Step4:Cycle 1

Now that a basic design is developed, it is tested under the selected load cases for strength. Observations made include multiple areas where stress exceeds the yield point and the arch structure distributing the loads along the entire span. This tells us that the arch is performing as expected as seen in figure 4.20. The component weights **1.604 Kgs** which is lighter than the CEVT design which weighs 2.745 Kg

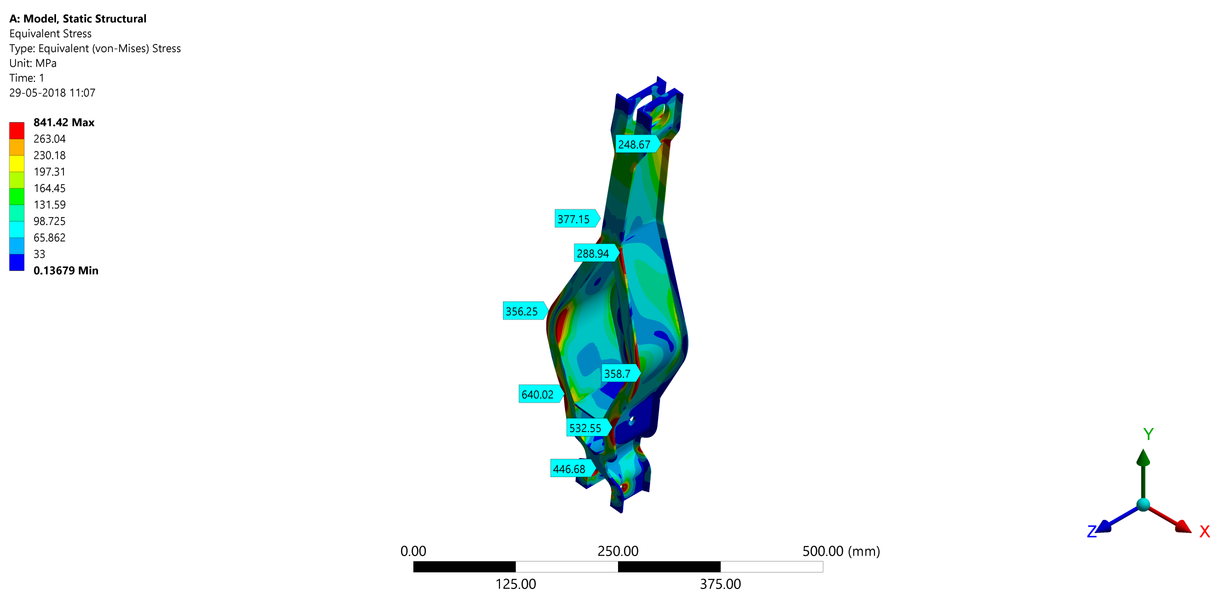

Figure 4.20: FEA of Concept design (cycle 1) under LC3

4.5.2 Cycle 2

Casting is a process where material can be added or removed creatively. To address the shortcomings from the first cycle, the flange profiles are adjusted by adding material to the flange length where stress is high and removing where stress is low applying general rules of thumb from section 2.3, doing so we arrive at a design as shown in figure 4.21.

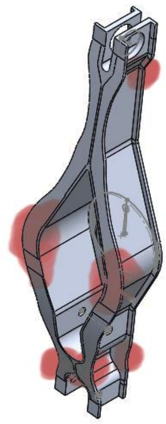

Figure 4.21: Concept design Cycle 2

Upon testing, it is observed that some of the local stresses were relieved. But stresses were high at hot spots and the overall spring cavity needs additional stiffness to control the stresses as shown in 4.22.The component weights **1.722 Kgs**

