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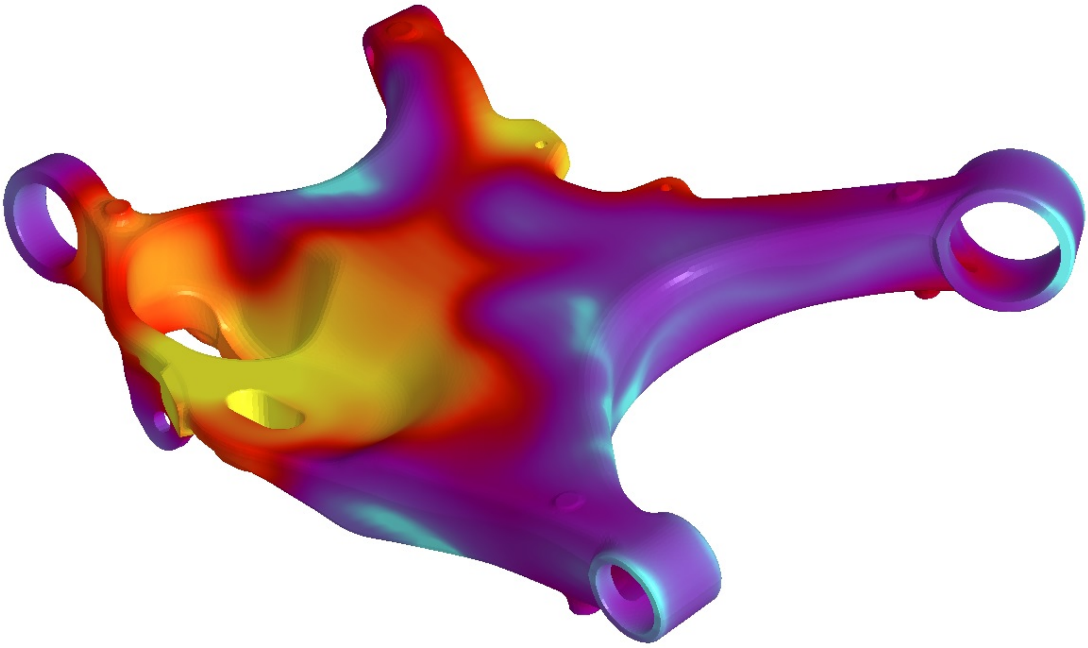

Cast Simulation and Manufacturing Constraints for Detailed Part Optimization

Master's thesis in Automotive Engineering

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Department of Applied Mechanics
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Cover: Topology Optimization and Cast Simulation of Rear Lower & Upper Control Arms.

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Abstract

Structural optimization and cast simulation tools has gained significant importance in automotive industry. The industry is slowly transforming into CAE driven design process, as the acceptance of CAE simulations in providing new and inspiring lighter designs with shortened development cycles is demonstrated in recent times. Optimization has become an integral part of design, there has been a demand for optimization of aluminum cast parts where engineers are challenged to guarantee both functionality and cast-ability of the component. On the other hand, casting simulation finds its applications in later part of design process particularly used by foundries for optimization of casting process by mold flow and solid simulation.

The purpose of this master thesis is to propose a methodology with emphasis on application of manufacturing constraints in the topology optimization and investigate the possibility of integrating cast simulation tools in optimization driven product development. In addition, to decrease the lead development time and number of iterations in design modifications to verify cast-ability of the components. Use of casting simulation among engineers is rather new and it helps CAE and design engineers to understand the process and identify the defects and problems in early concept phase, so that there is enough time and flexibility to make changes and evaluate different concepts and aid them in choosing the best possible design. Optistrut is a finite element based structural analysis software, used to study structural topology optimization and NovaFlow&Solid is a finite volume based CFD simulation tool, used to study solidification and filling process in casting for evaluating the generated concepts from different manufacturing constraints.

The proposed integrated component development process is verified on a simple and complex components, rear upper control arm (RUCA) and rear lower control arm (RLCA), respectively. The results of evaluation study confirms that the method works well in generating light weight concepts for RUCA with simple load cases without the design realization step. However, for RLCA with complex load case seems to generate bit heavy concepts than the current design, which confirms that CAD design realization loops involving CAD engineer can not be eliminated even when manufacturing constraints have been implemented. The thesis also put forward a template for calculation of threshold for optimal extraction of density plots. Different concepts from topology optimization are compared based on the cast simulations results and the results are discussed and future work is proposed.

Keywords: Cast simulation, Topology optimization, Chassis components, Weight reduction, Cast components, Optistruct, NovaFlow&Solid.

Preface

This master thesis in automotive engineering at Chalmers University of Technology is carried in cooperation with Volvo Car Corporation under weight and optimization department for fulfillment of 30 credits in Gothenburg during spring 2017. The examiner and academic supervisor was Professor Ragnar Larsson, Head of Division Material and Computational Mechanics, Department of Industrial and Materials Science, Chalmers University of Technology. Andreas Carlsson was supervisor in industry, Optimization Engineer Volvo Cars, Gothenburg.

This thesis was one part of thesis cluster proposed by Optimization Culture Arena, Where the objective is to develop optimization culture as a natural part of component development process and demonstrate capabilities of CAE driven optimization.

Acknowledgements

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Alireza Nilipour Tabatabaei
Chetan Krishnaswamyreddy
Gothenburg, December 2017

Abbreviations

RLCA Rear Lower Control Arm
RUCA Rear Upper Control Arm
NFS NovaFlow&Solid
TO Topology Optimization
DFM Design For Manufacturing
FE Finite Element
DOC Drive Over Curb
BIP Brake In Pothole
ROC Rearwards drive Over Curb

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1
Introduction

This master thesis is a part of Optimization Culture Arena under weight management and optimization department at Volvo Car Corporation in Gothenburg. The thesis mainly focuses on developing a generic understanding and methodology which integrate manufacturing constraints and casting simulations results in component optimization and development process using topology optimization and casting simulation tools. This chapter provides the necessary background information, followed by purpose and limitations of this thesis project. Subsequently, method workflow and framework of a thesis is explained.

1.1 Background

Structural optimization and cast simulation tools has gained significant importance in automotive industry. The industry is slowly transforming into CAE driven design process, as the acceptance of CAE simulations in providing new and inspiring lighter design with shortened development cycles is demonstrated in recent times. Optimization has become an integral part of design, there has been a demand for optimization of aluminum cast parts where engineers are challenged to guarantee both functionality and cast-ability of the component. On the other hand casting simulation finds its application in later part of design process particularly used by foundries to optimization of casting process by mold filling and solidification simulation.

Topology optimization tends to create design proposal which are hollow with rib structure. In general the material is added on outer area of design space which make them complicated to realize the design into castings. In the realization phase, design engineer tries to answer question on how feasible the new design is terms of manufacturing. It is followed by consideration of casting process design guidelines to modify the new component accordingly to pass the cast-ability assessment. In many cases, material is added during design realization phase which has no structural significance and out weights the benefits of topology optimization.

The Thesis focus on RLCA and RUCA components which are manufactured by aluminum castings. However, directional structural stiffness requirements, strength events, load cases and design space are well known for these components. A Linear isotropic material behaviour is assumed for optimization and solidification simulation is carried to investigate the casting feasibility and how close the optimized structure is to the design realization and also a need to reduce number of iteration between design and foundry in later stages of product development where their is less flexibility for optimal changes, it more natural to include topology and casting simulation in early phase of component development process.

1.2 Purpose

The main purpose of this master thesis is to improve casting development process by identifying relations between topology optimization and casting philosophy and propose a methodology which encourages the use of topology optimization and casting simulations tools in early phase of component development process for chassis components. The casting constraints origin from studying the process of casting method. The casting simulation is then used to investigate impacts of added manufacturing constraints in final designs.

1.3 Limitations

Three dimensional FE-meshed design space with no temperature dependencies, vibration free, time independent, multiple loading and linear elastic isotropic material within Hook's range is considered. Local approximation methods are used in sensitivity analysis for reducing the computation time. In order to formulate directional stiffness structural constraint, finite element problem with linear static behavior is preferred. Since it seems very difficult to formulate every studied casting requirements into topology optimization problem, only those manufacturing related constraints facilitated by Optistruct tool are used in this study. NovaFlow&Solid software is utilized as a casting process simulation tool. Although the software is able to model both filling and solidification process of the casting, only the solidification process is simulated. This is mainly due to the fact that filling simulation parameters are process dependent and differs from one foundry to other. The flow constrains are difficult to formulate. Influence of gravity is not considered in solidification and material model for temperature dependent properties like density, heat transfer coefficients are limited to standard data from Novaflow material library.The limitations of concept selection methods also applies.

1.4 Method

The Thesis work started with literature study on theory of structural optimization, aluminum casting process and casting simulation. Later on software training on both tools NovaFlow&Solid 6.0, and Optistruct were done at Volvo Cars by studying tutorials and attending workshops. For making an optimized casting component where the design is close to manufacturing, topology optimization is performed by implementing different available manufacturing constraints. With the help of parameter study considering different formulation with various combinations best setting is finalized. A method for finding the optimum threshold filter value for efficient extraction of results from density plots file is also proposed. Optimal setting to import filtered high density elements using function to NovaFlow&Solid where its re-meshed and boundary condition are setup for solidification simulation. This is continued by investigation on the solidification defects formed during this phase. The reasons of defects formation are then interpreted. A criteria for comparing the cast-ability is defined for evaluating the best design proposal which is tried upon RUCA. The solidification simulation of current RLCA and proposal from previous thesis is compared in terms of casting feasibility.

2
Theory

This chapter provides the necessary theoretical materials as well as concepts used in this thesis work. Section 2.1 briefs on basis of structural and topology optimization, we focus more on responses and constraints used in optimization setup. In addition, we classify the manufacturing constraints of interest to include in problem formulation. Sections 2.2 & 2.3 give a short description of the aluminum casting process, defects and simulation theory in detail. Eventually, section 2.4 addresses on Design For Manufacturing (DFM) for casting which captures the best practices and guidelines used by design engineer in design realization phase.

2.1 Topology optimization

Topology optimization is a numerical method which involves determination of size and number of holes and connectivity in a fixed design domain [1]. It is a most general type of structural optimization problem where optimization software looks for the optimal placement of isotropic material in the design space subjected to the given constraints. This method is generally applicable if the loads cases, support conditions, design volume and design restriction (non-design features) is well understood and approved for the component.
Density based methods are used by majority of topology optimization software commercially available today, one such popular and extremely efficient method that is used in Optistruct is called Solid Isotropic Material with Penalization Model (SIMP) which uses penalization interpolation scheme:

$$E(\rho_e) = \rho_e^p E_0, 0 < \rho_e \leq 1 \tag{2.1}$$

where ρ is the design variable with assumed material density and penalization power p. In Optistruct, parameter value is defined with Opti-control card which is always equal to $p - 1$. In order to see the effect of penalization it must take values $p > 1$, intermediate values of ρ contribute less to stiffness and more to mass of structure. Hence intermediate values will be eluded in setting up the optimization problem.

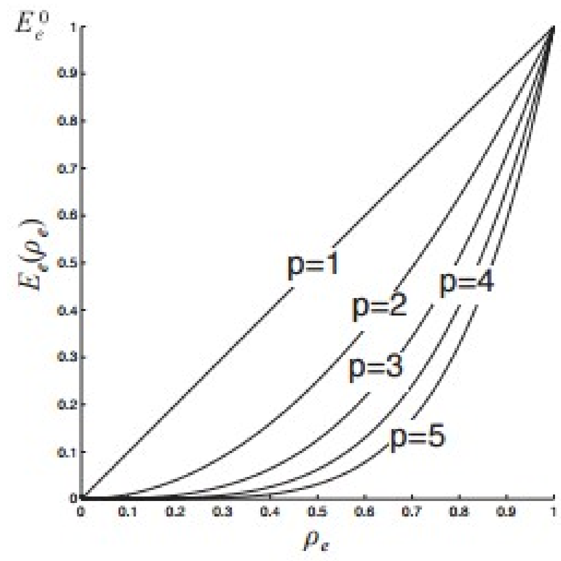

Figure 2.1: Youngs modulus as a function of design parameter p element for SIMP schemes [2].

Penalization parameter, p, pushes the topology optimization elements to material density 0 or 1. That is higher values of penalization will reduce intermediate density elements. Optistruct allows the p parameter to be between $2 \leq p \leq 4$. However, Optistruct recommends p of 2 as default, p of 3 for shell or solid structures with member size constraints but without manufacturing constraints. And p of 4 for solid elements with both manufacturing and member size constraints. Bendsøe and Sigmund [2] claims the relevance of continuous formulation is correct as long as condition on penalization power is fulfilled given by equation 2.2:

$$p \geq \max\{15\frac{1-\nu^0}{7-5\nu^0}, \frac{3}{2}\frac{1-\nu^0}{1-2\nu^0}\} \tag{2.2}$$

where ν^0 Poisson's ratio of original material. This condition is known as Hashin–Shtrikman [3] bounds which correlate the stiffness results from Solid Isotropic Material with Penalisation (SIMP) to composite material stiffness consisting of original and void materials. In general $\nu^0 = \frac{1}{3}$.

