Engine Redesign Utilizing 3D Sand Printing Techniques Resulting in Weight and Fuel Savings

By

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Abstract

Lightweighting is an important part of the automotive industry. As US manufacturers push the boundaries for lightweighting further every year, application of 3D sand printed molds for casting engine blocks and cylinder heads can play an expanding role. This masters thesis describes redesign of 350 Chevy engine with implementation of 3D sand printing featured into new design. Weight savings of more than 8lb. were achieved. A reverse engineering process was used to obtain the parametric data from the original engine castings. This was accomplished by using a 3D-scanner. Castings that have been redesigned include two cylinder heads, intake manifold and connecting rod. Castings were modified in CAD software SolidWorks. Weight savings were achieved by merging the intake manifold with two cylinder heads. This step allowed eliminating unvented bolt joints while creating highly complex part castable exclusively through molds fabricated by 3D sand printing. The implementation of lattice structure in connecting rod design provided weight savings of almost 2 lb. Seven different designs were proposed until the final design shape was obtained. New design of connecting rod was then verified through FEA. After the total weight saving were determined the fuel savings were calculated and extrapolated per fleet of the vehicles using similar engine. Annual fuel savings were provided and environmental impact of these fuel saving was found. Combination of intake manifold and cylinder heads into one casting eliminated the need for three gating systems. This modification saved more than 28lb of metal which would be considered as scrap if casting each part separately.
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Chapter 1 Introduction

1.1 Motivation
Additive manufacturing (AM) has been frequently implemented in rapid prototyping over the last 30 years. In order to exploit the benefits of additive manufacturing, it is mandatory to define manufacturing constrains and manufacturing capabilities of additive manufacturing. [1]. The aim of this research is to take advantage of the additive manufacturing processes to redesign castings originally designed for conventional manufacturing, while reducing the weight of the cast. Weight reduction without adjusting other important features of the castings has been usually achieved through the substitution of lightweight materials within conventional design configurations. In this study the weight reduction is accomplished by using features which are only possible to manufacture using additive manufacturing processes to make tooling for metal casting.

1.2 Background

1.2.1 Casting. Metal casting is manufacturing process where molten metal is poured into a mold, which contains a cavity of specific shape. Part created by solidifying of this substance inside the cavity is also called casting. To complete the process solidified part has to be ejected or broken out of the mold. This process is convenient when manufacturing parts of complex shapes, since other methods are either more expensive or not feasible. Casting process has two separate subsections where each of them is characterized by different methods. Non-expendable mold casting methods are as follows [2]:

- Continuous casting – widely used for high-volume production of metal (aluminium, copper and steel) parts with constant cross-section. Molten metal is poured into a cavity of water-cooled copper mold. This type of cooling allow to create a layer of solid metal on the inside surface of the mold cavity, whereas the center of the stream remains liquid. This type of metal casting is widely used due to its cost effectivity. [2]
• Centrifugal casting—also known as rotocasting. Advantage of this method is its independence of pressure and gravity, because the force feed is created by spinning the mold inside the centrifugal chamber. Results of this process are castings of almost any length thickness and diameter; usually flywheels, pipes and railway wheels. Typical materials used with this process are iron, steel, glass and different alloys of copper, aluminium and nickel. [3]

• Die casting – In this casting process the molten metal is forced into the cavities under high pressure. Materials involved in this casting method are mostly nonferrous metals, principally copper, zinc and some alloys of aluminium. This method is frequently used when casting parts with finer surface.[2]

Expendable mold casting involves the use of temporary molds. Methods are as follows:

• Sand casting – this is the most popular and simplest casting process. This process is generally used for small size operations. Depending on the sand used for making molds, this process allows to cast most of the metals. Green sand (wet) has almost no weight limitation for the part, whereas the molds using dry sand have part mass limit of 2300-2700kg. Sand grains are bonded together with chemical binders, clays and polymerized oils. Process is fairly cost-effective due to sand recycling.[4]

• Plaster mold casting – is very similar to sand casting except the molding material is plaster of paris. This process is regularly used for casting of small parts where smooth surface finish is required. Considerable disadvantage of this method is that it can only be used with low melting point non-ferrous metals (aluminium, copper, zinc). [4]

• Shell molding – similar process to sand casting, ideal for complex items of small or medium size. The molding cavity is formed by the hardened sand which is finer than the sand used for sand
casting and has a shape of the shell. Cast metals for this method include aluminium, magnesium, cast iron and copper alloys.[4]

- Investment casting – also known as lost-wax casting is considered to be the one of the oldest metal casting techniques. The process is characterized by pattern surrounded (invested) with a refractory material[5]
- Evaporative-pattern casting – this casting process uses pattern material that evaporate during the pouring of molten metal. Two familiar types of evaporative-pattern casting are lost-foam casting and full-mold casting[4]

1.2.2 Sand casting. Sand casting is a manufacturing process where sand is used as a molding material. It is known, that over 70% of all metal castings are created with this method [6]. Production rate of this method is low, because the sand mold is destroyed after each casting. However this method is widely used for casting parts with complex geometry. The process of sand casting involves mold-making, which includes pattern making, mold clamping, metal pouring, cooling, removal of the casting and machining. Each of these stages is briefly described below.

The initial phase in the sand casting process is the design of the mold. This step must be repeated for every casting. To create the mold, one must force the sand into each half of the flask called cope and drag. The sand is packed around the pattern, which represents the external shape of the desired casting part. In order to obtain the cavity, which will be filled by molten metal, the pattern must be removed from the sand mold. Any internal cavities of the part, which cannot be represented by the pattern, are composed by the cores which are made separately. A core box is fabricated which allows the molding of sand cores. The mold-production time depends on type of the mold, number of used cores and most important the size of the part. In order to maintain the shape of the mold during the casting process, the sand must be packed at specific temperature [7]. If the mold requires heating treatment, the time is
significantly extended. In order to ease the casting removal after the process, the surface of the cavity is often lubricated. This technique also enhances the surface finish and metal flow while pouring. Selection of the lubricant depends upon the sand type and temperature of the molten metal. The second stage of the process is mold clamping. At this point the cope and drag are secured together in order to prevent the loss of the material. Also the cores are positioned inside the mold. After this is done, the molten metal is poured into the mold. This step can be completed manually or by an automated machine. It is important to perform the pouring in short time to prevent early solidification of the metal. The next step in the process is cooling. During this stage the metal solidifies in the shape of the final casting. The cooling time depends on the type of the metal, its temperature and wall thickness of the casting. Shrinkage is a common defect that occurs at this stage. It is caused by non-uniform cooling. Moreover the low pouring temperature may cause unfiled sections inside the cavity [8]. After the cooling time elapsed, the mold can be opened. This can be done by vibrating machine that shakes the sand and casting out of the flask. Sand from casting molds and cores sometimes adheres to the surface of the casting. [6]In order to remove the sand particles from the surface shot blasting technique is used. The last step of sand casting process is machining. This step involves removal of the sprue, risers and runners which adhere to the part during solidifying process. Reconditioned scrap metal can be reused in next casting process. The detailed flow chart of metal casting process using sand molds is shown in Figure 1.

1.2.3 Mold design. Mold design plays a significant role in sand casting. For most of the cases, the mold consist of the cope – the upper half – and the drag – the bottom half. They are split by the parting line. In the traditional (non-3D printed) approach, both halves are incorporated inside the box called a flask. Cavities are formed by the patterns and internal surfaces of the casting by cores. Cores are usually made out of the sand due to easy removal after casting. Application of cores inside the mold cavity allow for production of castings with complex internal features.
Before the pouring, each core is fastened and positioned. This is accomplished by locking the core inside the cavity by chaplets. These are little metal anchors that are attached between the core and the cavity surface. The main reason for using chaplets is the tendency of cores to float in molten metal bath. Chaplets material must have higher melting point temperature than cast metal [8], otherwise they will melt during the casting and the cores could be moved. The excess material from chaplets is cut off after solidification. Figure 2 demonstrates the application of chaplets in sand casting process. In order to adjust the molten metal flow, specific features must be integrated into the mold design. The molten metal is poured into a pouring cup – large round-shaped cavity on top of the sand mold. Subsequently it flows through the main channel, called the sprue. Sprue is connected to series of channels called runners which deliver the molten metal into the cavity. At the end of each runner is gate which controls the flow rate and minimizes turbulence [8].

*Figure 1 Metal Casting process [44]*
To prevent shrinkage, chambers called risers are added to the system of channels. These provide an extra source of metal during the metal’s solidification process, when shrinkage occurs. Risers can be opened or invested inside the sand mold. To prevent early metal solidification within the riser, the tops of the open raisers are frequent covered with insulating material (refractory ceramic, exothermic mixture) [9]. Lastly, gas vents are important components of sand molds. They allow for gases to escape the cavity.

The sand that is utilized to make the molds is commonly silica sand ($\text{SiO}_2$) that is blended with binder, in order to preserve the shape of the mold cavity. The main advantage of using sand for mold making is its resistance to high temperatures. Depending on the sand mold preparation we differentiate four exceptional types of sand molds [8]:

- **Greensand mold** – sand mixed with water and binder or clay. Mixture consists of 90% sand, 7% binder or clay and 3% water. It is fairly inexpensive and widely used.
- **Skin-dried mold** – sand mixture is very similar to greensand compound, but additional bonding agent is added and cavity surface is dried by flame or infrared lamp to increase the strength of the mold. Molds created by this method are more expensive than greensand molds, thus they are used less frequently than green-sand molds.
• Dry sand mold – also known as cold box mold, sand is blended with organic binder. Baking the mold in the oven adds required strength to the mold. This mold technique is characterized by high dimensional accuracy.