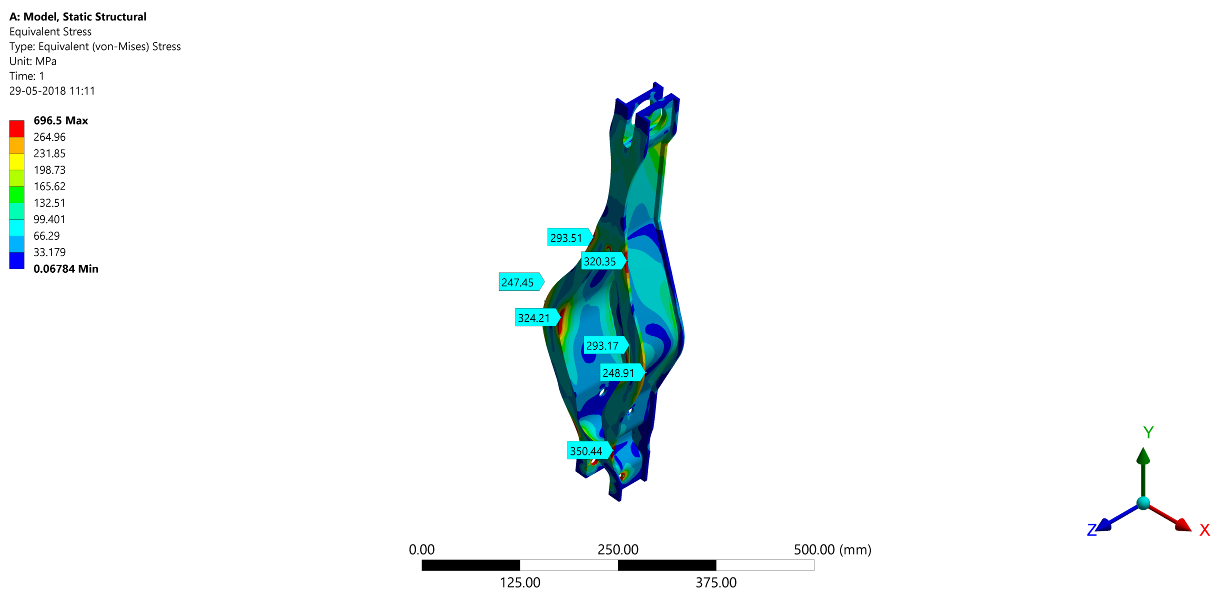

Figure 4.22: FEA of Concept design (cycle 2) under LC3

4.5.3 Cycle 3

To decrease the stresses around the spring cavity and to increase the stiffness, the cavity is divided by adding a curved wall to take on the loading, thus relieving stress at hot spots shown in red shaded regions in the figure 4.23

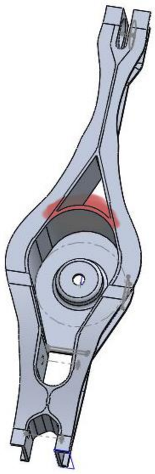

Figure 4.23: Concept design Cycle 3

The revised design is tested again to evaluate if the changes perform favourably. It is observed that the wall functions as intended but the hotspots near the wall still need to be solved as seen in figure 4.24. The component weights **1.797 Kgs**