Topology optimization problem formulated by applying finite element discretization and continuous interpolation formulation of Solid Isotropic Material with Penalisation (SIMP) can be written as:

$$\begin{cases} \text{min,} & \text{objective function} \\ f(\rho_e) & \\ \text{subjected to,} & \text{constraint functions} \\ LB < g(\rho_e) < UB, & 0.01 < \rho_e < 1 \\ F = KU & \end{cases} \tag{2.3}$$

where ρ is design parameter which is continuous in space and belongs to design domain space Ω, $f(\rho)$ is an objective function, which can be either volume, mass, volume fraction, mass fraction or individual compliance, weighted compliance of structure defined by the design vector ρ and $g(\rho)$ is a constraint function where UB and LB are upper bound and lower bounds limit on the constraint respectively.F is force vector, U is nodal displacement vector and K is global stifness matrix This formulation is solved by an iterative procedure also known as Method of Feasible Directions (MFD) which has following steps involved as shown in the flow chart below in Optistruct.

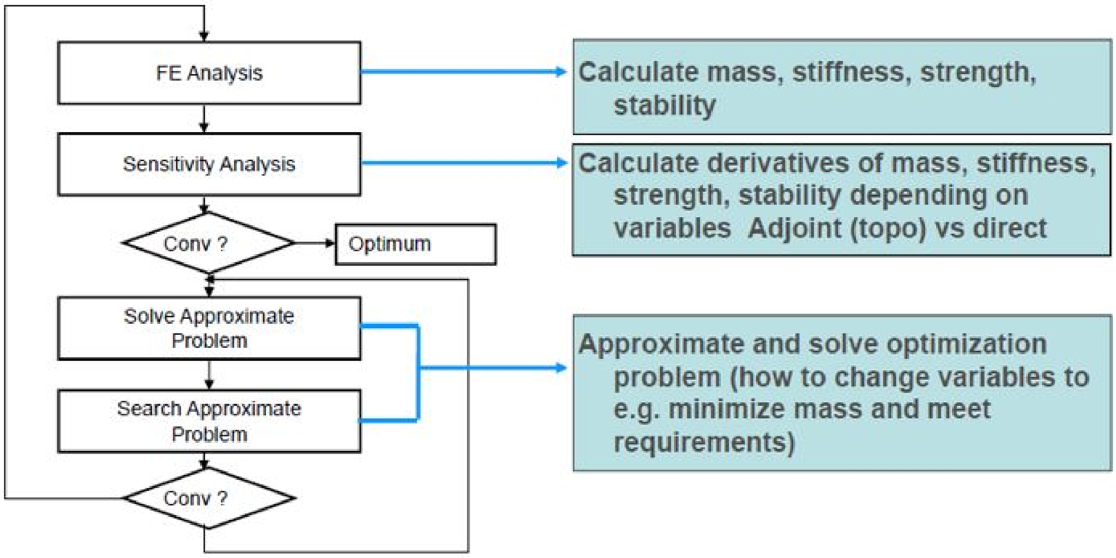

Figure 2.2: FEA-based structural optimization method in Optistruct [4].

Optistruct uses move limit bounds to reach convergence with minimum number of FE Analysis which enables large design variables changes in the first few iterations. In sensitivity analysis, second derivative of structural responses from the FEM analysis with respect to design variable is calculated. Next update of design variable is obtained by explicitly solving the optimization problem with sensitivity. Topology uses dual method which solves the optimization problem with Lagrange multipliers related to active constraints. This method is highly efficient with more design variable and less number of constraint which is true in the case of topology optimization.

2.1.1 Responses

Response are predefined variables types used to define objective and constraints in an optimization setup. There are numerous structural responses from which Optistruct allows to choose, for our study we will be mainly looking in detail of 4 responses (a) mass and volume, (b) weighted compliance, (c) compliance, (d) mass and volume fraction.

Mass and volume are global responses which can be defined for parts of interest of the structure or whole structure. Mathematically given by equation below:

$$M = M(\rho) = \sum_{e=1}^{N} \rho_e M_e^0 \tag{2.4}$$

$$V = V(\rho) = \sum_{e=1}^{N} \rho_e V_e^0 \tag{2.5}$$

Where, Me, Ve and ρ_e are mass, volume and normalized design parameter of e^{th} element respectively and N is total number of elements.
Weighted compliance is also a global responses defined for whole structure used to consider multiple load steps in a topology optimization. It is the sum of the compliance of each individual sub-load step. It is a single scalar value for the whole structure which approximates the structural performance or strain energy stored in the structure, lower the weighted compliance implies stiffer the structure.

$$C_W = \sum_{i=1}^{L} W_i C_i = \frac{1}{2} \sum_{i=1}^{L} W_i (U(\rho) \times F(\rho)) \tag{2.6}$$

Where C_W is weighted compliance,W_i is weights of each load case C is compliance of each load step,L total number of load cases, U is stiffness vector and F is force vector.
In Optistruct **compliance** is defined as summation of strain energy stored in all the elements in the structure for individual load case calculated using the following relationship:

$$C = \frac{1}{2} U(\rho)^T F(\rho) = \frac{1}{2} U(\rho)^T K(\rho) U(\rho) = \frac{1}{2} \int \epsilon^T \delta dV \tag{2.7}$$

The above relation is equation of strain energy in classical structural problem which is area of triangle in stress strain curve under linear region.
Compliance is inversely proportional to measure of stiffness K for a structure with applied load F.

$$C = \frac{1}{2} U(\rho)^T F(\rho) = \frac{1}{2} \frac{F(\rho)^T F(\rho)}{K(\rho)^T} = \frac{1}{2} f \frac{1}{K(\rho)} = Constant \frac{1}{K(\rho)} \tag{2.8}$$

Compliance is direct proportional to stiffness of structure with applied displacement U.

$$C = \frac{1}{2} U(\rho)^T F(\rho) = \frac{1}{2} U(\rho)^T K(\rho) U(\rho) = \frac{1}{2} u^2 K(\rho) = \text{Constant} K(\rho) \tag{2.9}$$

Mass and volume fraction are global responses both are different from each other given by equation:

$$Volume\ Fraction = \frac{\text{total volume at current iteration - initial nondesign volume}}{\text{initial design volume}}$$

$$Mass\ fraction = \frac{total\ mass\ at\ current\ iteration}{initial\ design\ space\ mass}$$

Static displacement are Nodal displacements of linear static analysis. They can be selected a total displacement or displacement along xyz axis of local or global coordinate system. They must also be assigned to each static load step during its definition in Optistruct.

2.1.2 Objective function

Objective is a single most quantitative parameter which evaluates a design and its associated response which is a function of design variable. A topology optimization problem can have only one objective function. The relationship between the objective parameter with and design variables is expressed in terms of mathematical formulation known as objective function. During optimization the goal is to search for maximum or minimum or min-max of objective function. In our study we will discuss mainly two responses which are used as objective of topology problems,Compliance and Volume fraction.

Compliance as objective In equation 2.8 we have shown that compliance is inverse proportional to stiffness of structure for an applied load which motivates us to use minimize compliance as an objective function. Compliance describes the stiffness of a structure for a specific load case and can be formulated as:

$$\begin{cases} \text{min} \\ C(\rho) = F(\rho) \times U(\rho) = U(\rho)^T \times K(\rho) \times U(\rho) = \sum_{e=1}^{N} {\rho_e}^p {u_e}^T K_e u_e \\ \text{subjected to} \\ V = f_v V_0 = \sum_{e=1}^{N} \rho_e v_e \\ F = KU \\ 0.01 < \rho_e < 1 \end{cases} \tag{2.10}$$

Volume fraction as objective It is used in optimization problem when weight reduction is the main goal and can be formulated as:

$$\begin{cases} \text{min} \\ V = \sum_{e=1}^{N} {\rho_e}^p v_e \\ \text{subjected to} \\ C(\rho) = \sum_{e=1}^{N} {\rho_e}^p {u_e}^T K_e u_e < C_{bound} \\ F = KU \\ Nodal\ displacement < UB \\ 0.01 < \rho_e < 1 \end{cases} \tag{2.11}$$

2.1.3 Constraints

Constraint is a restriction placed on the optimization problem, they are generally a limit value associated with a response which is expressed as inequality function of design variable and this condition must always be satisfied for the design to be valid. All the created responses can be used as a constraint expect the response associate with objective. There can be multiple constraints for an optimization problem. When all constraints are satisfied the design is feasible. Optimum design is one which gives the minimum of objective function satisfying all constraint equations, violation of any of constraints results in an in-feasible design.

Constraints can be classified mainly in to two categories, structural constraints and manufacturing constraints. Structural constraints can be any of the structural responses generated in linear static analysis. It can be compliance for a given load case, nodal displacement for given load case, volume or mass fraction of the design variable and mass of structure.
Manufacturing constraints impose restriction to the optimization problem. Optistruct makes mainly 4 manufacturing constraints available to include in the problem. Draw direction, member size control, pattern repetition and extrusion. The first three categories can be mainly related to casting process hence we will be discussing them in detail.

2.1.3.1 Draw direction

Casting process involves removal of pattern form the sand mold to form cavity or the sliding of moving die to remove the solidified component in die castings. The sand core used in hollow castings has to be removed from the mold for sand core production. This imposes a manufacturing constraint in placement of voids that are not open and lined up in the sliding direction to get a feasible optimized design. However, design from topology optimization more often contains voids that are not practical in casting. Draw direction constraint is a shape constraint, which facilitates de-molding operation. Optistruct facilitates two type of mold-ability constraints formulation into an optimization problem primarily based on number of moving die and placement of parting line in the castings (a) Single draw (b) Split draw . These constraints force the solution to produce shape which does not hinder the mold removal in their parting direction at the end of optimization.

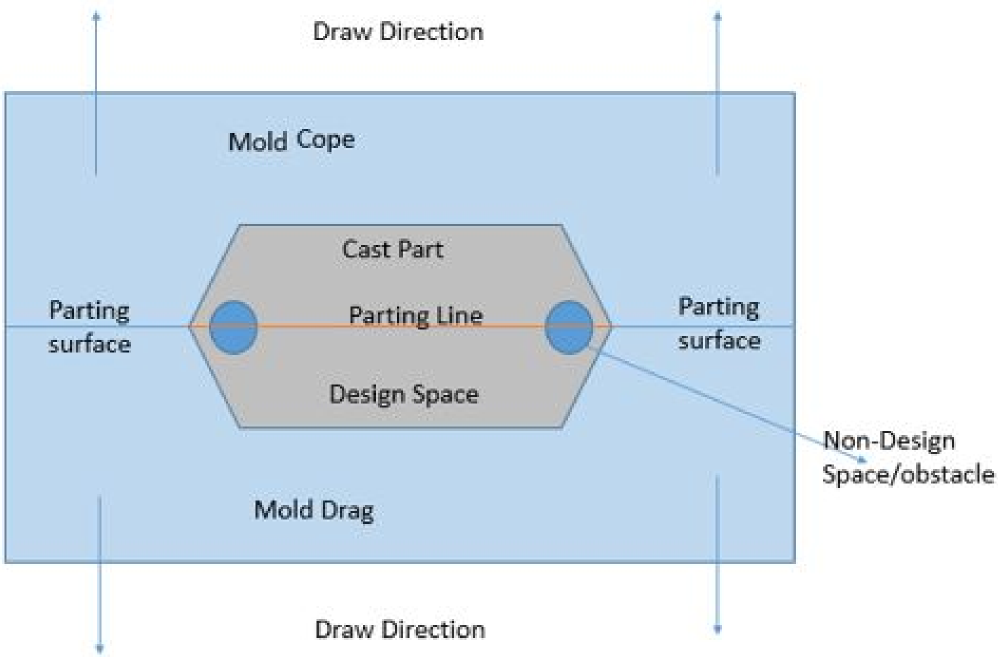

Figure 2.3: Simplified representation of casting system [5].

In most common cases it is not suggested to have through holes in castings as a flow

requirement. This can be accomplished by selecting No Hole check-box by which holes can be prevented in the direction of the draw. It can take many iterations to remove one layer as topology evolves gradually from the boundary layer at a time. An optimization problem may contain a non-design space which must be defined as obstacles to preserves the casting feasibility of the final design. Default minimum member size to use with draw direction constraints is 3 times the mesh size which should be specified using opt control card in the Optistruct software. With default value of discreet penalty parameter with manufacturing constraint the penalty starts at 2 and increases to 3 and 4 for the second and third iterative phases.
Single Draw As the name indicates single draw constraint considers one moving die which slides in the user defined drawing direction, Optistruct computes the contra part for the fixed die.
Split Draw Split draw allows to choose the parting plane where the two dies meet and it must be decided by the designer to set this constraint based on the symmetry and undercuts in the non-design volume. This can be approximately selected by looking at the topology optimization results of the same structure without draw direction constraint and allow by following standard design guidelines for placement of parting line. The parting surface is also optimized during the optimization process. An optimization problem with more than 2 moving die cannot be modelled in Optistrcut.

2.1.3.2 Member size constraint

Thin members are difficult to fill in casting and also results in deformation under high temperature resulting in residual stress after solidification. However, thick members should be avoided due to cooling issues and formation of porosity due to poor feed-ability. Number of ribs and gaps between each rib can also affect the flow pattern of liquid metal in the mold which in turn impact quality of castings. This imposes a manufacturing constraint on the optimization problem which can be addressed by member size constraint in Optistruct. Minimum member size control with default discreet parameter, the discreet penalty factor starts at 2 and increases to 3 for the second and third iterative phases. Member size constraint also helps to address the check board problem and mesh dependence of the optimization results. Minimum member size constraint prevents the formation of features below the set value. Default min member size is twice the average mesh size of the design space. Maximum member size constraint can only be set when minimum member size constraint is previously defined. It can take value not less than twice the minimum member value. Optistrcut also allows to define the gap between each feature and it can be defined if both minimum and maximum member size are pre-defined and the default value is as the same as the max member size.