• No-bake mold – sand is mixed with liquid resin and hardens at room temperature [10]

Sand used for metal casting is characterized by its grain size and shape, moisture content, strength, permeability (ability to vent gases), thermal stability, collapsibility and reusability. Typically, there are two types of sand used in metal casting involving sand casting:

• Naturally bonded sand – This type of sand is cost-effective, but contains several organic impurities that reduce the temperature of sand grain fusion, require a higher moisture content and lower the strength of the mold

• Synthetic sand – This is the laboratory-created type of the sand, starting from the pure sand base (SiO₂). Composition of the sand can be controlled. This implies higher strength, greater refractory strength and more permeability. This is the main reason why synthetic sand is preferred in metal sand casting. [10]

1.2.4 Tooling. Tooling process in sand casting deals with production of cores and patterns. Since this is a very important part of the process, a tool builder must have deep knowledge in foundry operations, especially in sand casting. In order to design the core or pattern, it is crucial to know the main function of the casting, be familiar with the metal flow during pouring, consider the shrinking and where it occurs while cooling and provide extra metal into these areas. Design of draft angles, parting line and amount of material for machining are also critical considerations while tooling process. The way how to build the pattern and cores is based on the shape and the complexity of the casting. This tool fabrication process is clearly illustrated in the Figure 3. At the beginning of the process is a 2D or 3D drawing of the casting provided by the customer. If traditional approach is preferred, tooling is created manually from hand
crafted prototypes of clay, wood or plastic [11]. When exact geometry capture is needed, part data are imported in the software and CNC machine will create the pattern shape by removing the material from the workpiece. Third option is the fast freeform fabrication. This process utilizes additive manufacturing technology, where tooling is created laying material in the layers on top of each other, resulting in desired part shape. Whereas two previous methods are good for parts with simple shapes, fast freeform fabrication process is good for cores and patterns with lots of blends, sweep and loft features. This method is possible only when 2D or 3D data of the part are provided. When deciding which tooling process is suitable for specific pattern or core, one must consider 3 aspects, cost of the method, its accuracy and lead time.

![Figure 3 Tool fabrication process [11]](image)

1.2.4.1 Cores. Cores are independent pieces of mold, which play a significant role in forming internal surfaces of the casting. They are usually made off sand bond together with organic binders or clay. However the organic binders are used more often than clay due to easier break down of sand after the
casting process. Core creation process starts by packing the sand in the core box (a), sometimes strengthen with metal rods, following with baking the core in the oven (c). This technique is performed in order to make the core structure stronger so it can be handled and resist the fluid flow of molten metal. The time spent in the oven and the baking temperatures are the crucial factors for appropriate core strength and collapsibility after the solidification [11]. Cores, which consist of more than one single part are assembled and glued together (d). Finally, the core surface is coated in order to improve the surface finish (e). Ultimately, cores should maintain their structure during the metal pouring and being capable of break down after the process. Except the traditional core making method in core box, cores can be made using CNC machines and also additive manufacturing techniques. Combination of these two processes can significantly reduce the core making time. Traditional core making process is displayed in Figure 4.

Figure 4 Core making process [11]
1.2.4.2 Patterns. Patterns are used in traditional sand casting in order to create the cavity inside the mold. W. Wang categorizes the patterns as follows [11]:

- Loose pattern – This type of pattern is replica of the original part, but design takes into account material which needs to be added due to the shrinking while cooling. Since this type of pattern can be produced quickly and cost effective it is often used for prototyping purposes. Loose patterns can be made of wood, metal, or plastic, sometimes wax.

- Gated pattern – In principle, a gated pattern is similar than loose pattern but gating system is incorporated in the pattern model. This feature allows saving time during the casting process, whereas in loose pattern the mold preparation time is prolonged by cutting the gating system manually. Moreover the metal flow and feeding while solidification is improved.

- Match-Plate Pattern – Match-Plate pattern is basically wooden or metal plate featuring cope side of the pattern on its top plane and drag side on the bottom. Gating system and parting line is often included in the design of the pattern. Although the production cost of this pattern is higher than previous two options, production rate and dimension accuracy are significantly improved. This method of pattern making is widely used for casting of small parts due to the weight and dimension limitations of the mold and flask.

- Cope and drag pattern – this version is similar than match-plate pattern, but cope and drag halves of the pattern are incorporated into separate plates. This option reduces the cycle time because each part of the mold can be packed at the same time. Disadvantage of this method is need for aligning the mold after packing, since both halves were created separately. To align cope and drag halves, set of guide pins and bushings is used. Despite this fact, cope and drag pattern method is used in high volume production, thanks to its time efficiency.
1.2.5 Defects in Sand Casting. Metal casting is a process where one may encounter risk of failure at any stage of the process. Most of the casting defects are connected with process parameters. Thus, to obtain no-defect results one must manage to control process parameters. Appropriate knowledge is needed to be able to control these parameters. The best way how to obtain this knowledge is analysis of casting defects. This analysis unveils root causes of the defects and provides solutions on how to reduce them and improve the casting. Referring to [12], casting defects are classified as follows:

1.2.5.1 Filling related defects

- **Blowhole** – Blowholes are the result of trapped gasses inside the metal casting during the solidification process. Blowholes are usually located on the cope side of the casting, since gases have lower density than molten metal they tend to upraise. The main causes of this casting defect are insufficient core venting, excessive amount of gasses released from core, low permeability of the sand and too high content of moisture in the sand. In order to eliminate this defect core venting has to be improved, amount of gases has to be reduced by reducing the amount of binder or using slow reacting binder, moisture content of the sand must be reduced and if necessary, coarser sand can be used to increase the permeability.

- **Sand burning** – Defect is characterized by sand adhering to the surface of the casting. Typical defect when casting thick-walled parts at high temperatures. High temperatures of molten metal cause sintering of bentonite and silicate components of the sand. The main causes include uneven mold packing, excessive pouring temperatures, uneven distribution of inflowing metal resulting in overheating, and low carbon content in clay-bonded molds. To overcome these problems increase portion of the carbon in clay-bonded molds, ensure uniform mold packing, reduce the amount of bentonite or use new silica sand, and reduce pouring rate and metal temperature.
• Sand inclusion – Sand inclusions look like small holes with sand grain on the inside surface of this hole. They usually form close to the casting surface and are hard to detect right after casting. Sand particles are often torn from the mold by the molten metal and then float to the surface of the casting. This can cause creation of metallic protuberances, which have to be removed. Sand inclusions which are trapped under the surface of the casting are usually detected during machining process. The main causes of this defect are uneven mold compaction, mold break-up during assembling and core setting, low core strength and core mismatching, excessive pouring rate with heavy impact against mold surface and too long pouring time. This defect can be eliminated by uniform mold compaction, using stronger cores with higher content of binder, avoiding core mismatching, avoiding high pouring rates and reduce the time of the pouring.

• Cold lap – This defect is characteristic by crack with round edges. It occurs when metal is not able to fill the mold cavity properly or when two metal streams do not merge together appropriately. This is often a result of low melting temperatures and wrong design of gating system. It is caused by lack of fluidity in metal stream or faulty gating system design. Adjusting the pouring temperature and modifying the mold design are two possible remedies for this defect.

• Gas porosity – Common problem when permeability of the mold is insufficient and gasses stayed trapped inside. This can be air which filled the cavity before pouring, dissolved hydrogen when casting aluminum alloys or moisture from die lubricants. Gas porosity is caused by slow metal pouring at low temperatures, interruptions during pouring and high gas pressure inside the mold resulting from redundant moisture content or low permeability. One can avoid this problem by increasing the metal pouring temperature, improving fluidity of the metal, ensuring appropriate mold venting and avoiding thin sections in casting design.
1.2.5.2 Shape related defects

- Mismatch – Mismatch is the problem of shifting the mold halves resulting in dislocation of the parting line. This problem can occur when cope and drag halves are not aligned and placed properly or when box pins are loose. Example of mismatch is shown in Figure 5. Defect can be eliminated by using appropriate molding box, closing pins and verifying the position of pattern on match plate.

![Figure 5 Mismatch](image_url)

- Flash defects – Flash defect is characterized as any excess metal attached to the casting after the process. This does not include gating system. Usually can be seen as a thin metal sheet at the parting line plane. There are many causes behind this problem. Most significant are damage to mold faces and die tools, cavity offset from center of the plane, inadequate mold clamping and excessive pressure when die casting. It is common in conventional casting for tall sprue molds.
where casting covers large area. Metal is forced into the cavity by hydrostatic pressure of the metal and sometimes culminate in the flash defect.

1.2.5.3 Thermal defects

- **Tear or crack** – Cracks are very common defect in casting. They vary in size from macro cracks to cracks which can be seen by naked eye. Possible causes of this defect are shrinkage, undercuts, thermal inequality in the die, insufficient draft angles, wrong design and high level of porosity. In order to prevent cracks one must reduce pouring temperature, implement chills into mold design, maintain sufficient cooling time and modify design to avoid undercuts and sharp corners.

- **Shrinkage** – This defect develops when there is not enough metal to fill gaps created while material shrinkage. Shrinkage can be classified into open shrinkage and closed shrinkage. Open shrinkage is opened to the atmosphere and is characterized by pipes and caved surfaces. Closed shrinkage occurs inside the casting at the places where still liquid metal is boarded by solidified metal. These areas are called hot spots and shrinkage occurs at the top of this area. The main reason why casting experiences shrinkage is the fact that molten metal has lower density than solidified metal. During transition from one phase to another it will shrink in size. Shrinkage can be prevented by providing molten metal into the cavity during solidification process.

- **Sink mark defects** – Sink mark is characterized as local shrinkage at thick section of the casting. It appears as a small depression on the surface of the part. This defect does not affect mechanical properties of the part. It is considered as a quality defect. Branch defect of sink mark is void. This is a hole enclosed inside the casting. It rises during the shrinking of molten metal bounded by the thin layer of already solidified metal resistant to shrinkage.
1.3 Rapid casting

It has been more than 25 years since sand casting industry started utilizing advantages of additive manufacturing. Additive manufacturing capabilities in metal casting are used in wide variety of industries including aerospace, automotive and electronics. Rapid casting is the adoption of additive manufacturing into the metal casting production process. This type of casting allows foundries to eliminate tooling from the process, since patterns or cores are manufactured in a matter of hours using this process. In this sub chapter I will explain additive manufacturing applications in investment casting and sand casting.