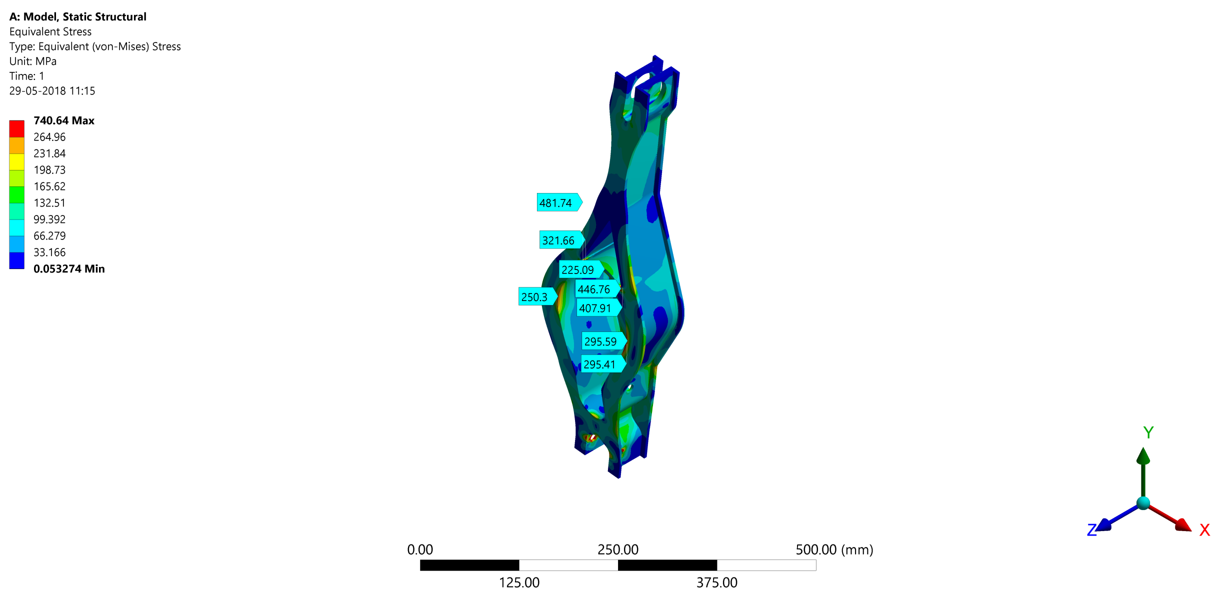

Figure 4.24: FEA of Concept design (cycle 3) under LC3

4.5.4 Cycle 4

Refining the flange profile by changing the amount of material near hotspots and optimizing the radii for hotspots near the wall results in a refined design. Material is removed near the edges of the geometry as shown with red shaded region as shown in figure 4.25 and it is evaluated for the load cases

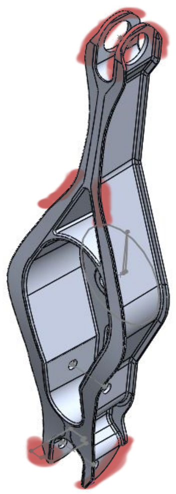

Figure 4.25: Concept design Cycle 4

Upon testing, it is found that the stresses throughout are relieved to within the yield limit, barring some extreme edges as seen in figure 4.26. It is also observed that the side walls are loading nearly uniformly which helps in distributing the stress across the whole geometry as seen in figure 4.27.