2.1.3.3 Symmetry constraint

Castings are designed symmetric between parting plane to reduce the complexity and to achieve easy fill-ability. This process can be modelled as a constraint in optimization problem by using Pattern grouping options which link topology variables together in such a way that facilitates the formation of desired reinforcement patterns. One-plane, two-plane, three-plane and cyclical symmetry pattern grouping can be achieved.

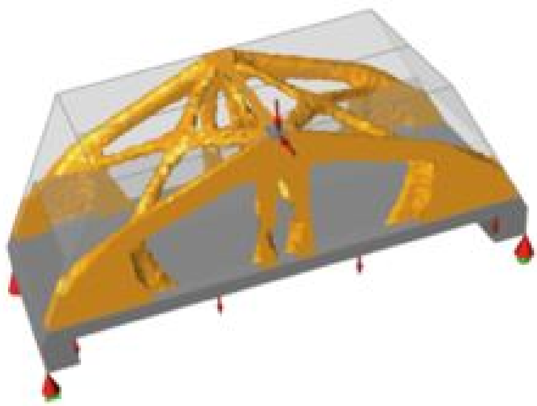

Figure 2.4: Topology optimization of over hanging bridge showing pattern grouping constraint in Optistruct [4].

2.2 Aluminum casting

Replacing aluminum alloy casting components instead of iron castings components will result in having weight reduction by more than half. It shows the wide range of application of aluminum casting in automotive industry where cutting the total weight of the vehicle has been always a concern. This replacement is very successful in engine blocks and power train parts and it can be extended to chassis and suspension components as well. As a result, automotive industry has become the largest market for aluminum castings [6].
The original method of forming aluminum into products is casting which can be done in different casting methods. The principle of aluminum casting is to pour molten aluminum into a mold cavity which has been already created by using the pattern of the desired shape. This process is followed by solidification of filled mold where it starts at liquidus temperature of the molten metal and ends at solidus temperature. Die casting, permanent casting and sand casting are the most important aluminum casting methods. A short introduction of each mentioned method is presented below [7].

2.2.1 Die casting

The die casting process is done under pressure applying from a plunger to force molten aluminum into a steel mold (die). This method is typically used for high-volume production where after removing the casted aluminum part from the mold, minimum machining and finishing operations are needed [7]. Engine cylinder heads, gas engine parts, brackets and heat sink for LED headlights are examples of die casting productions in automotive industry [8].

2.2.2 Permanent mold casting

Permanent mold casting consists of molds and cores made of steel or similar metals. The advantage of this method is that the mold can be reused. The procedure of permanent mold casting is fairly straight forward so that the molten aluminum is poured into the prepared cavity and after the metal has solidified the two mold halves are pulled away from the formed part [9]. It should be mentioned that depending on the shape of the cavity and used material, a liquid molten metal is subjected to gas pressure or vacuum. High-volume production of castings with uniform wall thickness and limited undercuts is the most tendency of using this casting method. For those aluminum alloy castings where maximum mechanical properties are required, heat treatment is used to improve mechanical properties [9]. Transmission case and intake manifold are good examples of permanent mold aluminum castings in automotive applications.

2.2.3 Sand casting

Sand casting is the most economical shape casting manufacturing process since there is no need of using high-cost metallic tooling [10]. Typically it is performed in the air atmosphere with sand mold at room temperature. Sand casting normally begins with the creation of a pattern as a replica of the desired shape. It is followed by pressing the pattern into the fine sand mixture to form a mold cavity. After preparation of the sand mold, liquid metal is poured through channel(s) into the cavity which relies on gravity until it gets completely filled with molten metal. The solidification is then started to transfer the poured metal from liquid to solid phase. Once the casting part is ready the sand mold should be broken to take the formed cast component out. This process compared to two other mentioned casting methods is slow and therefore is limited to have a high rate of production. However, casting quality of the sand cast parts is highly determined by foundry techniques [9]. Since the sand mold is used, the rough surface texture cast part with low dimensional accuracy has been produced which usually needs machining and finishing operations to ensure accuracy and surface quality of the final product. Moreover, components with thin ribs and walls have a limited capability to be manufactured in sand casting. In automotive industry, rear lower and upper control arm, RLCA and RUCA, in rear wheel suspension and steering knuckle arm in vehicle suspension system are examples of aluminum sand castings. The flowchart below shows the step-wise typical sand casting process:

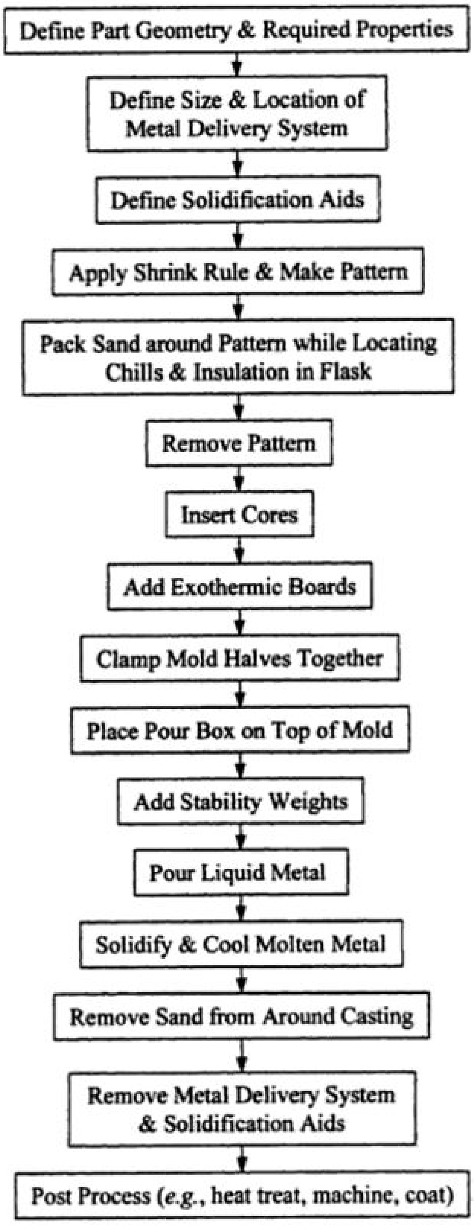

Figure 2.5: Step-wise casting process [10].

2.2.3.1 Different sand casting types

Sand in sand casting method can be either wet or dry. Green sand casting refers casting with wet sand that contains water or oil and organic bonding compounds such as clay. 'Green sand' statement origins from the fact that the sand mold is uncured even when it is filled by molten metal. On the other hand, in dry sand casting the sand mold is baked at a specific temperature to make the mold stronger as ensures accurate size for casting products [11].

2.2.3.2 Sand mold, core and pattern formation

Sand mold creation consists of packing sand around the pattern and holding the sand around the pattern by using box called flask which is removed after the metal has solidified.
In case of having hollow components or producing internal cavities and re-entrants as a result of casting, sand cores are used to create negative spaces in the final piece. Cores are made from sand with special binders and different making types exist [12]. They are placed into the mold after building the mold cavity and in addition to the desired shape of cores, there are extensions called core prints for correct positioning of the cores into the sand mold. In some sand castings due to the disability of making the exact desired cavity forming by pattern cores are used, an example can be a tight corner which cannot be perfectly shaped by sand. Normally sand cores are disposable units which will be destroyed to be able to get it out of the casting product.
As mentioned before, pattern is the replica of the part to be cast. It is used to form a cavity in the molding material where the liquid metal is poured later [13]. The sand cast patterns can be made out of different types of materials. Wooden, different types of plastics or even metals patterns are used in different casting conditions. In order to have a good pattern material selection, various parameters such as size and complexity of the shape, casting method, number of required casting products to be manufactured and characteristics of casting should be taken into considerations [14].
It should be noted that, patterns are commonly made slightly larger than the anticipated casting part to compensate shrinkage in solidification phase which occurs for nearly every metal alloy and also to compensate thermal contraction of the metal during cooling to room temperature. 'Shrink rule' is the phrase used for estimating amount of shrinkage in each metal according to molding process. For instance, the shrink rule for aluminum sand casting with hand packed sand is 1/8 inches [10].

2.2.3.3 Gating system

The liquid metal delivery system in casting is called gating system that must be considered in the casting process design. Typically a gating system includes a pouring basin, down sprue, runner and ingates. Based on the part to be cast, gating system is designed and built. The aim of using gating system is to fully feed the cavity from different regions before solidification takes place which has significant influences on the casting quality. With pouring molten metal into pouring basin of gating system the filling process is begun.

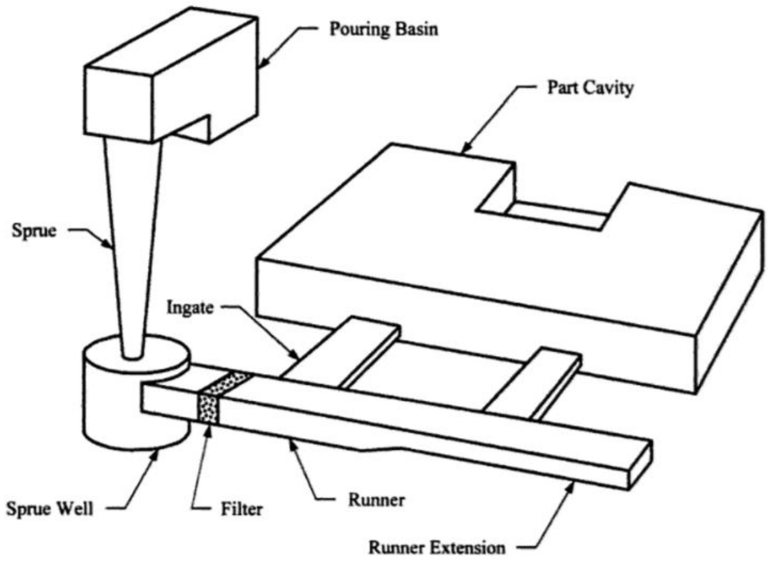

Figure 2.6: Typical gating system [10].

2.2.4 Mold filling

This step starts after completing all needed mold and gating systems preparations. Several considerations should be controlled during the filling process to have a desirable casting part. These considerations are mainly focused on avoidance of having incomplete filling and reduction of casting defects due to liquid filling process [10].
In sand casting mold filling, the first rule is to have a smooth and uniform filling. It means that the rate of liquid metal flow needs to be controlled based on filling requirements [10].
In order to reduce possible filling defects, gating systems should be always full of molten metal. Pressurized gating systems by keeping cross-sectional area of ingates smaller than runners ensure full of metal gating systems. Moreover, in order to have uninterrupted flow, the pour cup has to remain full of liquid in pouring operation [10].
Easy removal gating system after solidification is another general rule in filling of sand casting [10].
Filling all mold regions with liquid metal by means of gating systems should be ensured since a lack of liquid metal in mold filling process causes a wide range of casting defects [10].

2.2.5 Solidification

Solidification is changing the material phase from liquid to solid in a casting process. When the temperature drops, solidification starts. Pure poured liquid metal solidifies at a freezing point which is a constant temperature whereas, solidification for alloys does not occur in an exact temperature point. Depending on the composition of the alloy solidification takes place over a temperature range. This cooling down in the temperature highly affects mechanical properties and the geometric relation between volume and surface area of the casting product. Besides, most of the casting defects are solidification related defects which lead to investigations on the thermal effectiveness of the mold design. In thermal effectiveness of the sand casting mold two important issues are investigated. First, solidification progress must take place from the mold walls upward and towards the liquid feeders to have a good quality in casting products. This progression in the solidification phase is called directional solidification [15]. Secondly, the potential of providing desirable micro-structural constituents, shape and grain size by the mold design [10, 16]. Solidification plays an important role on the quality of the casting product, also time taken for production of the casting resultant shows the importance of solidification stage in casting industry [17].

2.2.6 Casting defects formation

Generally, casting defects can be categorized into two main casting processes, mold filling related defects and solidification related defects. Casting processing demands different physical phenomena such as fluid flow, heat transfer, thermal stress, defect formation and micro-structure evolution. Among mentioned phenomena, heat transfer, fluid flow and thermal stress are influenced by defect formation and the resultant casting quality [10]. Nowadays, different processes in casting are modeled and simulations can be done before or after the real casting either. This modeling significantly helps to detect casting defects and analyze different possibilities in the casting which is highly valuable in terms of time and also cost of the resultant castings. By having the possibility to simulate and model different casting scenarios the final quality of casting can be improved. Moreover, different physical phenomena in filling and solidifying are controlled which can results in having appropriate cast metal in both shape and mechanical property point of view. This method also avoids having trial and errors in casting industry which are hugely energy consuming [10]. Modeling for casting will be described more in details in the other section of this report.

2.2.6.1 Mold filling related defects

Although most of the sand casting defects are formed during solidification, several mold filling related defects also appear [10].

- **No-Fill**
  When the temperature of the liquid metal is inadequate and below liquidus temperature, refers to temperature above which the material is in full liquid state, of the alloy no-fill defect occurs. In fact, the solid fraction is too high and liquid metal cannot fill the cavity completely [10]. In order to reduce possibility of having this type of defect and providing a fully liquid flow front in filling process, the molten metal temperature should not be very high (super-heated) and mold preheat temperature needs to be hot enough. Thin walls are more likely to encounter with this problem in filling stage.
- **Entrapped gas**
  Due to turbulent mold filling pattern, gas can be entrapped into casting. Good gating systems design reduces the possibility of having high velocity mold

filling which cause turbulence and thereby decrease the risk of having gas entrapped in the casting [10].