1.3.1 Additive manufacturing applications in investment casting

As briefly mentioned above, investment casting is the type of the casting where patterns are made of wax. The surface of these patterns is coated with refractory ceramic coatings in order to create a ceramic mold. The wax pattern is melted at temperature 140°C in autoclave. The mold is hardened, heated and metal is poured into preheated mold [13]. However, traditional investment casting has several limitations. In order to produce wax patterns, metal tooling for the injection of the wax is required. This is expense for prototyping and custom orders. Moreover, production of this metal tooling for wax patterns takes a significant amount of lead time. Implementing additive manufacturing into investment casting is called rapid investment casting (RIC). RIC allows reducing the cost of metal tooling for wax injection process. It also reduces the lead time. RIC follows three approaches shown in Figure 6 [14].

1.3.1.1 Direct fabrication of investment casting patterns

The first approach utilizes additive manufacturing techniques to produce wax or non-wax patterns for investment casting. Wax patterns, which can be used in investment casting, can be produced by selective laser sintering or fused deposition modeling methods, which will be described later in this chapter [14]. However, this approach is limited by the thickness and brittleness of the wax pattern. Non-
wax patterns dispose of strength, durability and they are suitable for thin section patterns. VAT
Photopolymerisation is another process for fabrication patterns using additive manufacturing. This method involves curing the liquid photopolymer by ultraviolet (UV) light. Build platform lowers after every photopolymer layer which was hardened by UV light. Material used for this process is UV curable photopolymer resin [42]. Another pattern making process is Material jetting. During this process the material is deposited onto the build platform layer by layer where it is cured using UV light. Materials used for this process include polymers such as polypropylene, acrylonitrile butadiene styrene (ABS) or poly methyl methacrylate (PMMA) [43].

![Figure 6 Rapid casting approaches in rapid investment casting](image)

Fused deposition modeling is based on creating the pattern directly from acrylonitrile-butadiene-styrene (ABS) and from wax material. This thermoplastic material is extruded from a print head at specified temperature to create rigid patterns with high geometry accuracy [15]. The pattern is attached to gating system and enclosed by coat of ceramic slurry in order to create ceramic shell mold. The shell mold is then baked in the fire furnace at 1093°C and the pattern is burned out leaving just small amount of ash.
in the shell mold. This ash can be rinsed out or removed by blowing high-pressure air inside the hollow shell. Advantages of this method are clean pattern burn-out, ease of pattern production and dimensional stability. Disadvantage is the roughness of the pattern surface. Therefore one must place importance on patterns surface finish preparation.

Selective laser sintering method is using CastForm polystyrene as a material for creating patterns. CastForm polystyrene is a low-ash pattern material that can be used for production of high-quality castings [14]. Objects are built by using laser to selectively fuse together successive layers of material. Selective laser sintering is one of the fastest and cost-effective methods for low-volume pattern production. This method of pattern making is divided into two steps: building the green part, and impregnating it with wax (Dotchev et al., 2007). Pattern is immersed in liquefied wax in order to infill surface pores and increases its strength. This technique was first used to produce parts for F1 car (suspension supports, clutch box, steering box, and transmission).

1.3.1.2 Mold fabrication for producing investment casting wax patterns

For high-volume production where large amount of investment casting wax patterns is used, it is suitable to exploit wax injection mold to create patterns. This method recognizes two approaches: direct and indirect tooling. Results of direct tooling are molds which have not used any intermediate steps for their production. However, post-processing is required in order to achieve strength, accuracy and surface finish. Molds are produced on additive manufacturing machines. This approach is suitable for medium to high-volume productions. Indirect tooling approach involves production of the mold using master pattern fabricated by additive manufacturing techniques. Practically, molds fabricated by this approach do not incorporate additive manufacturing advantages but utilize master patterns produced by this process. Indirect tooling approach starts with fabrication of master pattern, which is embedded in silicon rubber mold. After rubber cures, mold is cut along the parting line to remove the master
pattern. Cavity is subsequently filled with wax, resulting in wax pattern. Steps involved in this approach are shown in Figure 7 (from left to right CAD model of the pattern, fabricated master pattern, silicon rubber mold and final wax pattern for investment casting).

1.3.1.3 Direct fabrication of ceramic investment casting shell molds.

This approach is characterized by producing ceramic molds and cores directly from the CAD data.

Figure 7 Pattern-making steps involved in indirect tooling approach [14]

The main advantage of this approach is ability to remove wax pattern production, ceramic shell production, pattern combustion and baking the mold from the process. Process also reduces the cost and lead time and eliminates the possibility of core shifting, since mold and cores are produced as a single piece. Cores can be made hollow and thickness of the shell mold can be adjusted. This helps to adjust rate of heat transfer from the casting. Process is based on bonding the refractory powder with colloidal silica binder. The residual powder is removed and shell created by bonding process is baked in the furnace in order to produce rigid shell mold, which can be used for metal casting [14].

1.3.2 Additive manufacturing applications in sand casting

Patterns and cores were traditionally manufactured by workers which used 2D drawings of these parts. This process of hand-carving the pattern was time consuming and costly. Additive manufacturing processes allow fabricating of patterns, cores, gating system and molds for sand casting in shorter time and cost effective at the same time. Additive manufacturing contribution into sand casting is divided into three approaches. Direct tooling approach provides patterns which can be used directly in sand
molding process. Approach is suitable for small to medium production. On the other side, indirect tooling approach is convenient for large-volume production. Methodology of this approach is similar to the one in section 1.3.1.2., but urethane is poured into the cavity. Pattern less mold approach use additive manufacturing benefits for direct production of sand molds [14].

1.3.2.1 Direct tooling approach for fabrication sand casting patterns.

Patterns made by this approach are built by depositing layers of material (metal, thermoplastics, and ceramics) on top of each other following the CAD design data. One AM manufacturing method that could be used for direct tooling is laminated object manufacturing (LOM). LOM is additive manufacturing process where parts are built from layers of material (paper, plastic, metal) coated with thermally activated adhesive [16]. Material layers are cut by laser beam and bonded on top of previous layer by hot roller. After the process is finished, excessive material is removed and part is pulled out of the platform. Whereas in other additive manufacturing processes the print head follows the entire area of the part in corresponding layer, in Laminated object manufacturing the laser follows just outline of the cross section. This can significantly reduce the lead time. This technique is rarely these days. Fused deposition modeling (FDM) is another type of AM process used for the direct tooling. FDM allows designers to create the model of the part fast and easy so it can be checked for any geometry errors. Main supplier using FDM is company Stratasys. The methodology of the process consists in the material filament extrusion out of the nozzle and it’s deposition onto a platform which lowers during the deposition process. The nozzle moves in X-Y plane while depositing the hot filament onto the platform in thin layers, which bond together. After each deposited layer, the platform lowers relative to the thickness of the layer. This layer thickness varies from 0.050 – 0.250 mm. The second nozzle deposits different material which forms the support structure. This structure is removed after the process is completed. Materials used with FDM include ABS, elastomer, investment casting wax and polycarbonate
Another type of AM process for direct tooling, widely used by company 3D Systems, is MultiJet Printing (MJP). MJP is an inkjet printing process that uses piezo print head technology to deposit materials layer by layer. This process is known for its high resolution in Z-direction. 3D System’s MultiJet printers are capable of printing layers of thickness as low as 0.016 mm. Print head of MultiJet printer contains numbers of tiny nozzles in the X-Y plane over the platform. Print head nozzles dispense drops of thermo-plastic material across the area where the material has to be deposited. Hot drops of material bond to the previous layer forming the shape of the model. Support structure for the model is printed simultaneously with the model if it is needed. In order to achieve smooth part surface, toluene finish is available. Patterns made by this process are used in investment casting [17].

1.3.2.2 Direct fabrication of sand molds.

Using the additive manufacturing technology, this approach produces the molds and cores directly form CAD data of the part. There is no need for additional patterns or cores. Process of creating objects is similar than the one in direct tooling approach. Sand mixed with hardener is spread evenly on the platform and bonded in areas designated by CAD data with binding agent provided by print head. This process is also referred to as binder jetting, widely used by ExOne. Binder jetting process is AM process in which a liquid binding agent is selectively deposited to join powder particles. Layers of material are then bonded to form an object. The print head drops binder into the powder. The powder box lowers after each layer of deposited binder and new layer of powder is spread by feed roller. The final part is created through the layering of powder and binder. In sand casting the material used in binder jetting process is silica sand. Moreover, when the sand is used with the furan binder, molds are considered as no-bake molds. This means that cores and molds printed by this method are immediately ready for casting. Additionally, this process does not employ heat during the process. [18]. Advantages of this mold making process involves endless part and pattern geometry, high complexity of the part, no need
for support structures and no build plate is required. This reduces the production cost and lead time [14]. Process is shown in Figure 8.

**Figure 8 Binder Jetting process [46]**

1.4 Designing in metal casting

For good casting design the key factor is to understand the best combination of casting processes and technology. Geometric freedom of metal casting using 3D sand printed molds allows separate parts to be casted together. This improves the mechanical and material properties of the casting and also reduces the weight of the casting. According to [19] there are several parameters that have significant impact on casting design:

1. Fluid life – Also known as fluidity is a dynamic property of liquefied metal, which can change as the metal is poured from the pouring ladle and is flowing down the sprue through the runner into the mold cavity. Fluidity influences the main design of the casting, such as minimum thickness allowances, length of thin sections and ability to fill the hard-accessible areas in the mold.

2. Shrinkage while solidification – Design of the casting is affected by three types of solidification shrinkage. Liquid shrinkage occurs right before solidification process begins. Liquid-solid shrinkage occurs during the transformation from the liquid state into the solid state. This type of shrinkage varies from alloy to alloy and one must consider the optimal mold casting design.
accordingly. Pouring temperature also plays a significant role in amount of solidification. Last stage of shrinkage is called Patternmaker’s contraction. It occurs during cooling, after complete solidification of metal casting. After this stage the final shape of the casting with its final dimensions is revealed. Therefore when designing pattern one must consider the casting shrinkage away from the mold walls.