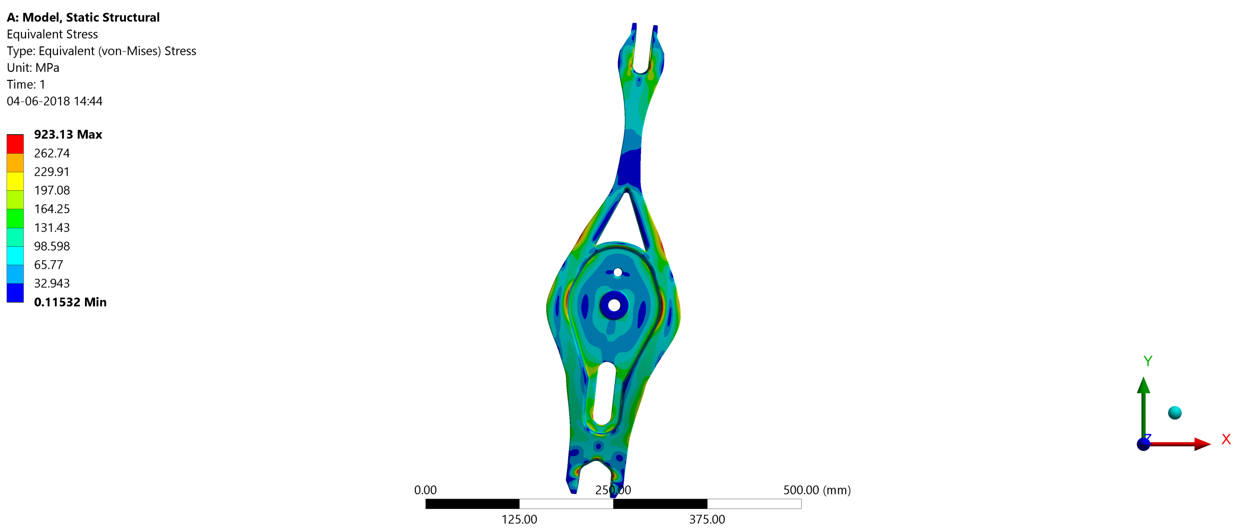

Figure 4.26: FEA of Concept design (cycle 4) under LC3, top view

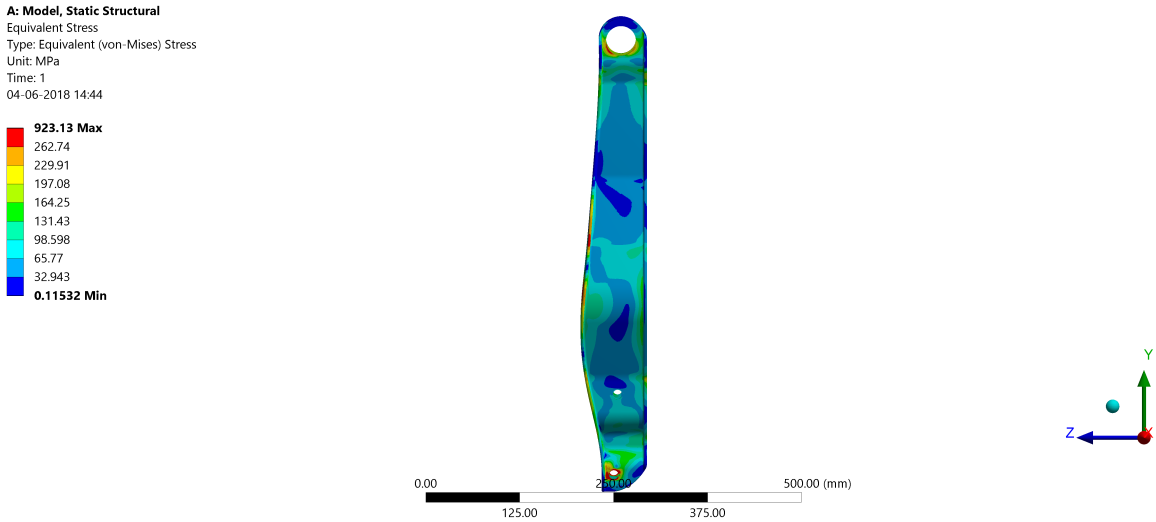

Figure 4.27: FEA of Concept design (cycle 4) under LC3, front view

This is a satisfactory result as the weight is reduced by nearly 36.5 % compared to CEVT component. The axial stiffness at pt 6 is 45KN/mm and vertical stiffness at pt 59 is 8.45 KN.mm and stress is within the yield limit. The performance characteristics of the concept design is found in Appendix B.

Table 4.3: Performance parameters comparison

Attribute	**Current design**	**Concept design**	**% change**
Weight	2.745 Kg	1.743 Kg	36.5 decrease
Stiffness pt 6	37 KN/mm	45 KN/mm	21 increases
Stiffness pt 59	6 KN/mm	8.45 KN/mm	40.8 increase

4.6 Final Design

The final output of the methodology is a concept design for LCA which is a cast aluminium component. The new component is relatively more compact, performs better under the selected load cases and also it is a single part instead of an assembly of many parts. The original design and the new concept design are as shown in the figure 4.30.

Figure 4.28: Current design & Concept design (iso view)

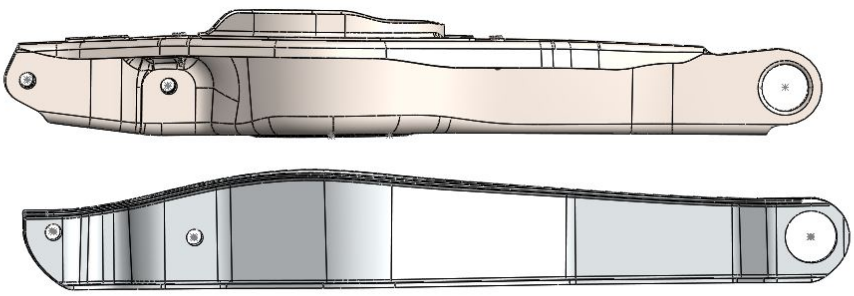

Figure 4.29: Current design & Concept design (side view)