2.2.6.2 Solidification related defects

Defects forming in solidification are various and they are not fully recognized even with the modern casting modeling. In below the most important defects which form during solidification in sand casting are briefly described:

- **Solidification shrinkage**
  As mentioned earlier, reduction in volume occurs in solidification due to metal phase transformation. Almost every metal alloy has this volumetric reduction after the heat loss and its range is between 3 to 7% [10]. In the isolated regions within the part cavity, liquid metal solidifies and subsequently shrinkage happens. Due to lack of liquid metal feeders in those isolated regions, solidification shrinkage cannot be compensated and therefore voids are created. The isolated areas with liquid metal are known as hot spots and voids are more likely to develop near the top of those areas [10]. The created voids shape and distribution are dependent on the type of alloy and its freezing range. For detecting this type of defect in solidification process in casting simulations, hot spots by using temperature contours are studied.

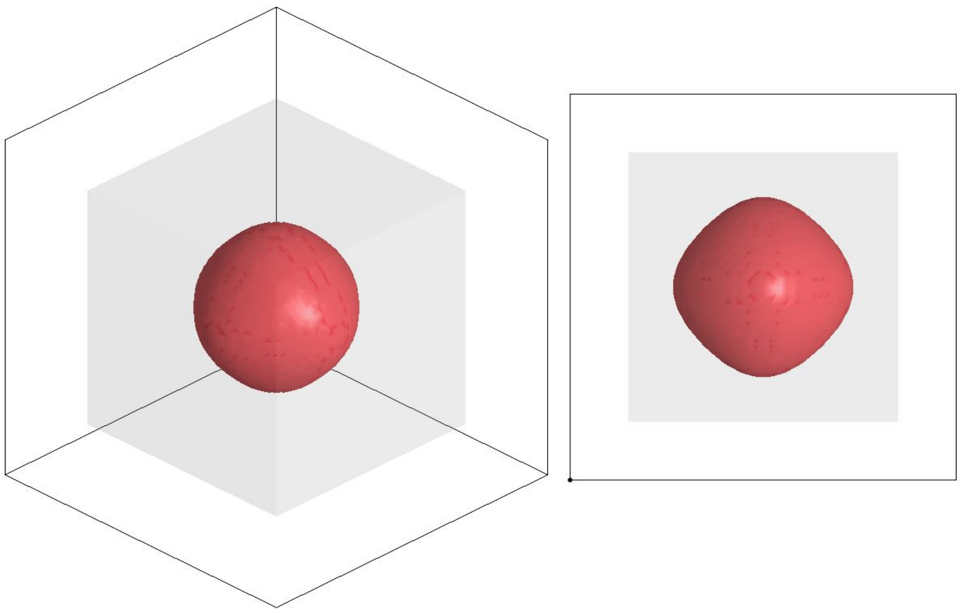

Figure 2.7: Solidification shrinkage example of Aluminum casting cube simulated in NFS with 6.81% volume shrinkage.

- **Gas porosity**
  This defect is not specifically solidification related defect and can be counted as both, filling and solidification related, defect. During pouring or solidifying the metal absorbs gasses which can not be rejected completely from the mold. Consequently, another void type is created which is called gas porosity [10]. The absorbed gasses may be either originated from chemical reactions between

molten metal and sand mold materials or presented inside sand and mold cavity. Some of the absorbed gasses are rejected when liquid metal solidifies but the rest remain in the bubble shape. Gas porosity defects tend to form in long freezing range alloys casting such as aluminum based alloys and since aluminum has a high gas solubility, gas porosity in aluminum is always a concern [10].

- **Hot tears and cracks, residual stresses and distortion**
  During solidification process when thin liquid film contracts, the hot tears and hot cracks can be formed. This is as a result of stresses in temperature reduction. On the other side, residual stresses shows the state of the casting when it has reached room temperature. All these phenomena are related to the strains happening due to thermal expansion, volume variations and solid phase transformations. Moreover, as long as there is no plastic deformation in casting, no distortion will form. But when the thermal stress is higher than yield strength of the cast metal, plastic deformation and nonuniform contraction takes place, therefore distortion in the casting can be found [10].
- **Macro-segregation**
  Macro-segregation defect can be controlled by taking care of local solidification time and the rate of cooling of the casting. This natural phenomenon affects final mechanical properties of the casting [10].

2.3 Modeling of casting process

As briefly mentioned, computational modeling for casting process has been recently made this ability to set the used casting method, in reality, and its related conditions to simulate the process of casting. Filling and solidification in casting involve several physical phenomena which by modeling them different casting possibilities, as well as predictions of the defects, can be checked before going to the foundry workshops. Although all of the defects in casting cannot be predicted, modeling of the casting process helps to improve the casting quality by changing the possible parameters. Especially for new designs with complex geometries, the casting simulations can be used to ensure that designed components are manufacture-able by casting methods. The other benefit which can be reached from the cast simulation is that the casting engineer or the foundry man is able to optimize the casting process. Additionally in defects prediction point of view, the casting resultants are reliable enough to avoid mechanical failures while providing the best solution for each casting scenario [10]. It is obvious that by applying casting process modeling, experimental castings and therefore time and cost can be significantly reduced.
In this master thesis, the software NovaFlow&Solid [18] has been used as a cast simulation software with the focus on filling and solidification process of the cast metal. By doing both simulations, filling and solidification, two main processes of the casting are modeled. The simulation will show visible results as well as numerical scales, so the user can evaluate the efficiency of the assigned casting factors and parameters. In some cases from the filling simulation results, the user understands that the gating systems need to be modified because the cavity is not fed properly. Moreover, by having the solidification results it is possible to check

the effectiveness of the selected orientation of the casting since different orientation selection bring different solidification defects in the cast product. These are only examples of casting modeling results usages. In below the most important benefits of using cast simulation software in the early phase of the production are itemized [18]:

- Standardization of the pouring method. Testing and optimizing the variant of feeding.
- Cast-ability measurement of various designs, particularly for structural and topology optimized designs.
- Investigation and prediction of casting possible defects, for instance, solids shrinkage percentage.
- Analysis of casting temperature changes to reduce energy consumption in the casting processes, especially for casting parts in mass productions.
- Optimization of the complete casting process to provide good casting quality at the lowest cost.

2.3.1 Early phase casting simulation

After understanding the fact of usefulness of the casting simulation in production industries, number of users has been grown rapidly. The best reason of this tendency is that every possibility in casting process can be modelled and the results can then be analyzed. This interest has not only captured for using in manufacturing areas but also engineers in design and product development phases have become one of the largest users of cast simulation computer programs.

In industrial companies, transferring information and feedback between development and production phase is always an important key to finalize feasibility of the new product. In fact, feedback loops between design or development and manufacturing department exist, in which a number of loops have dominant effects on the lead time of the new product. In the traditional development process after doing related analysis, feedback of Computer Aided Engineering (CAE) as well as production engineering were given back to design and development engineering department in order to modify the new product so that it can fulfill the requirements in both mentioned areas [19]. On one hand, stress, fatigue and fracture and even more analysis of the new design. On the other hand, the ability of manufacturing the designed or developed product and evaluation of the production cost cause iterations in the process.

New designs generated from topology optimization also need the mentioned iterations, especially feedback from the production point of view on the complex topology optimized designs. Nowadays, companies try to shorten the lead time beginning from early phase designs to final produced parts. This is the main reason of entering early phase evaluation on the design phase. Cast simulation program is a good example that can be used in the early phase assessment of new designs. By modeling the casting process in an early phase of product development, engineers are able to have rapid and short feedback loops between casting development and production. This leads to have feasible casting designs right after the development phase [19].

2.3.2 Solidification simulation post-processing

Once the simulation is finished, results should be analyzed. Normally, results are interpreted visually so that the defects, thermal gradient, solidification phase rate and etc. are checked by observations and comparisons of color coded contours at different instants of time. Liquid to solid phase transformation, solidification time, solidification direction, the shrinkage percentage, hot spots sizes and locations as well as chronological thermal modulus of the casting are the most important simulation's outcomes that help users to have a correct investigation on the solidification of the casting process. In below solidification simulation outputs are described:

- **Thermal modulus** The Modulus parameter is typically used to estimate the efficiency of the liquid metal delivery system [18]. The term modulus is a general notion expressing a comparable unit of mutual geometrical, physical or technical quantities which determine the course of the given process. The ratio of melt casting volume and its cooling surface area is used for indicating modulus [20]. The thermal modulus helps to have a study on the progression of solidification of the casting part. Once the solidification starts due to higher rate of melt volume reduction compare to surface area reduction rate, the initial value of the modulus decreases [20]. By having the simulation of solidification, the thermal modulus field has been calculated and the solidification progression can then be investigated. As mentioned in section 2.2.5, directional solidification is ideal for casting solidification which is started from thin sections toward thick sections during the solidification time [15]. It should be mentioned that the higher initial thermal modulus value expresses the higher demand for casting feeders' sizes due to the detection of thick parts. In addition, the higher thermal modulus value causes the more possibility of irregular solidification progression in different casting regions and therefore more defective areas are expected. In order to decrease the value of thermal modulus, increasing the surface area of the casting is recommended.

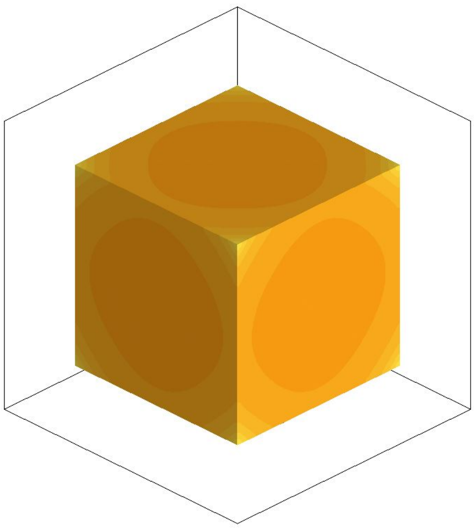

Figure 2.8: Thermal modulus example of Aluminum casting cube simulated in NFS, shows directional solidification.

- **Shrinkage** It has been explained in section 2.2.6.2 that during solidification almost every metal alloy shrinks and the percentage of shrinkage for aluminum alloys is approximately between 3% to 7% of its volume. For prediction of the shrinkage defects the cast simulation software needs to identify the liquid pools surrounded with solidified regions through solidification process and those regions where there is high risk of having shrinkage voids due to material contraction. The studies revealed this fact that long freezing range alloys like aluminum alloys tend to have too many small shrinkage voids over the casting part [10]. The improvement in casting shrinkage results can be done by modifying gating systems, risers, chills and all other filling parameters. If the filling simulation is not modeled, modification of the casting design based on temperature contours will be a good way of improving casting volume shrinkage after solidification simulation. It should be mentioned that all of the design-wise modifications are based on creating directional solidification in the casting part. These adjustments are introduced in details in section 2.4.
- **Hot spot** The liquid trapped pools inside already solidified regions are hot spots' results in the solidification simulation. The software predicts the hot spots result when the liquid phase reaches zero percent. After that, the number and size of the hot spots do not change by temperature reduction of the casting. The hot spots result represents directions of solidification but it should be noted that a number of hot spots are not as the same as a number of shrinkage and it proofs the fact that not all of the hot spots form shrinkage defects and gravity also has an impact on shrinkage formation. The location of formed hot spots are also predicted by the software.
- **Solid phase** The solid phase results represent the progression of the solidification visually. The filled volume value in percentage is calculated based on the solid phase. The areas without material after solidification shows the effect of gravity shrinkage on the casting; However the gravity influence calculation can be turned off when only solidification is simulated to prevent calculating massive gravity shrinkage on top of the casting. In fact, by expelling gravity influence from solidification calculation the result will be orientation independent. Moreover, areas which become solid at last can be indicated from the solid phase results. These last solidified areas are those where thermal modulus can not be predicted and the software shows them transparent in a thermal modulus optical result. In design point of view, thinner parts of the casting component become solidify sooner than thicker parts and this differentiation in solidification progression forms solidification defects. A general guidance for design realization of casting components which avoids defects formation will be discussed in section 2.4.

2.4 Design for casting - Guidelines for design realization

In section 2.2.6 the main concern about the formation of casting defects was explained. In addition to process dependent defect formation, design of the casting could bring weak areas in the casting products. Accordingly, modification on the casting's design is performed for eliminating defects causing because of the shape of the casting. Although the aim of this master thesis is to provide a design out of the topology optimization that does not encounter with manufacture disability, sometimes due to limited capability of the optimizer or after understanding of the solidification process with cast simulation results, changes are required. These modification will be applied to design in design realization phase to either omit minor design related defects or prepare the design for manufacturing. The general guideline below can be applied to all the casting designs, some of them are fulfilled after implementing manufacturing constraints into optimization, though.