3. Slag/Dross formation – These terms refer to residue left behind after the melting process of metals. Slag is typically waste produced during the melting of non-ferrous metals of high melting point. This waste contains liquid non-metallic particles which are the result of alloying and oxidation. Dross layer is typically the layer of residue formed at the top of the molten metal. There are few methods how to remove the non-metallic components from molten metal. Alloys with high fluid live can be poured through the ceramic filter, which reduces the amount of non-metallic inclusions. Another method is the melting and pouring in the vacuum, typically used when casting titanium alloys.

4. Pouring temperature – The design of mold and molding process is dependent on refractory characteristics of mold material. Patterns of casting geometry are very important when pouring temperature is close to the refractory limit of the mold. Pouring temperature determines what kind of molding material can be used. The most used molding materials are sands and ceramic, because their refractory limits are around 1650°C - 1820°C. Permanent metal molds designs are limited by maximum refractory limit which is about 1180°C.

During the structural design of specific part, designer is considering forces acting on the part and calculating appropriate stress and deflection. These features are affected by material, but choosing the geometry is the key factor of good casting design. Improvements of modeling software allow designers to evaluate stress and strain levels of desired geometry using Finite Element Analysis (FEA). This geometry can be further optimized based on the results of the analysis. However, resulting geometry
must be considered from casting point of view. This often results in increase of the cost or complete redesign of the model. A good way how to overcome this problem is the geometry compromise between structural and casting requirements. To achieve this compromise casting designers same as structural designers use software for simulation of mold filling and solidification process.

1.5 Designing in additive manufacturing

Before applying advantages of the additive manufacturing one must know their manufacturing capabilities and manufacturing constrains. Through different manufacturing principle than in milling or turning, additive manufacturing can be used to produce any geometrical feature. The slicing of the feature and building of a one section at a time helps to reduce complex 3D geometries into 2D production steps and facilitate the fabrication of complex parts [1]. Significant part of designing is the enforcement of lightweight designs. Manufacturers use the structural optimization tools in order to achieve such designs. Combination of topological optimization with lattice structure, appear to be the optimal choice for lightweighting. Topological optimization numerically determines the volume of the part which is structurally relevant to the given design space [20]. Results of topological optimization are rough designs that require further refinement and verification of the geometry and mechanical properties. The intent of designing process is to provide methodology of design while taking the advantage of additive manufacturing. This methodology has four stages. The first stage deals with analysis of specification of the part. Second stage is proposal of several rough geometries. According to the manufacturing constraints and requirements specified in the first stage, rough geometries are optimized in the third stage. The last stage involves validation of the proposed design [1]. This chapter provides detailed description of these stages on the single-part example.

1. Analysis of the specifications – Part is characterized by the set of functional surfaces, clearing volume and specified behavior. The functional surfaces serve to assemble the part with other
parts, they transmit thermal and mechanical loads and when needed they serve as a watertight surfaces. Clearing volume defines the space for part material in such manner that part is not in collision with other parts in the assembly. Specified performance of the part is defined by mechanical or thermal properties. These are later verified with FEA. According to the part performance and the selection of the manufacturing process, the part material is chosen.

Example of the redesign using additive manufacturing will be demonstrated on square bracket, which was fabricated on 5-axis milling machine. Bracket is fabricated from two perpendicular planes that serve as functional surfaces. Each plane has eight holes for mounting the bracket. Faces exhibit mechanical loads that tend to close the bracket. As seen from the Figure 9, two extra ribs were added to provide additional support to the bracket [1]. The new redesigned part has to withstand the same mechanical loads while maintaining the same maximal displacement values.

2. Initial geometry proposal – The purpose of this stage is proposal of one or more rough geometries. Based on the [1], there are couple methods how to choose this geometry: expert-based and automated method. Expert-based method is often ineffective, because senior engineers are influenced by the experience and tend to stick to their existing design concepts. The automated method uses topological optimization to find the initial rough geometry.

Designer has to define the functional surfaces of the part, their geometry, maximum volume of the part and mechanical behavior. In bracket example functional surfaces are defined by two perpendicular planes with eight holes in each of them. The mechanical load is represented by the distributed force on the back side of the plate, as can be seen form the Figure 10a. Since part has to withstand the mechanical load and be light at the same time functional surfaces must be connected. To maintain lightweight design, thin walls have been proposed. Figure 10b
shows variable designs for three and five thin walls, since the wall dimensioning wasn’t done at this stage.

Figure 9 Original design of square bracket [1]

Figure 10 Initial geometry proposal (a) functional surfaces and mechanical load (b) cross sections of proposed design [1]
3. Definition of parameters and optimization – To optimize the original geometry of the part, proper parameters have to be defined. For the bracket example the outer dimensioning are defined, but thickness of the functional surfaces, thickness of the walls, position of the walls and fillet of the radii must be specified. The aim of the optimization is to reduce the weight and minimize the volume while take into account the specified behavior. This can be accomplished by various optimizing software. Parameters are optimized in order to obtain minimum volume part, which can withstand the same mechanical loads as original. After every iteration of the process, software verifies if the part complies with the specified behavior. This method is difficult on computational time, especially when design contains complex lattice structure [1]. Figure 11 shows resulting design of the bracket example.

![New design of the bracket](image)

**Figure 11** New design of the bracket [1]

However, the software calculates the optimal material allocation according to the set parameters and specified behavior, but final design manufacturability might be not possible. Therefore, it is the designer’s responsibility to interpret the optimized design and convert it into the lightweight design capable of manufacturing [20]. An example is shown in Figure 12. A
bracket, originally made of aluminium was redesigned and optimization result was remodeled in CAD software to achieve appropriate geometry.

![Redesigning process](image)

**Figure 12 Redesigning process [20]**

4. Validation of the geometry – The last stage of the redesigning process is validation of the optimized design. Part is evaluated from manufacturing point of view. This is accomplished by simulating the deposition of the material as well as thermal simulation of every step during the process. Due to the limitations in software computations, designs are often validated by direct manufacture of the part and measurement conducting.

### 1.6 Weight and fuel savings calculations

Vehicle travel associated cost are dependent on many factors such as distance traveled, load of the vehicle, speed at which is the vehicle traveling, condition of the road, fuel consumption, etc. Considering the transportation cost, fuel consumption mainly depends on distance traveled and load of the vehicle. For instance, transportation cost of a fully loaded vehicle is always more than cost of empty vehicle when traveling along the same road [21]. As can be seen from the Figure 13 load of the vehicle has significant impact on fuel costs. This figure represents distance traveled per unit of fuel dependent on weight of the vehicle. Data are collected form four different types of vehicles. Manual transmission (MT) vehicle data are displayed with yellow color, automatic transmission (AT) with pink color,
continuously variable transmission (CVT) data are green and hybrid vehicle data are displayed blue. According to the report published by the Ministry of Land, Infrastructure, Transport and Tourism of Japan, the distance traveled per volume unit of fuel is strongly correlated to vehicle’s gross weight, as can be seen from Figure 13 (Yiyong Xiao, 2011). In order to process the data form Figure 13 the result of discrete point was estimated and represented by red line with square mark in Figure 14 [22].

![Figure 13 Statistic data on vehicle's traveled distance per unit of fuel dependent on vehicle weight](image)

Further data from Figure 14 were directly extracted and by linear regression a new set of data was obtained. The linear regression by [22] is formulated as follows:

\[ Y = 0.0000793X - 0.02 \]  

Eq. 1
Figure 14 Estimated result of discrete data points form Figure 13 [47]

Figure 15 Fuel consumption rate dependent on vehicle weight [47]
This resulting set is displayed on Figure 15 as a green line with blue dots, together with the original fuel consumption rate data from Figure 14. However, axis notation of Figure 15 is different than notation of previous figures. X coordinate represents the vehicle weight in kilograms and Y coordinate represents fuel consumption rate in liters per kilometer of distance.

1.7 Research Objectives

1.7.1 Rationale for the Study

Reducing the weight of automobiles and vehicles has been of interest for many years. The main reason for weight reduction—or lightweighting is the desire to optimize the fuel economy resulting in lower costs. Corporate Average Fuel Economy (CAFÉ) standards are United States regulations that deal with improving fuel economy of cars and light trucks produced in the United States [23]. These regulations were established by Congress in 1975. In the past the lightweighting process has been considered just as a material replacement. Weight reduction was achieved by replacing original material with lighter alternatives. Now, the weight reduction process involves material replacement and also changing the structural shape of the part (I-beams, tubular members, lattice structures) [21]. This was not possible in the past due to the level of casting and designing technology. Computer analysis software allows designing complex-shaped parts that are evaluated and optimized and modern casting technologies allow the production of these parts. When considering optimization of the shape of specific part, part data must be provided in order to redesign it. If data are missing, they are obtained through reverse engineering of original part. Part is scanned with 3D-scanner and data are later processed in CAD software. Starting with the original shape, several new designs are proposed and evaluated. The result of this process is redesigned part, which weight is reduced in compare with original part.
1.7.2 Hypothesis

The aim of this research is to redesign engine parts using advantages of 3D sand printed molds resulting in weight and fuel savings. As provided in [24], 3D sand printing provides manufacturers with ability to cast parts with almost unlimited complexity. Complex designs of engine blocks, cylinder heads and intake manifolds are fabricated by conventional metal casting process, but 3D sand-printed molds provide advantages when it comes to designing racing engines and prototyping. This is the moment when 3D sand printing technology tends to be more feasible than conventional casting when designing or redesigning car engine. In order to reduce the weight of the engine parts reverse engineering process is used. To preserve the important features of the engine, the casting has to be scanned and CAD model is created. Subsequently the casting can be redesigned. Comparing the original casting and redesigned casting the calculations for weight and fuel savings can be made.