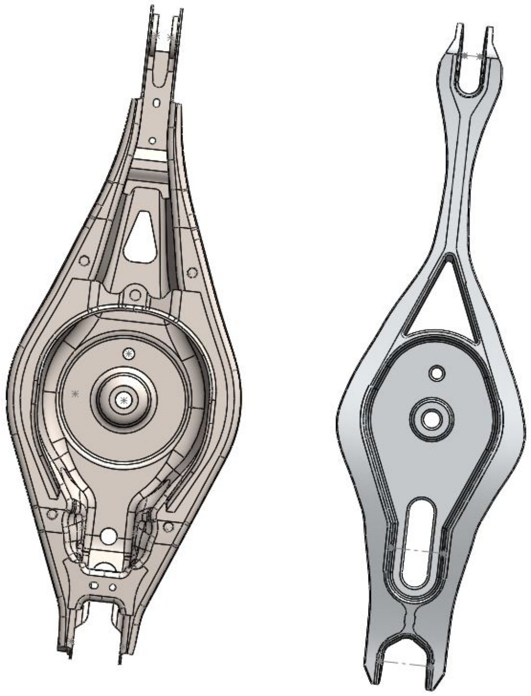

Figure 4.30: Current design & Concept design (top view)

5 Conclusion

In conclusion, after studying the theory behind generic product development process as proposed by Ulrich and Eppinger, observing how components are developed in the industry a component development process was developed to account for the shortcomings and improve when opportunities present themselves. This methodology was then validated to develop light weight components and it delivered a promising component with considerable weight and performance advantages.

A concept design strategy for light weight design was employed to the rear LCA of the CMA 1.5 platform and proved to be successful with with 36.5 % weight reduction. The developed concept design performs well under all the load cases provided by CEVT

However care should be taken into reading this result, as working with constraints some attributes were not addressed as mentioned in the limitations but since the most important parameters i,e strength and stiffness are well within the target values the changes to the weight of the structure when the other attributes such as NVH, crash test, durability and fatigue data etc when considered will not be major.

The analysis was simplified with more emphasis on stress distribution and investigation on structural behaviour/performance under load cases studied. The process followed focused more on developing a concept design and evaluation of the concept design is only in general details and has room for further improvements.

6
Further work

During the thesis work, limitations forced some parameters to be ignored and procedures to be shortened to meet the final objective of the thesis. To continue researching with this thesis, further work is suggested.

6.1 Further work in methodology

While validating methodology, concept development was shortened to produce a single concept. Ideally, the full procedure of concept development and its various data collection techniques, concept screening and concept selection should be done. This ensures that that multiple concepts are generated and are compared against each there to selectively arrive at the best possible concept. DBT cycle was shortened as well but ideally each DBT cycle spawn variations of the same concept and some might perform better than others. To explore this possibility, the full DBT cycle as illustrated should be performed.

6.2 Further work in design

Certain geometry like pt6 and pt4 were not fully realized as knowledge regarding incorporating clamping force during the analysis was limited and hence not considered. Full suite of performance metrics like NVH, fatigue, crash worthiness should be performed for realisation of the final design. Linear material models were used in this thesis, however non linear models provide more accurate FEA results which aides in fine tuning the design even more. While choosing materials, material indices and loading conditions can be considered for better choices. Our validation work focused on minimizing weight while preserving strength. This meant that the first step in choosing materials was based on the material index, yield strength to density ratio. However if the objective was to improve stiffness, a material with high Young's modulus to density would be better [12]. Similarly depending on the loading conditions and objectives, different material indices can be chosen.

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A

CEVT DPR

Table A.1: Hardpoints Definition

Point Number [PT]	Interface
PT4	SF and rear LCA
PT6	Knuckle and rear LCA
PT56	Damper and LCA
PT59	Coil Spring and LCA

Table A.2: Design Volume of existing model

Axis (Global)	Dimension (mm)
x	222.46
y	624.94
z	97.375

Table A.3: Loading Channel description

Channel	Channel Name	Description	Load	Side	Unit
1	f6zlocL__rlca__rsusp	Knuckle to rear LCA	axial force	left	N
2	f56xL__rlca__rsusp	Damper to rear LCA	x-force	left	N
3	f56yL__rlca__rsusp	Damper to rear LCA	y-force	left	N
4	f56zL__rlca__rsusp	Damper to rear LCA	z-force	left	N
5	f59xL__rlca__rsusp	Coil spring to rear LCA	x-force	right	N
6	f59yL__rlca__rsusp	Coil spring to rear LCA	y-force	right	N
7	f59zL__rlca__rsusp	Coil spring to rear LCA	z-force	right	N