2.4.1 Design of junctions

Junctions in the casting designs refer to the intersection of ribs or walls where a meeting of two or more elements occurs. After simulating solidification of the part to be cast, the software predicts the location of the shrinkage porosity. One of the common places which shrinkage forms is at casting junctions [22]. The reason of formation of a defect in such an area is that liquid metal at the junction does not have sufficient surface area and therefore molten metal in junctions cools down and solidifies at the end. It has been already mentioned that metal shrinkage can not be compensated in areas that are surrounded by solidified regions and this causes shrinkage porosity formation at the junctions' locations. Note that as the number of intersections in the place of junction increases, surface area decreases which results in having higher tendency for porosity defect formations [22].
Design for manufacturing (DFM) studies try to propose a guideline for casting junctions. According to a study in the locations where two or more sections meet, by keeping constant outer and inner fillet radius more surface area for both internal and external corners can be created and therefore the possibility of having porosity shrinkage will reduce. This can be a good guideline for design engineers to slightly change the geometry after analyzing the casting solidification results to either reduce the potential of forming defects or make an optimized design more close to the production phase [22].

2.4.2 Draft angle

One of the manufacturing considerations in a design of the casting components is draft angle. The draft angle which specifies in degrees represents the possibility of removing the casting pattern from the sand mold without damaging the created mold cavity. Hence, a positive draft angle should be applied to vertical surfaces of the casting design. By considering positive draft angles in the casting design, the component can be easily manufactured in a cost-effective way since pattern making and cavity creation is assured. It has definitely impact on the quality of the part to be cast with sand casting manufacturing method [23]. The general standard for a minimum positive draft angle in sand casting is 2 degrees [24]. It should be mentioned that by adding draw direction as a manufacturing constraints in topology optimization software negative draft angles are avoided.

2.4.3 Wall thickness

One of the limitations in the casting methods is that each method has its own ability to cast minimum or maximum thicknesses. Different parameters such as the fluidity of chosen alloy, required mechanical and metallurgical quality and the complexity of the casting shape are taken into account when the thickness of the casting component is designed. A recommended minimum thickness in sand casting for aluminum alloys is approximately $3.2mm$ in almost every casting instruction. However, desirable aluminum casting thickness has been recommended as $4.76mm$. Thus, the minimum thickness should be satisfied in the design of the casting. Moreover, padding in the sections with various thicknesses is performed to avoid sudden thickness changes. There is a general rule in the geometry of the casting products which encourages to have a uniform thickness. In case of disability, gradual thickness' growth is suggested. Nevertheless, it brings the need for adding extra material which is opposed to the aim of optimization [25]. As a manufacturing constraint in structural optimization tool, minimum and maximum member size define the limitations for the thickness of every section created in topology optimization. It has been already explained in section 2.1.

2.4.4 Fillet radius

The sharp edges in casting components influence on the quality and manufacturability of the products. Sharp edges are difficult to be fed properly and always redesigning or adding extra feeders are required. By eliminating sharp corners the stress concentrations in these areas are removed and the quality of the casting parts is increased. It should be mentioned that prevention of having sharp edged also helps to have less solidification related defects since directional solidification is more likely to be happened by having internal and external fillet radius instead of sharp corners. A general rule of thumb for an aluminum casting component is to apply rounded corners with the radius of 1.25 times of its wall thickness for internal edges and summation of an internal radius and wall thickness for external radii of the fillet. In case of having various section thicknesses in a joint, it is recommended to select minimum thickness to calculate internal and external radii. An internal radius should be accompanied with an external one to prevent a localized thick section in the corner of the casting [26].

2.4.5 Parting line

During the design of the sand casting component, the place and type of the parting line are crucial concerns. The parting line shows the plane where the mold halves are pulled apart from each other in two different directions to withdraw a casted part at the end of the sand casting process. The parting line typically defines how the manufacturing of the component is difficult. One of the important constraints which can be set during optimization is a draw direction. By adding this manufacturing constraint into optimization setup the casting design has a specific feature to be manufactured based on its parting line. This feature in optimizer brings the possibility of making pattern and cores easier, the orientation of the mold cavity in casting process is also specified.

3

Method

Integrated component development process using topology optimization and cast simulation tools are presented in Figure 3.1. This process starts with CAD modelling of design space considering kinematic motion of neighbouring components of the system and packaging space of the component of interest. On the other hand, in many cases the current components are simplified and de-featured to get the design space which is less time consuming and intended to improve the performance or reduce weight of existing design. In the next phase, the design space is imported to FE pre-processor such as HyperWorks, where the geometry is discretize in to FE mesh. Materials, boundary constraints and loading conditions are then applied. The geometry is grouped into design and non-design elements which are used to retain certain features, critical for assembly and also for application of different manufacturing constraints in certain areas of design space. Further in the software Optistrct user interface, parameters such as responses, objective function and structural displacement constraints related to topology optimization are setup. A parameter study is done by running different optimization formulation and the best formulation is selected by simplifying many nodal displacement constraints into single weighted compliance or volume fraction which is global responses and verifying the results. Further optimization with different combinations of manufacturing constraints along with stiffness requirement constraint is performed with objective as minimizing volume fraction to get the promising designs which are optimal and close to cast-ability requirements.
The concepts which give feasible designs which have weight below the target weight is further post processed using HyperView. Threshold value for filtering low density elements for extracting density plot is calculated by using the proposed template. Appropriate export setting are used to create file which is acceptable in NFS tool where the volume based mesh is generated and boundary conditions, material properties for heat transfer analysis and conditions to terminate the simulations are setup to run solidification simulation.
Criteria for comparing the cast-ability of different concepts is formulated and all the concepts are compared by scoring Kesselring matrix and best concept is taken forward to CAD realization phase where final design modification are made based on standard design guidelines and casting simulation input. At last structural analysis is done to validate the component performance. If the condition are not satisfied the process is looped until satisfactory design is reached. However this step is beyond the scope of this thesis.

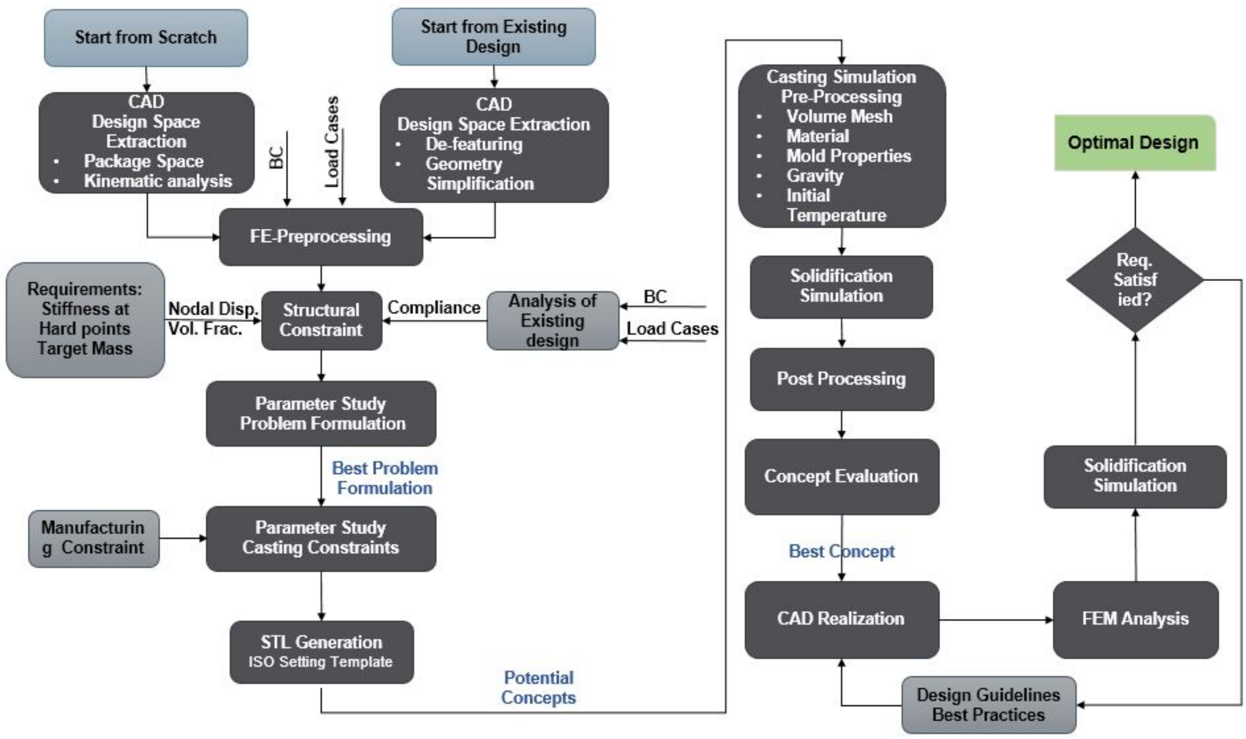

Figure 3.1: Flowchart of the component development process using topology optimization tools integrated with cast simulation tools.

3.1 FEM pre-processing

The design volume is meshed as per the standard solver requirement. In general for getting a good result in topology optimization a solid mesh is used with some guidelines on mesh quality. The SPC boundary condition are setup using HyperWorks workbench and loads are applied.

3.2 Parameter Study

Parameter study is conducted which has resulted in proposal of best possible optimization parameter settings for achieving good quality results which is close to realization of casting. This section includes study of different problem formulation followed by comparison of different manufacturing constraints and varying of opti-control setting in Optistrcut.

3.2.1 Problem formulation Study

In product development of automotive components optimization based method is preferred in two cases; (a) Designs from scratch where the inputs are generally design volume by package space analysis, static loads cases from dynamic simulation of critical manoeuvre or durability tests and stiffness or displacement requirement at the hard points and critical regions. (b) Improve the design of existing components to their optimal where goal is trying to reduce weight of component satisfying the requirement or to increase stiffness of component with the same weight where optimization is difficult due to less flexibility and in some cases to find a completely new solution, where maximum mass or volume fraction is an input to your formulation of optimization problem. Formulation of an optimization can be done in many ways and it is very important to choose the best formulation in order to understand objective, constraints and direction of getting the optimal solution. The flow chart below shows all possible combination of problem.

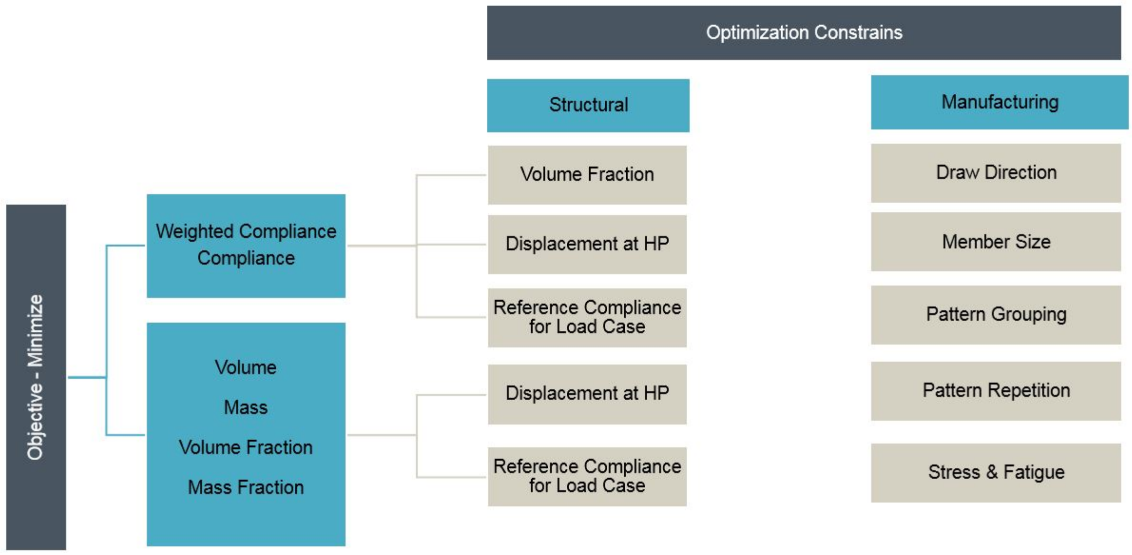

Figure 3.2: Optimization problem formulation possibility.

In this study different manufacturing constraints formulated by Optistruct, as discussed in theory section, is applied to study its influence on compliance and volume fraction.

3.3 Methodology for selecting optimal ISO threshold value

Optistruct uses material distribution method in topology optimization. Material density of each element in design volume forms the design variable which is defined as:

$$\rho_i = \frac{\rho_{ai}}{\rho_{0i}} \tag{3.1}$$

where, ρ_{ai} is the assumed material density, ρ_{0i} is the true material density and i is the normalized material density of the ith element. Material in design space is assumed as non-homogeneous as elasticity properties is a function of density, element density is penalized to force the design variables to take values between 0 and 1. In the course of optimization process the density value continuously changes from 0 to 1. In the last iteration each solid element has taken more or less a material

density which is based on the strain energy that means the higher strain energy in an element the higher normalized density and closer to 1.
The important output files generated from topology optimization solver, Optistruct, are .hist, .mvw, .sh files and .OSSmooth file. Shape file (.sh) contains the material density values, void size parameters and void orientation angle for each element and its IDs in the analysis for the final iteration.
The density plots can be opened in HyperView for better visualization of the colour density counter plots as shown in Figure 4.3 and 5.5. With default colour settings red colour indicates load bearing elements with a density of 1. Blue refers to less important elements with a density of 0.01. The density contour plot shows the structurally important regions in design volume. However, there is a challenge involved on understanding and interpreting intermediate density elements such as elements with a density of 0.3 or 0.7.
Interpreting the topology optimization result has always been a major challenge for integrating optimization with cast simulation tools and design realization phase. ISO value is a parameter in Optistruct which aids in interpreting designs and understanding load paths. The default settings of ISO value is 0.505.
ISO threshold value is manually varied between 0 and 1 in order to decide a solution. This threshold value is chosen by the designer where he feels confident. By choosing this value the designer is excluding all elements with a density value below the threshold, which implies that their respective contribution to the overall compliance of the structure will also be neglected. This is compensated by assigning all elements above the selected ISO threshold with the new standardized density value of 1, which also implies that the compliance of the structure is increased. This demand to have a method to select an exact ISO value can stabilize these effects. This value plays an important role as it will be used in OSSmooth function to extract and import the final design geometry from topology results into casting simulation software as .STL file exchange or .IGES format is used to generate and export surfaces into CAD tools for design realization.
In this thesis an automatic process that uses an excel template which calculates the ISO value for every topology result is proposed. The following steps and formulation are used to get the optimum ISO threshold value.