1.7.3 Analysis goals

This research was performed in order to reach four main goals. First goal was to redesign engine castings taking advantage of 3D sand printing. This step was achieved by scanning the original castings and modifying their parametric models. Since 3D scanner could capture just outer geometry of the scanned object, castings were further modified in CAD software where they were also redesigned using advantages of 3D sand printed molds for metal casting. Second goal of this thesis was to calculate weight savings achieved by redesigning castings. This step was performed by evaluating the weight of the original parts in CAD software and then compared with the weight of the redesigned parts. Next goal was to calculate resulting fuel savings of redesigned engine. Calculation of fuel savings involves just the weight reduction, not engine performance optimization. One part of the fuel calculation step was to extrapolate the calculated fuel savings across the fleet of the light weight Chevrolet trucks and provide
implications. The last goal of the research was validation of proposed design of connecting rod. The design was evaluated by FEA of connecting rod model in static structural analysis.
Chapter 2 Methodology

In order to accomplish the research goals first the engine for redesign had to be identified. To identify the type of engine, cylinder head model and intake manifold, the casting number from each part was recorded. Engine block casting number is 14093638, cylinder head casting number is 14102188 and casting number of intake manifold is 3905393. [25] This engine was not pulled out of the Chevrolet truck.

2.1 Engine identification and disassembly

Based on the numbers on the engine block, cylinder heads and intake manifold the engine was identified as a Chevrolet Small Block V-8 350 (5.7L). This engine belongs to a series of V-8 engines produced by the Chevrolet division of General Motors Corporation. Engine was designed by leading engineer Ed Cole. Besides the Chevrolet brand, this engine was used by many manufactures including Buick, Cadillac, Oldsmobile and Pontiac. This type of engine was installed in commercial vehicles, station wagons, sports cars, boats and even airplanes. However, the airplane version of this engine was highly modified. The 350 small block came in many variants. The L46 version was used in 1969 Chevrolet Corvette, and the L48 version was used in Super Sport version of Chevrolet Camaro. The engine chosen for redesign has a version number LT-9. This engine was installed in Chevrolet K20 and K30 pickup trucks, rarely in motorhomes and stepvans. The production years were from 1981 – 1986. Engine could provide 160 break horsepower (bhp) at 3800 rpm and torque of 250 lb-ft at 2800 rpm. Compression ratio of the engine was 8.3:1. Engine was equipped with quadrajet cylinder heads and swirl port intake manifold [26, 27]. Once the engine was identified the engine assembly was disassembled. Parts considered for redesign involve cylinder heads, intake manifold and piston assembly (piston, Gudgeon pin and Connecting rod). Original engine assembly is shown in Figure 16. Disassemble process started with removing the piping responsible for coolant fluid feed to the engine and piping responsible for
outgoing exhaust gasses. Process followed with unbolting the exhaust manifolds, valve covers, air filter, spark plugs and distributor cap. Once the carburetor was detached, the intake manifold could be separated.

2.1.1 Intake manifold

Intake manifold also referred as inlet manifold is set of tubes which are attached to engine block, cylinder heads and carburetor (for engines without direct fuel injection). This engine part is responsible for distribution of fuel – air mixture into the cylinders. It must be however properly designed. When the intake valve on the specific cylinder is open, fuel – air mixture is being sucked into the cylinder through the intake manifold tubes. After the valve shuts the inlet, incoming air forms a high-pressure wave which travels to the end of the intake runner, where it bounces and travels back down the runner. If the
runner has proper length, pressure wave arrives back to the intake valve just at the moment of opening for next cycle [28]. Intake manifold considered for redesign is shown in the Figure 17.

![Figure 17 Chevy 350 intake manifold](image)

**2.1.2 Cylinder head**

The cylinder head is mounted directly on top of the engine block and sealed by head gasket. This engine part feeds fuel–air mixture directly into the cylinder and also allows exhaust gases to escape from the engine. It is formed by passages called ports or tracts, which deliver fuel–air mixture from intake manifold to the inlet valve of the head. They also allow exhaust gases to travel form exhaust valve to the exhaust manifold. The number of cylinder heads for one engine may vary. Inline engines are usually equipped with one cylinder head which provides fuel–air mixture to the cylinders [29]. However, V–engines has cylinders aligned to the shape of letter V, so they are equipped with two cylinder heads.
Chevy 350 engine has 8 cylinders arranged in V – 8 formation with four cylinders on each side of the engine. One of the cylinder heads for this engine is shown in Figure 18.

![Figure 18 Chevy 350 Cylinder head](image)

2.1.3 Engine block

Engine block also known as cylinder block is part of the engine which incorporates cylinders and passages for coolant fluid flow, intake and exhaust passages and crankcase [30]. As said before, V – engines are separated into two cylinder sides called cylinder banks. Each bank comprises one or more cylinders. Furthermore cylinder blocks are divided into two groups, based on their design. Wet liner cylinder block design incorporates entirely removable cylinder walls. This design is preferred by some European manufacturers. On the other hand dry liner design features cylinder walls which are inserted into the engine block[30].
2.1.4 Exhaust manifold, Piston assembly

The exhaust manifold gathers exhaust gases from cylinders into one pipe. This engine part used to be cast in the past, but due to the lightweighting, exhaust manifolds or also known as headers are now fabricated from steel tubes. Exhaust manifold of Chevy 350 engine has been cast and is significantly heavier than manifolds produced these days. Replacing this casted manifold by one made of steel tubes would rapidly reduce the weight. Purpose of this research is to reduce the weight of the engine using advantages of 3D sand printing. Since replacing the manifold is not part of this research although it would made engine lighter, it is not considered for redesign. The original manifold can be seen in Figure 19. The piston assembly is very important component of the combustion engine. Together with the connecting rod the purpose of the assembly is to transfer translational motion of the piston head into rotational motion of the crank shaft. Later in this thesis the connecting rod will be one of the main subjects intended for redesign. Lattice structure in various forms will be implemented into the design to reduce the weight of the rod and also overall weight of the engine. The original piston assembly from Chevy 350 Small Block engine is shown in Figure 20.

2.2 Obtaining CAD data

As was mentioned before, when doing reverse engineering of one part or assembly of parts, drafts, blueprints or set of CAD data must be provided in order to recreate the part in CAD environment. Since the Chevy 350 engine was not provided with CAD data the castings and other parts of the engine had to be reverse engineered. This means that parts had to be measured manually and then drawn in CAD software or 3D scanned. The cylinder heads and intake manifold were too complex for manual measurements and therefore they were scanned in order to obtain exact surface geometry. However, parts like pistons, connecting rods, intake or exhaust valves, and exhaust manifold have less complex geometry and I was able to draw them in CAD software. The CAD software used for these drawing was Solid Works from company Dassault Systems. This is 3D modeling software that can turn a design idea
into a 3D model. The software is designed to work with a solid object, create the assemblies of these objects, and perform analysis of proposed designs. It can also handle work with surfaces and sheet
metal. The primary use of Solid Works in this thesis was to design less complicated parts of the engine and also modified parts of the engine which were identified for redesign. This also includes parts which were scanned in other software and were later imported into Solid Works for modification. The drawing process started with intake and exhaust valves since they have simple geometry. Outside diameters were measured at different cross sections then sketched and revolved around the axis of the valve to obtain a solid feature. The same technique was applied to draw both valves. The next suitable part for drawing was exhaust manifold. To draw the same geometry part in Solid Works Vernier Calipers were used to obtain dimensions of the part by measuring it at various cross sections. Once the dimensions were set the sketches of the cross sections could be drawn and then the loft function used to obtain the shape of original exhaust manifold. The loft function creates a Solid Works feature by making transition between two or more sketch profiles. It can be base, boss, cut or surface. To create a solid loft, the starting and ending profile of the feature must be model faces created by split lines. When creating a new loft feature, the desired sketch contours must be highlighted in profile window and guide curves may be specified in guide curves window. If no guide curve is selected, Solid Works will automatically suggest the shortest-path guide curve. However, in this case the user is asked to manipulate the start and end points of the guide curve. Proper alignment of these points determines the loft feature shape. Moreover, when designing parts like the intake or exhaust manifolds, transitions between different loft features must be smooth. In order to create smooth transitions between loft features, the user has to set the start and end constraint of guide curve normal to sketch profile of the feature. The exhaust manifold was designed using Loft, Cut-Loft, Boss-Extrude or Cut-Extrude and Shell features. Cut-Loft feature works similarly as the Loft feature, the only difference is that this feature removes the material from the model. Boss-Extrude and Cut-Extrude features add or remove the material normal to the profile, specified by sketch geometry. Shell is a specific feature used for the design of the pipes. When designing the exhaust manifold, the user has to look at it as a set of pipes. Outer geometry was created
by the Loft feature, but cross section was filled with material. By using Shell feature user can specify faces, where the feature will create the hollow pipe. Important parameter is the shell thickness, which specifies the thickness of the exhaust manifold. This was set to 3 mm. Once the main geometry of the manifold was created, sharp edges were filleted. The resulting geometry is shown in Figure 21 together with applying the Shell feature to the starting and ending faces of manifold.

Figure 21 Shell feature demonstration and final exhaust manifold

Another engine part which was easier to draw than scan was the piston assembly. The piston assembly consists of Connecting rod, Gudgeon pin and piston itself. The whole assembly has been drawn in Solid
Works. Starting with the piston part, I used Boss-Extrude, Cut-Extrude, Revolve and Cut-Revolve, Chamfer and Fillet features. As mentioned before, Fillet feature smooths out the sharp edges and Chamfer feature creates a bevel feature along an edge or chain of the tangent edges. In order to maintain geometry and draw exact copy of original piston design a caliper was used to obtain dimensions from the original piston part by measuring it with caliper. The next part of the assembly is the Gudgeon pin. Part was modeled by extruding the profile sketch and chamfering the edges. The last part of the piston assembly is the connecting rod. Dimensions for the CAD model of the connecting rod were obtained in a similar way as the dimensions for previous parts. Features of the model involve the same features as used before and in addition Variable Fillet. This feature had to be used because of complexity of edges where value of the fillet varies along the edge. Since this particular part is the object of redesign, the material properties for this part are given in the following table.