Table A.4: RLD from CEVT

LC_id Event	LC1 (N) ROC_20kmh	LC2 (N) DOC_110	LC3 (N) BIP	LC4 (N) OWT	LC5 (N) DOC_110kmh
f6zlocL_rlca_rsusp	15768	-2611	-18435	71	8694
f56xL_rlca_rsusp	22	-405	583	-327	-983
f56yL_rlca_rsusp	-334	365	-242	-21	360
f56zL_rlca_rsusp	-5424	5237	-3595	-6522	-19191
f59xL_rlca_rsusp	-262	-78	252	167	34
f59yL_rlca_rsusp	1093	127	-31	3091	3402
f59zL_rlca_rsusp	-10010	-7572	-6851	-12777	-12685

B

CAE results of Concept Design

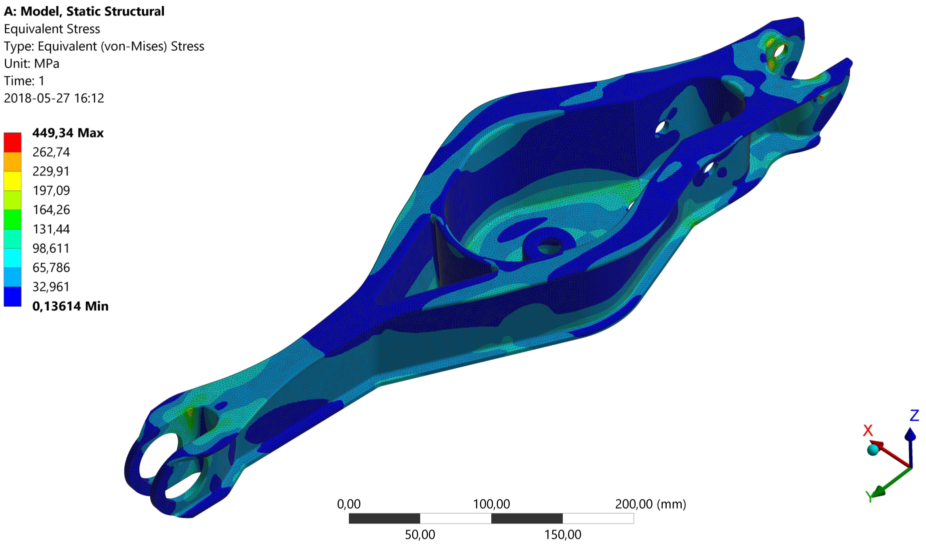

Figure B.1: FEA of Concept design (cycle 4) under LC1

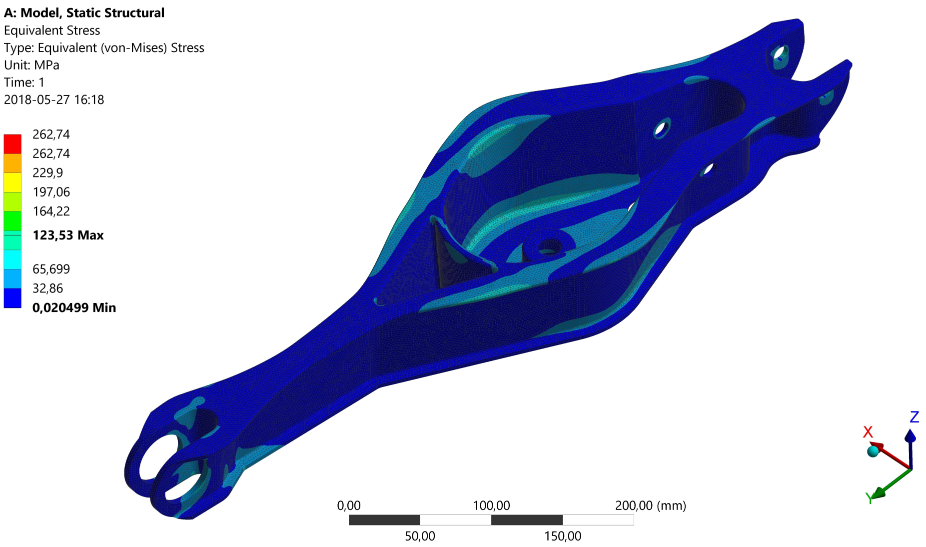

Figure B.2: FEA of Concept design (cycle 4) under LC2

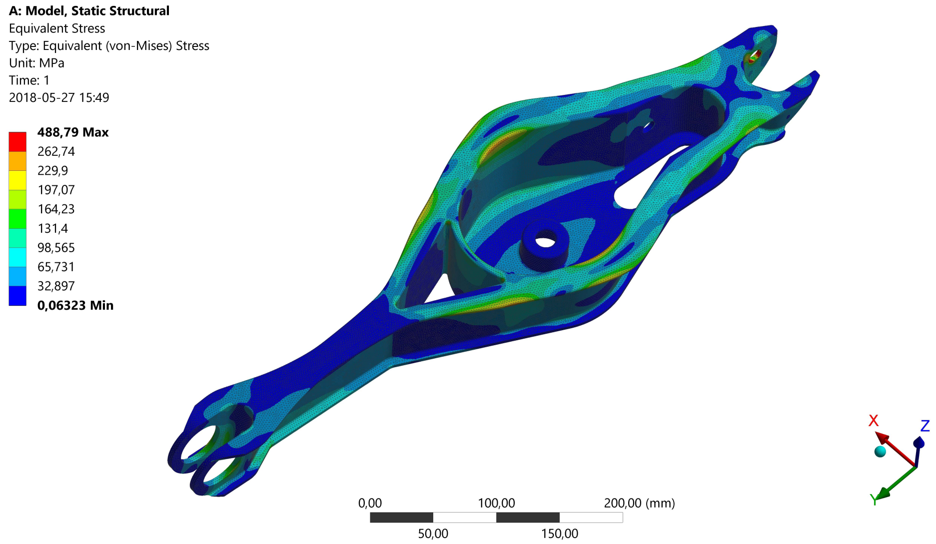

Figure B.3: FEA of Concept design (cycle 4) under LC3

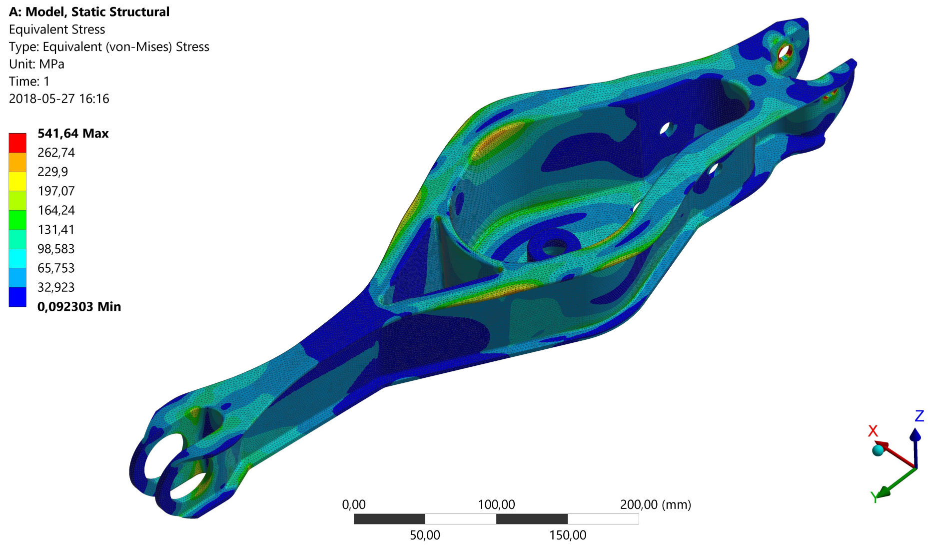

Figure B.4: FEA of Concept design (cycle 4) under LC3, front view

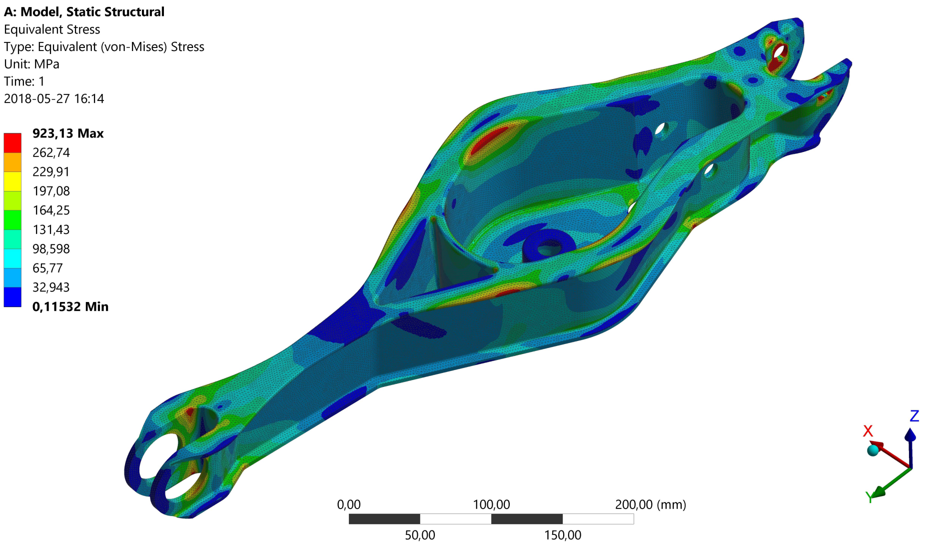

Figure B.5: FEA of Concept design (cycle 4) under LC5

C

Material Properties from CES Edupack library

C.1 YS420: stamped steel