- Open .sh file in Microsoft Excel program using text import wizard choose ‘fixed with’ radio button to import the element id and its corresponding normalized element density into columns. Sort the data with increasing value of density.
- Paste the sorted data in Sheet1 of template with element ids and densities in A, B columns, respectively. The template itself calculates the threshold value which can be used for further extraction.

The Sheet2 of the template contains the element id in first column and its corresponding element volume in the second column. This can be extracted from .fem file which gives coordinates of each nodes and element ids with corresponding node ids for tetra4 solid element. With this data volume of tetrahedron can be computed using distance formula.
Sheet3 of the template file contains all the calculation details. Vlookup excel function is used to arrange the data in sheet1 and sheet2 such that all elements which form the design and Non-design space are arranged with element id and their cor-

responding volume sorted with normalized densities from largest to smallest. The sum of product of volume and its corresponding density is then computed. This value is searched with the cumulative sum of volume of elements in order by row. The ISO value of the matching row is the threshold. The method is validated by calculating mass with the sum of volume of all elements above the threshold and it matches closely with result of optimized mass.

Element_id	Volume	Normalized Density	Volume x Norm density	Cuml_Vol_Sum
34037	2,471293332	1	2,471293332	2,471293332
34044	3,124259914	1	3,124259914	5,595553246
34046	2,632064371	1	2,632064371	8,227617617
34047	3,157142995	1	3,157142995	11,38476061
34051	3,019929062	1	3,019929062	14,40468967
34052	3,44826926	1	3,44826926	17,85295893
34053	3,271932176	1	3,271932176	21,12489111
34054	3,414513469	1	3,414513469	24,53940458
34056	3,638200476	1	3,638200476	28,17760506
34058	3,044416944	1	3,044416944	31,222022
34060	3,135145624	1	3,135145624	34,35716762
34061	2,954083703	1	2,954083703	37,31125133
460115	1,446930489	0,410853	0,594475732	295965,76
504476	1,406825978	0,410836	0,577974758	295967,1668
468087	1,106240439	0,410835	0,454482291	295968,2731
117456	1,164470436	0,410813	0,478379593	295969,4375
570276	1,829284994	0,410813	0,751494056	295971,2668
707612	1,409222783	0,4108	0,578908719	295972,676
178015	1,776022602	0,410786	0,729565221	295974,4521
643528	1,889283118	0,410749	0,776021152	295976,3413
339910	2,485258593	0,410742	1,020800085	295978,8266
607840	1,798667613	0,410736	0,738777541	295980,6253

Sum_ISO	148427,9
Sum_Volume	1667801
Sum of Vol*Norm_density	295974,7
Threshold ISO value	0,410786
Row number	148641
Volume	295974,5
Density	2,80E-09
Mass	0,000829

Figure 3.3: Template to find the threshold ISO value for OSSmooth extraction.

The whole process is automated and can be easily implemented for another component, which is very crucial for integrating topology optimization.

3.4 Cast simulation

In NovaFlow&Solid program [18], the two important casting processes, flow and solidification modeling, can be simulated. In the production phase, the cast part is always simulated in both modeling modules. Whereas in an early phase evaluation of the design, the cast component is modelled only in solidification module. This is because of vast required data to set up the flow simulation. Typically, many fluid considerations should be taken into account for filling simulation. Usually many flow parameters are not even clear for foundries. Besides, the filling parameters and melt pouring types are very facility dependent and that is not an identical operation in every foundry. In fact, precise flow simulation is not an easy work in an early design development phase without having sufficient detailed knowledge of casting and the parameters can be varied case to case. Despite, having complete cast simulation helps to evaluate the gating systems' design and its effectiveness in filling, optimize the design, location and the size of the material delivery system belongings, optimize the casing process and ensure the robustness of the manufacturing process.
Subsequently in this master thesis, we will be focused on solidification simulation

module of NovaFlow&Solid program to evaluate the topology optimized designs with respect to manufacturing constraints.

3.4.1 Solidification simulation setting in NovaFlow&Solid

The casting simulation setup starts with importing the geometry of the part to be cast. It can be either only one single part or a few pieces of designed geometry with all assembly parts such as cores, risers, sleeves, ingate system and channels. It has been discussed earlier that in the current master thesis project the solidification simulations are the main concerns and therefore there is no need of having other assembly parts of the whole casting design except the designed casting component. After importing the casting .STEP or .STL geometry file the orientation of the casting needs to be fixed. The casting orientation defines how the casting cavity and its mold will be orientated in the casting process. The simulation setup is followed by generating desired mesh for the casting and the mold. The number of cells after building the meshed part will definitely affect the precision as well as the computational time of later simulations. Note that, volume mesh is generated by NovaFlow&Solid from imported file [21]. There is a recommendation from the software instruction shows how the fine meshes should be. NovaFlow&Solid recommends having meshed cast geometry so that all the casting sections trapped at least in three mesh cells to ensure precise simulation results. The structural boundary conditions are automatically taken care by the software. The next step is assigning materials for the casting. The casting metal, the mold and even the gas or liquid material inside the cavity mold need to be set. An identical material which is assigned for all of our cast parts is 'EN AC-44100', aluminum based alloy. All the specified parameters and properties for mold and cast material are shown in Table 3.1 and 3.2. For solidification simulation setup, initial temperature distribution, preheating conditions, simulation parameters, shrinkage calculation model and heat transfer model are then set to consider the exact casting solidification conditions. The default values have been used for these mentioned parameters. Before running the simulation, stop criteria of the simulation can be selected based on the casting process. It is possible to either stop the simulation at an exact time or at a specific volume of the liquid phase or even when the temperature of the alloy reaches a particular value. After all these possibilities in modeling different casting conditions, the model is ready to simulate.

Table 3.1: Aluminum casting material details [21].

Casting Material	Initial Temperature [$°C$]	Solidus Temperature [$°C$]	Liquidus Temperature [$°C$]	Initial Density [kg/m^3]	Heat Conduction [$W.m^{-2}.°C^{-1}$]
EN AC-44100	690	573.9	591.4	2360	100.01

Table 3.2: Green sand mold material details [21].

Mold Material	Initial Temperature [$°C$]	Rigidity	Gas Permeability [$m^2.pa^{-1}.s^{-1}$]	Initial Density [kg/m^3]	Heat Conduction [$W.m^{-2}.°C^{-1}$]
Green Sand(S)	20	0.5	4.250	1520	0.73

4

Topology optimization for Rear Upper Control Arm

This chapter explains the component development process proposed in methodology for RUCA using structural optimization tool, Optistrcut, and cast simulation tool, NovaFlow&Solid. Rear Upper Control Arm is casted with aluminum which is bolted to sub-frame and knuckle. RUCA is subjected to forces via knuckle and has a important functionality in the chassis system.

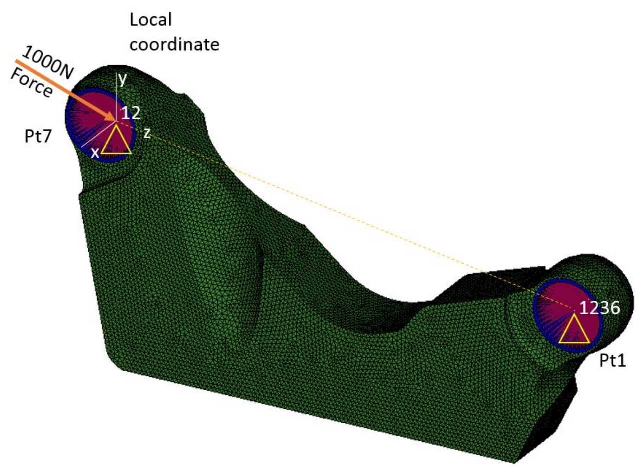

Figure 4.1: RUCA pre-processing setup and boundary condition.

Linear Tetra4 elements are used with average element size of 1.5mm considering mesh quality criteria as per mesh guideline for solid chassis components. Hard point 1 assembles with the sub-frame and hard point 7 to the knuckle. Two nodes are created at pt1 and pt7 hard point coordinate as shown in Figure 4.1. These two nodes constitute reference nodes in connecting couplings. The couplings at pt1 and pt7 are for each reference node grouped is created by node based surface set solely containing the nodes on the surfaces with a normal perpendicular to the bushing axis. A local rectangular coordinate system is defined with its Z axis passing through between pt7 and pt1, oriented in the direction towards pt1. Furthermore, three defined hard point nodes are transformed into this local system.

Load application and stiffness requirement Unit load of 1000N is applied in hard point pt7 as single static load case. The structure stiffness, when loading in positive/negative local Z direction (compression/tension), is of interest. The displacement should not be more than 0.06mm (scaled value) in both positive and negative local Z direction for an unit load.

4.1 RUCA problem formulation study

In this study first, a simple component RUCA, Rear Upper Control Arm, with one unit load case with a displacement requirement of 0.06mm (scaled value) at hard point 7 is considered and we setup the problem without considering any manufacturing constraint. In this case, there is a choice of either minimizing volume fraction or minimizing compliance of structure for the unit load case as objective constraint with displacement requirement. The table below shows the results of optimization with different possible combinations.

Table 4.1: Results of different optimization formulation of RUCA (scaled values).

Objective	Constraints	Compliance	Volume Fraction	Mass [kg]	Displacement [mm]
Min Vol.fraction	Displacement 0.06	29.93	15.73	0.79	0.059
Min Vol.fraction	Displacement 0.06 & Compliance 30	29.94	15.73	0.79	0.059
Min Compliance	Volume fraction 15.73%	30.63	15.73	0.79	0.060
Min Compliance	Vol. frac. 15.73% & Displacement 0.06	30.20	15.73	0.79	0.060
Min Compliance	Displacement 0.06	6.84943	99.39	4.64	0.059

The FE model of actual RUCA component is not available as a given input. Hence, the information about the compliance of the actual structure is not clear. It is best to consider minimize volume fraction with the given displacement constraint. Output of this run gives us the optimum value of compliance and mass as it is a well-known fact that optimal solution is a trade-off between compliance and mass. It is also observed that formulation with minimized compliance with displacement constraint does not work as the optimization solver will stop soon as it fulfills the displacement requirement, “optimal design is probably not reached if the requirement is too easy to fulfill, since the optimization stops too early”. This gives a hint of adding a volume fraction constraint for the next problem formulation.
The following conclusions can be derived out of this study:

- Minimize volume fraction as objective with displacement constraint is the best formulation as it gives the optimal compliance and minimum mass.
- Compliance is a direct measure of displacement. It is observed that for unit load case the compliance is inverse of $\frac{1}{2}$ the displacement that is $C = (\frac{1}{2}0.06)^{-1} \cong 30$ (scaled values) which follows the definition of compliance in theory.
- In order to use minimize compliance as an objective, displacement requirement is not enough. It is recommended to use volume fraction constraint which in turn satisfies the displacement requirement. It can also be considered that if compliance requirement is fulfilled, nodal displacement requirement is taken care automatically.

4.2 RUCA manufacturing constraints study

Optimization with all possible combinations of casting constraints are tried with two different penalization factors of p=2 and p=4 and the result is plotted as shown in Figure 4.2.

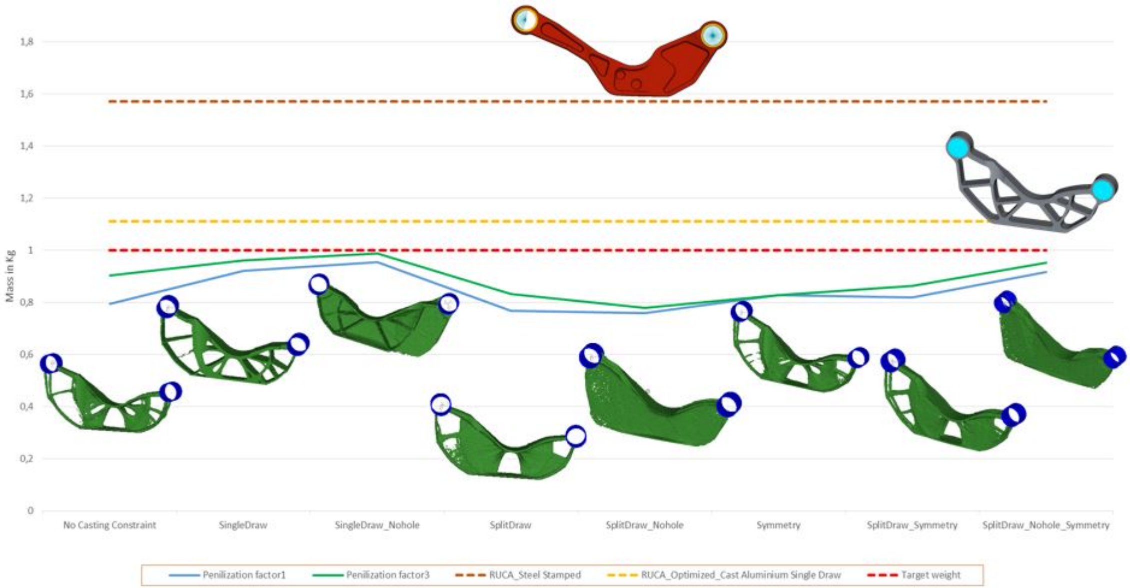

Figure 4.2: Comparison of optimization with different casting constraints of RUCA.