**Table 1 Properties of Connecting rod**

<table>
<thead>
<tr>
<th></th>
<th>Metric</th>
<th>Imperial</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Material used</strong></td>
<td>ASTM 100-70-03(ISO 700-2, EN-JS 1070) Ductile Cast Iron</td>
<td></td>
</tr>
<tr>
<td><strong>Units</strong></td>
<td>Metric</td>
<td>Imperial</td>
</tr>
<tr>
<td><strong>Mass</strong></td>
<td>500.68g</td>
<td>1.104lb</td>
</tr>
<tr>
<td><strong>Volume</strong></td>
<td>69538.8 mm³</td>
<td>4.24in³</td>
</tr>
<tr>
<td><strong>Density</strong></td>
<td>7200 g/mm³</td>
<td>449.5lb/ft³</td>
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<tr>
<td><strong>Small end inner diameter</strong></td>
<td>26.99mm</td>
<td>1.06in</td>
</tr>
<tr>
<td><strong>Big end inner diameter</strong></td>
<td>56mm</td>
<td>2.20in</td>
</tr>
<tr>
<td><strong>Center to center length</strong></td>
<td>145mm</td>
<td>5.7in</td>
</tr>
</tbody>
</table>
2.3 Obtaining scan data

As was mentioned before, certain parts of the engine have very complex surfaces and to capture their exact geometry by caliper is almost impossible. Therefore the Capture 3D scanner from 3D Systems was used to capture the surface geometry of these parts. The Capture structured light 3D scanner is compatible with Geomagic Design X and Geomagic Capture software. This 3D scanner uses blue light with structured lines to scan across the object. Scanner projects a series of linear patterns onto an object and using trigonometric triangulation and examining the edges of each line in the pattern, system calculates the distance from the scanner to the surface of the object. This is a high resolution scanner with low noise image production. Capture capabilities are sensitive to surface finish and lighting of the scanned object [31]. Scanner specifications are provided in the table below.

Table 2 Scanner specifications [48]

<table>
<thead>
<tr>
<th>System Configurations</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scan Speed</td>
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<tr>
<td>Field of View (diagonal)/Near End - Far End</td>
<td>172 – 260 mm</td>
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<tr>
<td>Field of View (X-Y)/Near End - Far End</td>
<td>124 x 120 mm – 192 x 175 mm</td>
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<td>Clearance distance</td>
<td>300 mm</td>
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<tr>
<td>Depth of Field</td>
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<td>Resolution</td>
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<td>Average Points</td>
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<td>Average Polygons</td>
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<td>Point to Point Distance</td>
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<td>Accuracy / Near End – Far End</td>
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<td>Calibration</td>
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</tr>
</tbody>
</table>
There were 2 engine parts considered for scanning with the structured light 3D scanner. Both, the intake manifold and cylinder head have complex shapes and can be transformed into CAD software by using 3D scanning technology. In order to achieve good geometry capture accuracy manifold was coated with white color to underline contrast between scanned object and black background.

2.3.1 Scan aligning

Every scan process starts with capturing several scans of the object. Number of scans depends on the part size and complexity. The intake manifold and the cylinder head were captured with 50-75 different scans. Based on the lighting conditions in room the exposure was adjusted. Scan resolution was set to medium and device registration was set to target markers. For better registration and scan aligning, the target markers in the shape of circle were glued on the surface of the manifold as can be seen from Figure 17. Scanning process starts with capturing several different scans, each very close to the previous one. This technique significantly improved scan registration process and reduced scan aligning time. The registration process aligns scans by overlapping and aligning common areas of neighboring scans. The user has to pick 3 or more points from each of two scans he or she wants to align. The methodology of aligning and picking points for the best possible results is as follows:

- Pick 4 to 8 points – Aligned mesh surface can be obtained by picking 3 nodes from each scan and aligning these scans. However, at this setup, the mesh results are very coarse and inaccurate. Scan alignment accuracy increases with picking more significant points. This approach however significantly increases the overall alignment time, and by very complex parts like engine cylinder head it can reach up to 24 hours. Thus the important skill for aligning process is to know the balance between good aligned scan and working time.

- Pick significant surface features – In order to achieve good alignment of two scans the distance between pick-points must be as short as possible. The best approach how to achieve this is to
pick significant features (surface imperfections like dimples, dents, crumbs, bulges) of the surface, which are included in both surface scans.

- **Data merging after each scan** – When merging scan data in Mesh Buildup menu the best possible alignment is achieved by merging the data of scan with merged data of previous scans and repeat this procedure for every next scan.

After all the scans were aligned and unwanted geometry data were removed, a mesh structure was created. This mesh structure contains several millions of polygons as a result from scanning process. Since the resolution of the scanner is almost 2 million of polygons per scan, the resulting mesh feature was represented by almost 90 million surface polygons. This resolution was higher than required. Therefore this number was decimated down to 5 – 10 million polygons per part. Even though the geometry capture accuracy was optimized by painting the part and scanning on contrast base, some portions of part’s surface remain uncovered. This was caused either by light reflection from shiny surface or by complexity of the part. The mesh surface of intake manifold results in less geometry flaws and mesh holes, while complex geometry of cylinder head in spring valve area disclose wider uncovered area. For further process and data import in CAD software these mesh holes have to be closed.

2.3.2 Hole filling

The process of filling holes in mesh structure has a significant impact on parametric surface generation process. Simultaneously, the parametric surface cannot be extracted from the mesh surface as long as there are holes in the mesh structure. These holes vary in size, but closing process is same for all of them. Also there is a certain skill level needed for closing holes and it has to be acquired to close the holes properly. There are two main settings in the closing holes menu. The Flat hole command is suitable for holes which are at flat surface. Holes at curved surfaces have to be filled with curvature method of filling. This option has intensive requirements to fill such holes. The flatness level of filled
holed can be adjusted. This method is good for holes of area no larger than one square inch. Trying to fill larger holes than that may lead to a corrupted and bulked surface mesh. For closing the bigger holes the bridge feature was used. This feature allows connecting two mesh nodes at the boundary of the hole. The surface area of the hole is getting smaller by creating bridges and hole filling process is more controlled. Another purpose of using the bridge feature is to obtain uniform area for the hole filling process. An example of using direct hole filling and bridge method is shown in Figure 22. The direct hole filling process at an appropriate level of surface curvature setting not only created an additional bulge but it also failed to fill certain gaps in the hole shown in red circle. The hole filling process controlled by bridges helped to eliminate additional bulge at the sharp edge and also succeeded in filling the hole at once. An important fact to understand here is the time spent by creating additional bridges. A hole can be closed by using certain number of bridges, and this number may vary from 1 to infinity. In order to use the time effectively the designer has to obtain certain skill in creating bridges. Otherwise the result consists of unwanted bulges and dimples, and the hole closing time might take more time than required. During the hole closing process features like Add bridge, Fill gulf, Remove peninsula, Remove island and Delete polyface were used. Fill gulf feature was used to fill certain gulfs in the hole. Remove peninsula feature could remove unwanted mesh data in order to obtain uniform hole boundary. Randomly scattered data in the model were removed by Remove island feature. Delete polyface feature is designed to delete any polygons in the selection area. Bulge geometries in my models were added to quick fill the gaps which will be later modified in Solid Works.

2.3.3 Surfacing

Once all the holes of the model were filled, the model was globally remeshed to create a water tight mesh. This step is required before extracting parametric surface from the mesh structure. Moreover, the model was segmented into regions to help align the model into reference planes. Once this was done parametric surface was extracted from the mesh structure [32]. This step is shown in Figure 23 for both
parts, cylinder head and intake manifold. The parametric surface is displayed with a yellow color, mesh structure with blue dots representing nodes in the structure.

Figure 22 Hole filling process - top left - original hole, bottom left – direct hole filling with bulge fault and unfilled gaps, top right - proposed bridge design, bottom right - result of filling using bridge structure
Bulges and dimples in the surface are just temporary. They will be eliminated in Solid Works while cutting inner tubes. The success of this step depends on the hole filling process. If there was any intersecting geometry left in the model, the parametric surface was extracted with flaws or the extraction totally failed. In the Surface menu the mesh was set to the mechanical instead of organic which is good for 3D structures of bones. Geometry capture accuracy was set to the maximum. The extracted surface however does not contain interior tubes for air–fuel mixture, water cooling, and exhaust gases. Thus the surface was imported into Solid Works for further modifications.

Figure 23 Surface extraction process
2.3.4 Solid Works modifications and redesign

This chapter describes modifications of parametric surfaces obtained from Geomagic Design X software and methods used for redesign of 3 specific parts: intake manifold, cylinder head and connecting rod. First, the feature modifications of cylinder head and intake manifold will be described, and then the weight saving redesign of these two parts, following with redesign of connecting rod will be discussed. Final designs are described in the Chapter 3 (Results).

Parametric surfaces were imported from Geomagic Design X into Solid Works. This step was done by direct Live Transfer option in Geomagic software. Result of this transfer was Solid Works parametric surface, but with some missing features. The part surface was divided into small surfaces which size was determined in parametric surface generation step. Some of these surfaces were not imported properly and had to be replaced. Solid Works has a diagnostic feature for surfaces imported from other CAD environments. This feature was used to determine the size and location of missed surface so it could be patched. Once the surface was complete, the solid model was generated. Both parts have inside channels for flow of cooling water, exhaust gases and mixture of fuel and air. Location and geometry of most of the channels was easy to determine. There were few channels where a back lighting method was used to determine their geometry. This method consists in lighting the interior of the channel with a strong light source and determining the corresponding inlets and outlets of the channel. Using the Cut-Loft, Boss-Extrude and Fillet features, following the contours of the channels and maintaining the minimum wall thickness of original casting 3mm, the interior channels were created. As was mentioned before, for the surface import into Solid Works all of the surface holes and gaps had to be closed. This involved also bolt holes and openings for carburetor. These components were recreated by using the feature Extruded-Cut. Also for the best possible scanning results of the cylinder head studs holding the rocker arm pivots were cut-off. Using the Solid Works feature Boss-Extrude these studs were
incorporated back into the model. The final CAD models of the cylinder head and the intake manifold are shown in Figure 24 and Figure 25.