Physical properties					
Density	ⓘ	7,8e3	-	7,9e3	kg/m^3
Mechanical properties					
Young's modulus	ⓘ	200	-	221	GPa
Specific stiffness	ⓘ	25,5	-	28,1	MN.m/kg
Yield strength (elastic limit)	ⓘ	420	-	520	MPa
Tensile strength	ⓘ	470	-	590	MPa
Specific strength	ⓘ	53,5	-	66,3	kN.m/kg
Elongation	ⓘ	17	-	26	% strain
Compressive strength	ⓘ	* 420	-	520	MPa
Flexural modulus	ⓘ	* 200	-	221	GPa
Flexural strength (modulus of rupture)	ⓘ	* 420	-	520	MPa
Shear modulus	ⓘ	* 77,1	-	85,1	GPa
Bulk modulus	ⓘ	* 167	-	184	GPa
Poisson's ratio	ⓘ	0,286	-	0,315	
Shape factor	ⓘ	50			
Hardness - Vickers	ⓘ	* 151	-	183	HV
Elastic stored energy (springs)	ⓘ	422	-	640	kJ/m^3
Fatigue strength at 10^7 cycles	ⓘ	* 230	-	268	MPa
Fatigue strength model (stress range)	ⓘ	* 197	-	313	MPa

C.2 A357:Sand cast

Physical properties

Density	2,69e3	-	2,74e3	kg/m^3

Mechanical properties

Young's modulus	70,6	-	73,4	GPa
Yield strength (elastic limit)	281	-	311	MPa
Tensile strength	345	-	380	MPa
Elongation	2	-	2,4	% strain