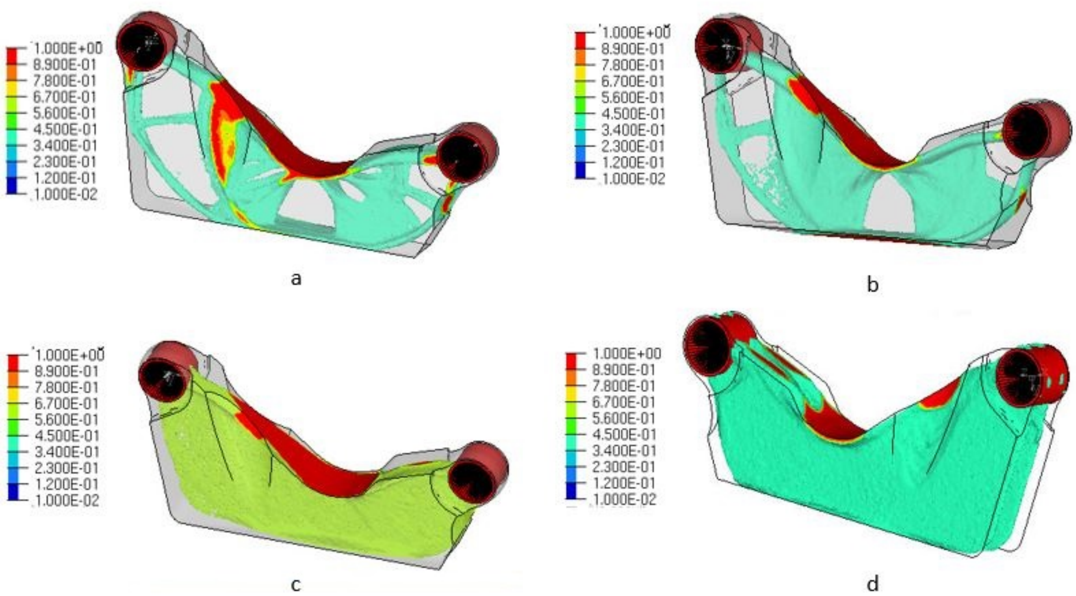

Figure 4.3: Density plots of optimization results with different casting constraints (a)No manufacturing constraint, (b)Split draw, (c)Split draw with No-hole, (d)Split draw with No-hole with Symmetry.

All the concepts generated with different manufacturing constraints have the same structural performance with global compliance response 30 (scaled values). It can also be seen that the problem with no manufacturing constraint is heaver than the problem formulation with split draw and split draw with no-hole constraints with same compliance value and nodal displacement. This is interesting observation which confirms that by applying manufacturing constraints, the Optistrcut solver takes different formulation which can lead to better optimized solution. One more observation is when we combine a split draw with no-hole with symmetric constraints, instead of forming one single shear plane on auto mid plane as in case of split draw with no-hole constraint, the optimization converges with two parallel shear planes. However, when no manufacturing constraint is applied it gives a hollow structure with ribs on outer surface of design space as shown in Figure 4.3. The formulation with split draw no-hole and stamped does not converge to optimal. It can be seen that all formulations in RUCA resulted in less weight than the previously optimized and redesigned component with single manufacturing constraint. Now, it is required to continue with 4 best concepts to next step for casting simulation in order to understand the cast-ability of these designs.

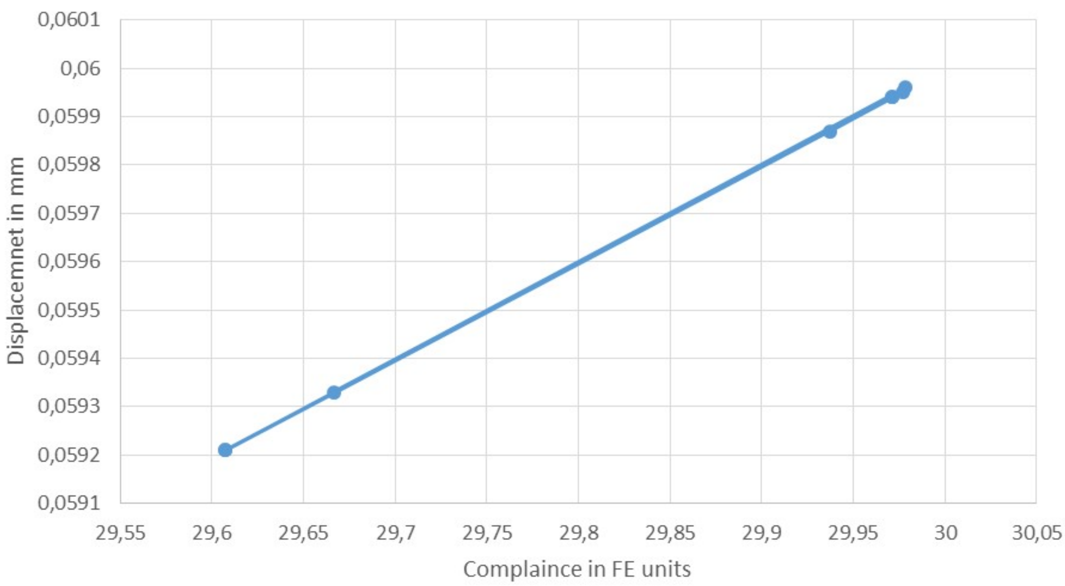

Figure 4.4: Compliance vs displacement for different casting constraints.

4.3 Casting simulation for RUCA

The cast simulation results for solidification of different topology optimized RUCA designs are presented in Figure 4.5 to 4.7. It needs to be mentioned that all the simulations are done without performing any CAD realization phase.

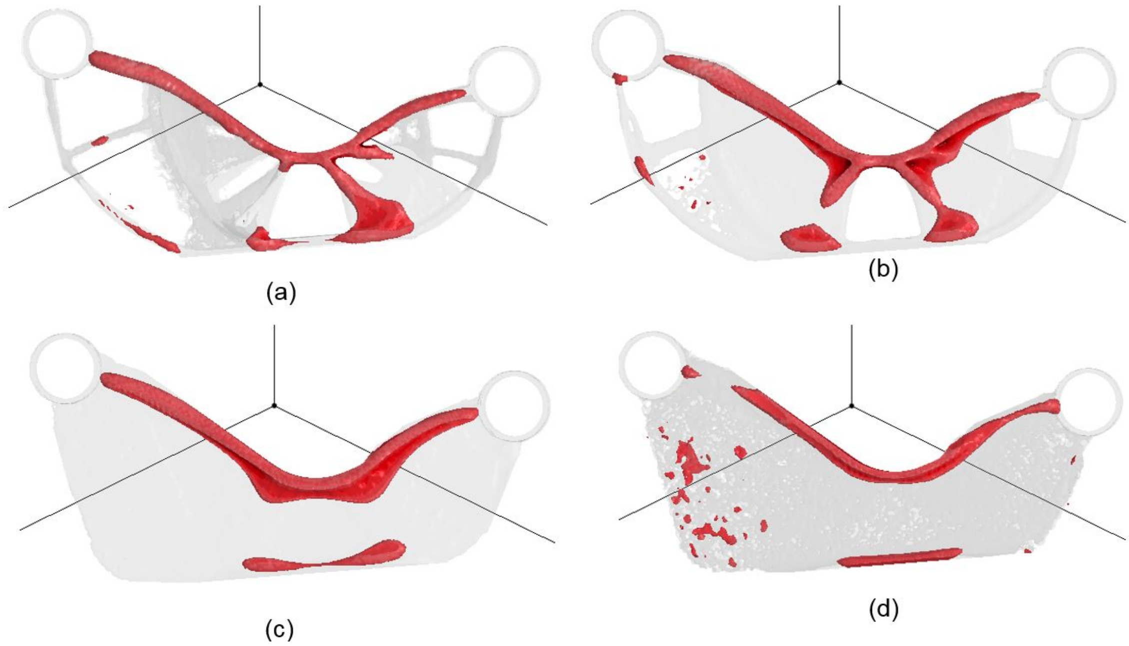

Figure 4.5: Volume shrinkage indication of RUCA showing defective regions for different casting design. Optimization with (a)No manufacturing constraint (b)Split draw (c)Split draw No-hole (d)Split draw No-hole Symmetry.

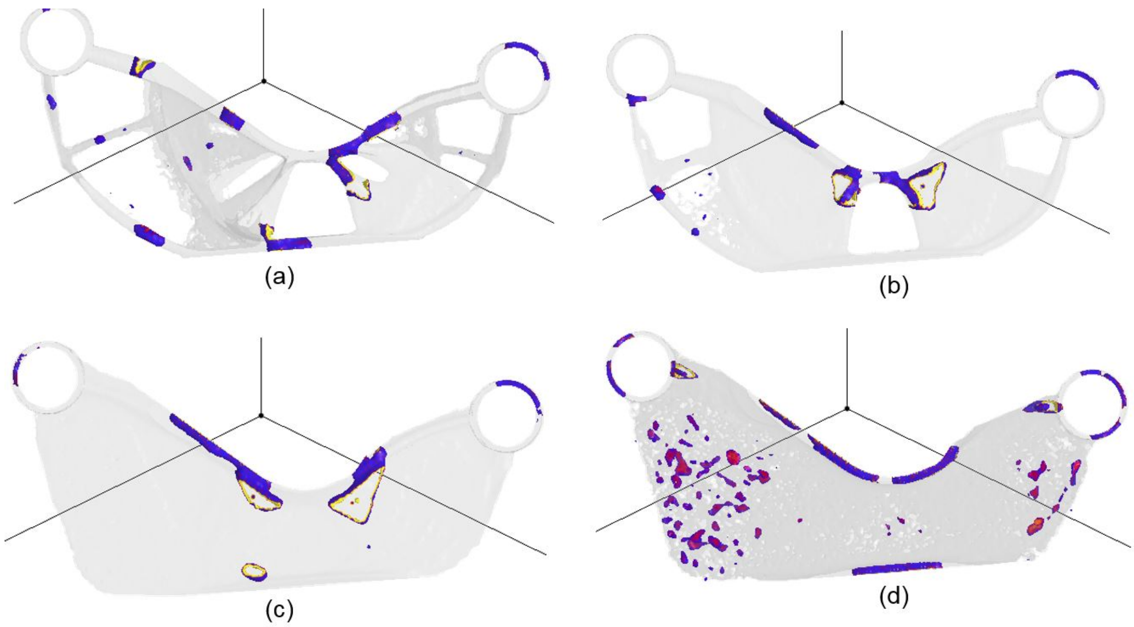

Figure 4.6: Hot spots of RUCA showing directional solidification for different casting design. Optimization with (a)No manufacturing constraint (b)Split draw (c)Split draw No-hole (d)Split draw No-hole Symmetry.

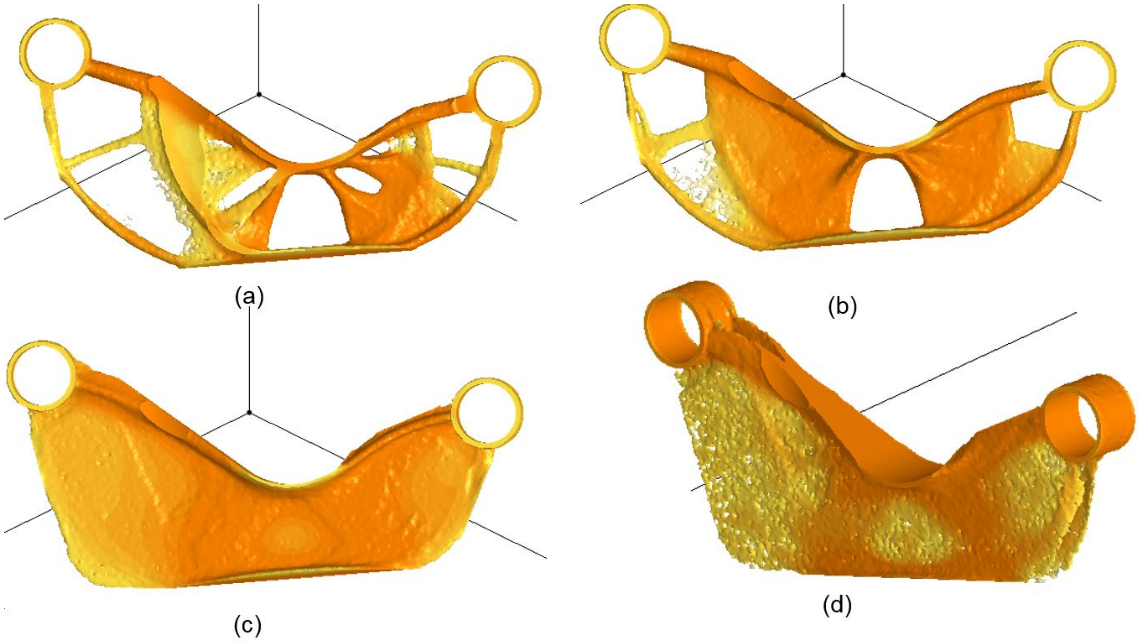

Figure 4.7: Thermal Modulus of RUCA showing directional solidification for different casting design. Optimization with (a)No manufacturing constraint (b)Split draw (c)Split draw No-hole (d)Split draw No-hole Symmetry.