Figure 24 CAD model of Cylinder head
The requirement of the new design was weight reduction and implementation of the sand casting process involving 3D sand-printed molds. Both the cylinder head casting and the intake manifold casting can be cast with a conventional casting method by implementing temporary cores which can be shaken off after the casting solidifies. Considering casting all three parts (intake manifold and two cylinder heads).
heads) together as one casting will be costly and ineffective by using conventional casting methods. Nonetheless, this is possible by using 3D sand printed mold and cores. This thesis looks at the weight reduction by implementing 3D sand printing process so a new design was considered as a one casting merging intake manifold with cylinder heads on sides. Besides the undercuts and 0° draft angles used in the new design, significant amount of weight was reduced by eliminating bolt brackets used for joining these parts together when cast separately. The new design and properties of the part are described in Chapter 3 (Results). New design of connecting rod consists of lattice implementation into the web of I beam. Lattice structure is design element which can be cast by using 3D sand printing. In connecting rod design it helped to reduce the weight of the rod. 7 different designs were proposed, concluding in a final lattice design which is described in Chapter 3 (Results). Since this part is exposed to high forces, design geometry was validated with Finite Element Analysis (FEA).

2.4 FEA of Connecting rod

Following the four steps process of part optimization, after analysis of the specification of the connecting rod and initial design proposal, the connecting rod design was optimized and a new design was validated with FEA using Ansys software. Six proposed designs of connecting rod were evaluated by FEA as unacceptable. Designs developed deflection and stresses higher than acceptable. The material used for new design was the same as used for the original, which is ASTM 100-70-03 Ductile Cast Iron [33]. This material has very good castability properties and is also suitable for casting thin lattice features. Mechanical properties of the connecting rod material are provided in the table below. FEA analysis was performed to show that new connecting rod design can resist the forces occurred inside the cylinder. As provided in [34] the maximal load exerted on the connecting rod is compressive load during the power stroke and has value of 17,000N. Therefore the analysis was performed at this condition evaluate the design at the moment of maximal possible stress and deflection. Boundary conditions of the analysis and setup are shown in Figure 26. Fixed support condition was applied to the
crank end of the connecting rod [35]. A bearing load of 17,000N was applied at the pin end of the connecting rod. The element size of the mesh was set to 0.8mm. After generating the mesh, model was represented by 488,907 nodes and 301,310 tetrahedron elements.

Table 3 Material properties of ASTM 100-70-03 Ductile Cast Iron

<table>
<thead>
<tr>
<th>Material</th>
<th>ASTM 100-70-03</th>
</tr>
</thead>
<tbody>
<tr>
<td>Units</td>
<td>Metric</td>
</tr>
<tr>
<td>Density</td>
<td>7.2 g/cm³</td>
</tr>
<tr>
<td>Young’s Modulus</td>
<td>180 GPa</td>
</tr>
<tr>
<td>Tensile Ultimate Strength</td>
<td>690 MPa</td>
</tr>
<tr>
<td>Tensile Yield Strength</td>
<td>480 MPa</td>
</tr>
</tbody>
</table>

Figure 26 FEA boundary conditions of connecting rod
2.5 Weight and fuel savings

By redesigning the engine parts overall weight was reduced. The resulting fuel savings can be calculated by knowing the weight of the truck and using Equation 1 from Chapter 1. This section provides the methodology of obtaining the weight of the engine parts and shows example of calculating the weight and fuel savings on example of connecting rod. Weight savings at the connecting rod were not as significant as weight savings obtained by redesigning and merging intake manifold with cylinder heads. Original design of connecting rod was drawn in Solid Works. This CAD software has option to evaluate the mass properties of 3-dimensional model. Input factors for mass evaluation are material density and model geometry. Based on the drawn geometry Solid Works evaluated the volume of the model and by knowing the material density the weight of the connecting rod was calculated [36]. Weight of the original model and new design is shown in table below.

Table 4 Weight of the original and new design of connecting rod

<table>
<thead>
<tr>
<th>Original connecting rod design weight</th>
<th>500.68 g</th>
<th>1.104lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circle lattice connecting rod design weight</td>
<td>495.84 g</td>
<td>1.093lb</td>
</tr>
<tr>
<td>Weight savings</td>
<td>4.84 g (0.96%)</td>
<td>0.011lb</td>
</tr>
</tbody>
</table>

Considering average weight of the 2015 Chevrolet Silverado [37], the weight difference using original connecting rod design and new design was calculated. Values were plugged into Equation 1, where Y represented fuel consumption in liters per kilometer and X represented weight of the vehicle in kilograms, and final fuel savings were calculated. This example shows fuel savings achieved only by considering connecting rod design. Sample calculations are shown in following table.
### Table 5 Weight and fuel savings

<table>
<thead>
<tr>
<th>Design</th>
<th>Original connecting rod</th>
<th>Connecting rod with lattice design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part volume</td>
<td>69,538.8mm³ 4.244in³</td>
<td>68,867mm³ 4.2in³</td>
</tr>
<tr>
<td>Material density</td>
<td>7.2g/cm³ 449.5lb/ft³</td>
<td>7.2g/cm³ 449.5lb/ft³</td>
</tr>
<tr>
<td>Part weight</td>
<td>500.68g 1.1lb</td>
<td>495.84g 1.09</td>
</tr>
<tr>
<td>Weight savings (8 rods)</td>
<td>38.69g (0.96%)</td>
<td>0.011lb</td>
</tr>
<tr>
<td>Overall truck weight</td>
<td>2,173,614.6g 4791.9lb</td>
<td>2,173,575g 4791.9lb</td>
</tr>
<tr>
<td>Fuel savings per truck per km</td>
<td>3.068x10⁻⁶l</td>
<td>6.748x10⁻⁷ gal</td>
</tr>
</tbody>
</table>

#### 2.6 Environmental impact

Car manufacturers are forced to reduce the \( \text{CO}_2 \) emissions of their cars every year. According to [38] the European legislation defines a value curve that limits emissions of \( \text{CO}_2 \) depending on the weight of the vehicle. To the 2012, the trend of this curve averaged at 130g of \( \text{CO}_2 \) per kilometer. Equation for calculating the emissions of \( \text{CO}_2 \) involves the correction factor for the vehicle weight and is set up as follows [38]:

\[
\text{Emissions of } \text{CO}_2 [\text{g}] = 130 + a \times (M - M_0)
\]

Eq. 2
where $M$ is the weight of the vehicle in kilograms, $M_0$ has a constant value of 1,289kg, and $\alpha$ has a constant value of 0.0457 g CO$_2$/kg. According to this equation the difference in CO$_2$ emissions was calculated between original design and new design.
Chapter 3 Results

This chapter provides the design proposals of connecting rod, describes their variations and material properties. Final design is shown and described as well. Next, the chapter introduces the resulting design of merging intake manifold with cylinder heads and provide the material properties of the design. Next, the FEA results of verified connecting rod design are provided. Chapter concludes with calculated weight and fuel savings and environmental impact of those savings. These values were extrapolated per all registered lightweight trucks in US assuming the average annual number of miles for trucks in this class. As mentioned before, the new design of connecting rod consists in incorporating lattice structure into the web of the I-beam while maintaining the mold wall thickness greater or equal to 1/8” [39].

Several designs were proposed and they are shown in Figure 27 and Figure 28. Top design of Figure 27 was rejected because of high stresses occurred at a stress concentrator in the lattice area. The middle design of Figure 27 is a modification of the previous design with filleted edges of squared lattice structure. However this was rejected from the same reason as the previous design. The bottom design of the same figure represents incorporation of the circle lattice design. The circle lattice was proposed in order to eliminate the occurrence of high stresses in lattice structure. However, this design was rejected due to abnormal deflection of the connecting rod. It was the result of high density of lattice pattern in I-beam. The top design of Figure 28 is a circle lattice design, but the density of the pattern was reduced. Unfortunately, even this design resulted in more deflection than allowed. The circle lattice design was modified and replaced by the square lattice with filleted edges inside and on the sides, shown in the middle of the Figure 28. The deflection for this design was considered acceptable, but the bottom surface of the squared lattice experienced higher stresses than allowed. Stress concentrators for this design were located in these areas. They are described later in this chapter. In order to reduce the stress in these areas the filet radius was increased and the final design was verified. To reduce the weight of
the connecting rod even further, the crank end and piston end were modified. Final design of the connecting rod is shown in Figure 29.
Figure 28 Lattice structure designs in connecting rod and final design
Figure 29 Final design of connecting rod

All designs were validated through FEA in software Ansys. Unsatisfactory designs either showed abnormal deflection in I-beam or stress concentration in edges of the lattice was too high. Analysis was performed on both, original connecting rod and redesign connecting rod. Results of the approved design are displayed in Table 6 together with FEA results of original design. Number of tetrahedron elements is higher in lattice design model due to higher concentration of smaller elements in lattice area.

Table 6 Results of FEA of connecting rod designs

<table>
<thead>
<tr>
<th>Property</th>
<th>Original design</th>
<th>Redesigned connecting rod</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum stress (Von-Misses) [MPa]</td>
<td>243.5 (35,320psi)</td>
<td>352.2 (51,080psi)</td>
</tr>
<tr>
<td>Deflection [mm]</td>
<td>0.059 (0.002343in)</td>
<td>0.066 (0.002598in)</td>
</tr>
<tr>
<td>Mesh size [mm]</td>
<td>0.8 (0.0315in)</td>
<td>0.8 (0.0315in)</td>
</tr>
<tr>
<td>Number of elements</td>
<td>277135</td>
<td>301310</td>
</tr>
</tbody>
</table>
Table 6 shows that deflection of new design and original design are in similar range, but maximum stresses of new lattice design are significantly higher than stresses of original design. This is due to the shape of the cut-outs in lattice structure as can be seen from the Figure 30. Area of maximal stress is magnified in Figure 31. Since the stresses were below yield stress value design was approved.

![Figure 30 Stress distribution in lattice design of connecting rod](image)

![Figure 31 The maximum stress area of lattice design](image)
FEA results of first 6 unsatisfactory designs are displayed in the table below.