Compressive strength	109	-	121	MPa
Flexural modulus	* 70,6	-	73,4	GPa
Flexural strength (modulus of rupture)	* 296	-	326	MPa
Shear modulus	* 26,4	-	27,8	GPa
Bulk modulus	* 66,1	-	75,5	GPa
Poisson's ratio	0,322	-	0,338	
Shape factor	23			
Hardness - Vickers	100	-	110	HV
Fatigue strength at 10^7 cycles	55,8	-	68,2	MPa
Fatigue strength model (stress range)	105	-	130	MPa

C.3 A357:Permanent mold cast

Physical properties

Density	ⓘ	2,65e3	-	2,71e3	kg/m^3

Mechanical properties

Young's modulus	ⓘ	70,6	-	73,4	GPa
Yield strength (elastic limit)	ⓘ	244	-	263	MPa
Tensile strength	ⓘ	306	-	332	MPa
Elongation	ⓘ	3,8	-	4,6	% strain
Compressive strength	ⓘ	* 244	-	263	MPa
Flexural modulus	ⓘ	* 70,6	-	73,4	GPa
Flexural strength (modulus of rupture)	ⓘ	* 244	-	263	MPa
Shear modulus	ⓘ	* 26,4	-	27,8	GPa
Bulk modulus	ⓘ	* 66,1	-	75,5	GPa
Poisson's ratio	ⓘ	0,322	-	0,338	
Shape factor	ⓘ	26			
Hardness - Vickers	ⓘ	* 96	-	111	HV
Fatigue strength at 10^7 cycles	ⓘ	* 76,5	-	93,5	MPa
Fatigue strength model (stress range)	ⓘ	* 125	-	152	MPa