<table>
<thead>
<tr>
<th>Design</th>
<th>Maximum Stress</th>
<th>Maximum Deflection</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>493Mpa</td>
<td>0.092mm</td>
<td>489.65g</td>
</tr>
<tr>
<td></td>
<td>71503psi</td>
<td>0.0036in</td>
<td>1.08lb</td>
</tr>
<tr>
<td>2</td>
<td>487Mpa</td>
<td>0.103mm</td>
<td>489.75g</td>
</tr>
<tr>
<td></td>
<td>70633psi</td>
<td>0.004in</td>
<td>1.07lb</td>
</tr>
<tr>
<td>3</td>
<td>477Mpa</td>
<td>0.813mm</td>
<td>492.11g</td>
</tr>
<tr>
<td></td>
<td>69182psi</td>
<td>0.032in</td>
<td>1.08lb</td>
</tr>
<tr>
<td>4</td>
<td>378Mpa</td>
<td>0.074mm</td>
<td>493.66g</td>
</tr>
<tr>
<td></td>
<td>54824psi</td>
<td>0.003in</td>
<td>1.08lb</td>
</tr>
<tr>
<td>5</td>
<td>374Mpa</td>
<td>0.077mm</td>
<td>495.52g</td>
</tr>
<tr>
<td></td>
<td>54244psi</td>
<td>0.003in</td>
<td>1.09lb</td>
</tr>
<tr>
<td>6</td>
<td>362Mpa</td>
<td>0.076mm</td>
<td>495.84</td>
</tr>
<tr>
<td></td>
<td>52503psi</td>
<td>0.003in</td>
<td>1.09lb</td>
</tr>
<tr>
<td>7</td>
<td>352Mpa</td>
<td>0.066mm</td>
<td>395.63g</td>
</tr>
<tr>
<td></td>
<td>51053psi</td>
<td>0.002in</td>
<td>0.87lb</td>
</tr>
</tbody>
</table>

Two other engine parts considered for redesign were intake manifold and cylinder heads. As mentioned before, these parts were merged together to create one part. This allowed to eliminate unwanted bolt joints and unused coolant channel intake. Same as the redesign of connecting rod, even this redesign was done in Solid Works but in assembly environment. Parts were aligned together and then fixed and saved to form one solid object. This part was not the subject of the FEA. However, minimum wall
thickness of 3 mm was preserved while redesigning. New design is shown in Figure 32 and detail of removed bolt joint area in Figure 33.

Figure 32 Redesigned intake manifold and cylinder heads
Figure 33 Detail of eliminating bolt joint bracket

Redesigning process concluded in determining the weight reduction and calculating the fuel savings achieved by this weight reduction. Solid Works feature Evaluate was used to determine the volume of the original and new design. Next using the volume-mass-density relationship the mass of the connecting rod and engine head was calculated. After mass was determined, fuel saving were calculated using Equation 1. Results are presented in following tables.

Table 7 Weight savings from new design of connecting rod

<table>
<thead>
<tr>
<th>Units</th>
<th>Metric</th>
<th>Imperial</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Original</td>
<td>Redesigned</td>
</tr>
<tr>
<td>Connecting rod</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volume</td>
<td>69.54cm³</td>
<td>54.95 cm³</td>
</tr>
<tr>
<td>Part weight</td>
<td>8x500.68g</td>
<td>8x395.63g</td>
</tr>
<tr>
<td>Weight savings</td>
<td>840.4g (20.98%)</td>
<td>1.85lb (20.98%)</td>
</tr>
</tbody>
</table>
Table 8 Weight savings from new design of intake manifold

<table>
<thead>
<tr>
<th>Units</th>
<th>Metric</th>
<th>Imperial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intake manifold, cylinder heads</td>
<td>Original</td>
<td>Redesigned</td>
</tr>
<tr>
<td>Volume</td>
<td>11,050.63cm³</td>
<td>10,701.04cm³</td>
</tr>
<tr>
<td>Part weight</td>
<td>79564.4g</td>
<td>77047.5g</td>
</tr>
<tr>
<td>Weight savings</td>
<td>2,516.9g (3.16%)</td>
<td>5.547lb (3.16%)</td>
</tr>
</tbody>
</table>

Table 9 Total weight savings and fuel savings per one kilometer

<table>
<thead>
<tr>
<th>Units</th>
<th>Metric</th>
<th>Imperial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total weight savings including eliminated bolts</td>
<td>3676.14g (4.39%)</td>
<td>8.104lb (4.39%)</td>
</tr>
<tr>
<td>Total fuel savings per 1 km</td>
<td>2.92x10⁻⁴l</td>
<td>7.7x10⁻⁵gal</td>
</tr>
</tbody>
</table>

To bring a significant meaning to amount of saved fuel in the Table 9, this number was extrapolated, assuming all the light trucks considered for this analysis would use GM 350 small block engine.

According to [40] annual average vehicle distance traveled in miles for Light Duty vehicles with long wheel base (light trucks, vans and sport utility vehicles) for June 2015 is 11,712 miles. According to [41], for 2013 there were registered 51,512,740 Light Duty vehicles with long wheel base. Considering this, annual amount of fuel saved was calculated and is shown in Table 10.

Table 10 Annual fuel savings per fleet of light duty trucks

<table>
<thead>
<tr>
<th>Units</th>
<th>Metric</th>
<th>Imperial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual average distance traveled</td>
<td>18,848km</td>
<td>11,712miles</td>
</tr>
<tr>
<td>Annual fuel savings per 1 vehicle</td>
<td>5.49l</td>
<td>1.45gal</td>
</tr>
<tr>
<td>Total annual fuel savings</td>
<td>283,040,000l</td>
<td>74,770,000gal</td>
</tr>
</tbody>
</table>
After the total weight savings were determined, the environmental impact was calculated. Emissions of CO₂ per kilometer were used to calculate the vehicle’s impact on the environment. Using Eq. 2 the CO₂ emissions were calculated for both original and new design. Value of the emitted CO₂ was extrapolated per fleet of the light duty trucks and annual value was evaluated. Results are shown in following table.

**Table 11 Annual CO₂ emissions savings**

<table>
<thead>
<tr>
<th>Units</th>
<th>Metric</th>
<th>Imperial</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Old design</td>
<td>New design</td>
</tr>
<tr>
<td>Truck weight</td>
<td>2173.6 kg</td>
<td>2169.9 kg</td>
</tr>
<tr>
<td>(Silverado 2016)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂ emissions</td>
<td>170.42 g/km</td>
<td>170.26 g/km</td>
</tr>
<tr>
<td>∆ CO₂ emissions</td>
<td>0.16799 g/km</td>
<td></td>
</tr>
<tr>
<td>Annual CO₂ emissions savings</td>
<td></td>
<td>163,100 t</td>
</tr>
</tbody>
</table>

Chapter concludes with proposal of the gating system for new casting design. This gating system design was compared with gating system design of each individual casting in assembly. This was done to evaluate the weight savings of metal poured into the mold. Results showed that new design not only saved 8.1 lb of part weight but also allowed to merge three gating systems into one. Even though final gating system is more complex than gating systems of individual castings, this option saved 39.02 lb of metal which would be considered scrap metal if casting each part separately. Gating designs are showed on following figures.
Figure 34 Gating system of new design

Figure 35 Gating system of intake manifold
Figure 36 Gating system of cylinder head
Chapter 4 Conclusions

4.1 Conclusions

The main goal of this thesis was to redesign car engine, which was specified as 350 Small-Block Chevrolet engine and calculate the fuel economy of the car, which will use redesigned engine. Fuel economy of the new engine was improved due to the weight savings achieved during the redesign process. To determine the fuel savings the weight difference between the old design and new design was determined. Possible solution for the weight determination was to redraw the original parts into the CAD software and evaluate the weight of the part directly. Since parts were too complex for simple CAD drawing, they were scanned using 3D scanner and data were transferred into the CAD software, which could determine the exact weight of the part. Once the weight of the original parts was known, parts were redesigned and weight difference was obtained. By implementing lattice structure into the body of the connecting rod and by modifying its crank end and piston end and by merging intake manifold with cylinder heads the total weight saving of 8.104lb was achieved. New fuel consumption was determined and compared with original fuel consumption. This fuel consumption model was calculated considering one truck driving the distance of 1km. The amount of saved fuel per distance of 1 km was too small; therefore it was extrapolated per fleet of the registered light duty vehicles which annually traveled 11,712 miles. Resulting fuel saving of new design was 74,770,000gal. This is the amount of fuel which would be saved annually if all the vehicles would use similar engine than the one considered for this thesis.

To assure the castability of the new design of the connecting rod the minimum wall thickness for mold and also for casting wall was set to 1/8”. The feasibility of the design was verified through the FEA. Only one loading scenario was modeled and that is the one where the connecting rod experiences the maximum load. Crank end of the connecting rod was constrained as a pin and piston end bearing load of
17,000N was applied at the piston end. FEA analysis showed that the deflection of the new design (0.066mm) is just slightly longer than the deflection of the original design (0.0595mm). Maximum stress of the original was 243.5 MPa and was experienced in the corner of the I-beam and the crank end, whereas the maximum stress of new design was 352.1 MPa and it was present at the corner of the lattice design. Stress difference was higher than expected, but the value was within the range so the design was accepted.

4.2 Future work

There are four main research topics that can be done in the future. For the first, engine block was not considered for the analysis. Parts which were merged to form one single object attach directly to the engine block. Considering implementation of engine block into the design there is space for even more weight reduction and fuel savings.

Secondly, the part designed by merging cylinder heads and intake manifold was not verified from the mechanical point of view. Forces and temperatures inside the engine and flow of the coolant fluid and fuel-gas mixture were not considered for this research. For anything moving forward that can be done the CFD of the new part is important to verify the feasibility of the design.

Thirdly, the surface mesh of the scanned manifold and cylinder head was directly converted into the parametric surface format that could be imported into the SolidWorks. For the better geometry capture accuracy object can be created by forming the parametric features around the original mesh surface of the part.

For the last, analysis of the connecting rod was performed in the static mode. However, to obtain the best possible results dynamic analysis of the design can be performed. This type of the analysis will reveal the stresses that connecting rod experiences during all four strokes not only during combustion stroke.
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