After optimizing RUCA with different manufacturing constraints, it has been decided to evaluate the different topology optimization designs by considering different requirements. This concept evaluation is mainly proposed when more than one optimization result exists and a decision regarding the final selected concept with respect to cast-ability needs to be made. In this evaluation, categorized requirements are weighted based on the results of both topology optimization and cast simulation and that concept wins which has collected higher weight summation. The evaluation matrix with considered requirements for four final RUCA concepts is shown below:

Requirmnet specification			Concept 1		Concept 2		Concept 3		Concept 4	
			No manufacturing constraints		Split draw		Split draw Nohole		Split draw Nohole Symmetry	
	Requirment	Criteria	Value	Weights	Value	Weights	Value	Weights	Value	Weights
Structural	Target Mass	Less than 1 kg	0,819	2	0,848	1	0,793	3	0,674	4
	Compliance	Lower the better or 30 FE units	29,937	2	29,979	1	29,666	3	29,607	4
	Stiffness	More than 16.66 at Hardpoint 7	16,702	2	16,678	1	16,855	3	16,889	4
Cast-ability	Draw Direction	Depends on complexicity of result	High	1	Medium	2	Low	3	Least	4
	Number of cores	Less the better	1	3	0	4	0	4	0	4
	Thermal modulus	Less the better	0,293	3	0,351	1	0,311	2	0,169	4
	Solidication time	Less the better	134	2	143	1	115	3	60	4
	Directional solidification/ Isolated pools	Less the better	10	3	9	2	4	4	15	1
	Number of junction with more than 3 ribs	Less the better	9	2	5	3	0	4	0	4
	Hotspots counts	Less the better	12	1	7	3	5	4	10	2
	Shrinkage %	Less the better	7,337	1	7,182	3	7,097	4	7,303	2
Sum of weights			22		22		37		37	

Figure 4.8: Concept evaluation matrix for four topology optimized RUCA designs with different manufacturing constraints.

Note that an objective function for all four concepts coming from topology optimization is minimizing mass. The Figure 4.8 shows how different topology optimized concepts have been weighted based on structural and cast-ability criteria. The ranking method gives higher weight to the best concept in each aspect.
Out of four different concepts for RUCA, concept 3 and concept 4 have received higher total weight. It means that these two concepts are closer to the casting process and they are the best-optimized concepts by considering cast-ability requirements. When it comes to comparing the two final concepts, the cast-ability evaluation can be taken into account. In other words, in our evaluation system the concept which fulfills the cast-ability requirements more than the other would be a better choice to continue with. This can be a good technique to differ the final concepts.
After evaluating concepts with the suggested matrix and having the result of cast simulation for the selected concept(s), design modifications in development phase can be accomplished to make the design ready for manufacturing phase.

5

Topology optimization for Rear Lower Control Arm

Rear Lower Control Arm is studied which is an aluminum cast component bolted to sub-frame, knuckle, damper and leaf spring attachments. RLCA is subjected to many forces and moments through adjacent components.

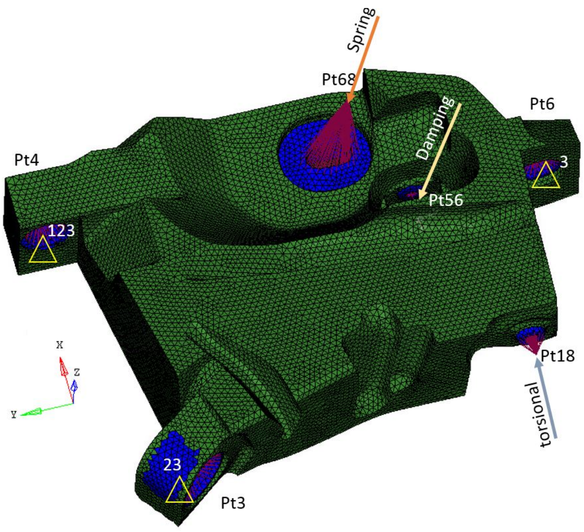

Figure 5.1: RLCA pre-processing setup and boundary condition.

Hard point 3 and 4 assemble to the sub-frame, whereas pt6 and pt18 assemble to the knuckle. The pt56 engages the damper and the pt68 attaches to the spring element (Leaf or Air spring) as shown in Figure 5.1. Second order tetra4 solid elements are used with average FE grid element size of 6mm and mesh quality criteria to be used for the RLCA are as per the standard mesh guideline for solid chassis components. At each hard point coordinate, a node is created for couplings connection where the loads and boundary condition are applied. The coupling uses RBE2 element for pt3, pt4, pt6 and pt18 for each hard point grouped into a node based surface set solely containing the nodes on the surfaces with a normal perpendicular to the coupling axis. The damper interface couplings are a part of the clevis bracket which is modelled rigid coupling for simplicity and also the pre-tension of bolts are neglected. The c-beam element with steel material properties is used which connects the series of coupling and forms the spring connection at hard point pt56.

Load application and stiffness requirement The six leading load cases channels are selected from load extraction from chassis rig cycle test and different dynamic loading events.

- Torsional load is unit load of $1000N$ applied at pt18 along positive x direction.
- Damping load is unit load of $1000N$ applied at pt56 along negative z direction.
- Spring load is unit load of $1000N$ applied at pt68 along negative z direction.
- Drive over curb – DOC is set of load and moments applied at all hard points.
- Rearwards drive over curb – ROC is set of load and moments applied at all hard points.
- Brake in pothole – BIP is set of load and moments applied at all hard points.

The structure stiffness when loading in negative Z direction in three different points, are of interest named as Torsional, Leaf spring attachment and Damper attachment stiffness. Displacements are measured which must be less than 1.0989, 0.33, 0.033 (scaled values) for unit loads at respective loading points are pt18, pt68 and pt56.

5.1 RLCA problem formulation study

Rear Lower Control Arm, RLCA, is a complicated problem with 6 load cases and 3 displacement constraints at hard points Pt68, Pt18 and Pt56 for spring, torsional and damper loads, respectively. The linear static analysis of the existing component is run in Optistruct solver to benchmark the structural responses of the component so that these values can be used to study different problem formulation. The result of analysis is given in Table 5.1.

Table 5.1: Static linear analysis of current design of RLCA, compliance in FE units and displacements in millimeter (scaled values).

Load Case	PTL6	PTL3	PTL4	PTL68_Spr	PTL56_Damp	PTL18_Torsi	Compliance
ROC	2.046	0.462	0	1.584	1.287	2.244	8417
BIP	2.970	0.396	0	2.706	1.188	3.366	11601
DOC	2.343	0.297	0	6.6	3.762	12.27	47432
Torsional	0.165	0.066	0	0.165	0.033	0.825	115
Damper	0.066	0.033	0	0.231	0.099	0.132	32
Spring	0.033	0.003	0	0.099	0.099	0.033	13
Requirement				0.33	0.132	1.0989	67613

Following conclusions can be derived out from the FE analysis of current RLCA component:

- The displacement requirement at hard points of interests is satisfied for torsional, damping and spring loads cases.
- The load case DOC is dominating load case and load case BIP is the second dominating load case.
- The requirement displacement constraints will not be enough to define an effective optimization problem.
- The original component is 9% of current design volume.

In the case of RLCA, all the load cases and its corresponding compliance and displacements are available, since the design volume of this component is given from packaging space analysis. Therefore, the topology optimization problem can be formulated in many different ways as listed below in Table 5.2 with the results of optimization.

Table 5.2: Results of different optimization formulation of RLCA (scaled values).

Objective	Constraints	Weighted Compliance	Mass [kg]	Volume Fraction [%]
Analysis current RLCA	RLCA	67613	4.75	9
Min Volume fraction	36 Displacements	67432	4.005	7.75
Min Volume fraction	6 Compliance	67056	3.80	7.28
Min Volume fraction	3 Displacement & 3 Compliance	67413	3.69	7.01
Min Volume fraction	Weighted Compliance	50548	3.50	6.55
Min Volume fraction	3 Displacement	1496406	2.32	3.74
Min Weighted compliance	3 Displacement & Vol. frac. 9%	41480	4.52	8.99
Min Weighted compliance	Volume fraction 7.28%	41094	3.80	7.28
Min Weighted compliance	Volume fraction 9%	39887	4.52	9.0
Min Weighted compliance	3 Disp. & 3 Compl. & Vol. frac. 7.3%	56723	3.82	7.3
Min Weighted compliance	3 Disp. & 3 Compl. & Vol. frac. 9%	40047	4.528	9
Min Weighted compliance	3 Displacement & 3 Compliance	3640	42.68	99.99
Min Weighted compliance	36 Displacements	3640	42.68	99.99
Min Weighted compliance	3 Displacement	3640	42.68	99.99

The results of competent optimization problem formulation is plotted graphically for better understanding of effect of problem formulation on results and how optimal compliance and volume fraction varies and also to facilitate the selection process.

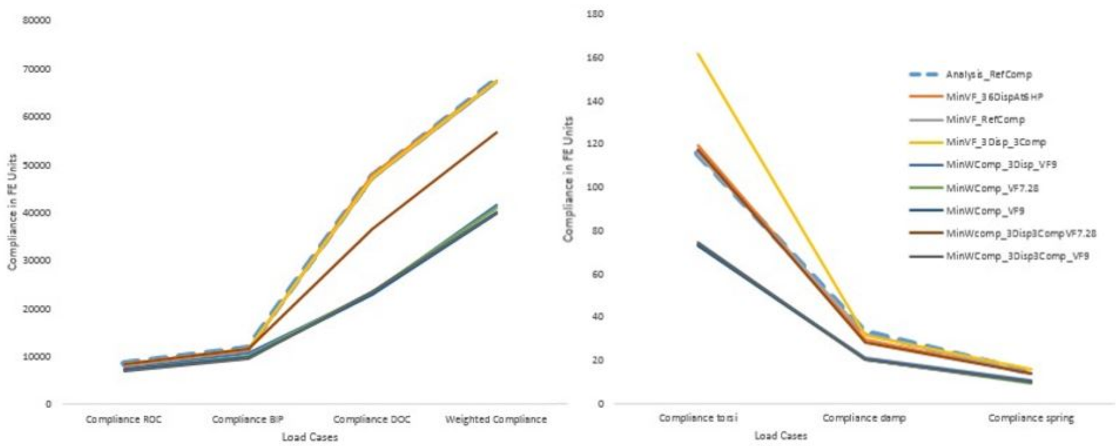

Figure 5.2: Comparison of compliance for different optimization formulation study.

The dotted blue line shows the reference compliance performance of the current component with their respective load cases and all the curves which are on this line or below this line are good problem formulations. The following conclusions can be derived out from this study:

- In problems with minimize volume fraction as objective all formulations except constraint with 3 displacements result in stiffer solutions than the reference component. Hence, the best formulation can be chosen considering the criteria of minimum volume fraction. The formulation with 6 reference compliance constraints which give 7.285 percent of volume fraction is chosen as the best formulation.
- It is also observed that problem with minimize compliance with volume fraction constraint obtained from previous runs reference component results qualifies individual compliance requirements. Which indicates that in problem with multiple load cases and displacement requirements this method can be used to convert the complex formulation into single constraint and objective problem.
- Minimize volume with 36 displacement constraints captures the classical trade off optimization problem of compliance and weight.
- Compliance decreases with increase in mass fraction constraint.

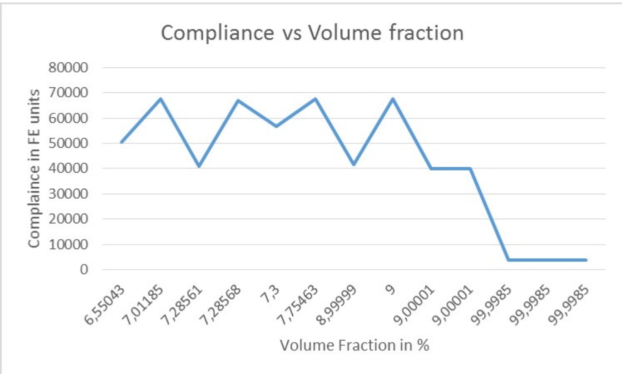

Figure 5.3: Trade off between compliance and volume fraction for different formulation.

The trade-off between compliance and volume fraction is shown in the figure above. The case with minimum volume fraction and weighted compliance gives more optimal solution. The case with problem formulation of minimizing volume fraction with 6 reference compliance as constraints gives the best solution.

5.2 RLCA manufacturing constraints study

Optimization with different combinations of available manufacturing constraints are applied in this study. The formulation shown in the Figure 5.4 is a minimize volume fraction as objective function and 6 compliance responses form 6 load cases as structural constraints obtained by FE analysis of current RLCA displayed in Table 5.1 coupled with each of the manufacturing constrains as following:
(a) discreet parameter, (b) minimum member size, (c) minimum member size + maximum member size, (d) minimum member size + maximum member size + gap

between each member generated, (e) single draw direction, (f) split draw direction, (g) split draw with no-hole with uniform thickness.

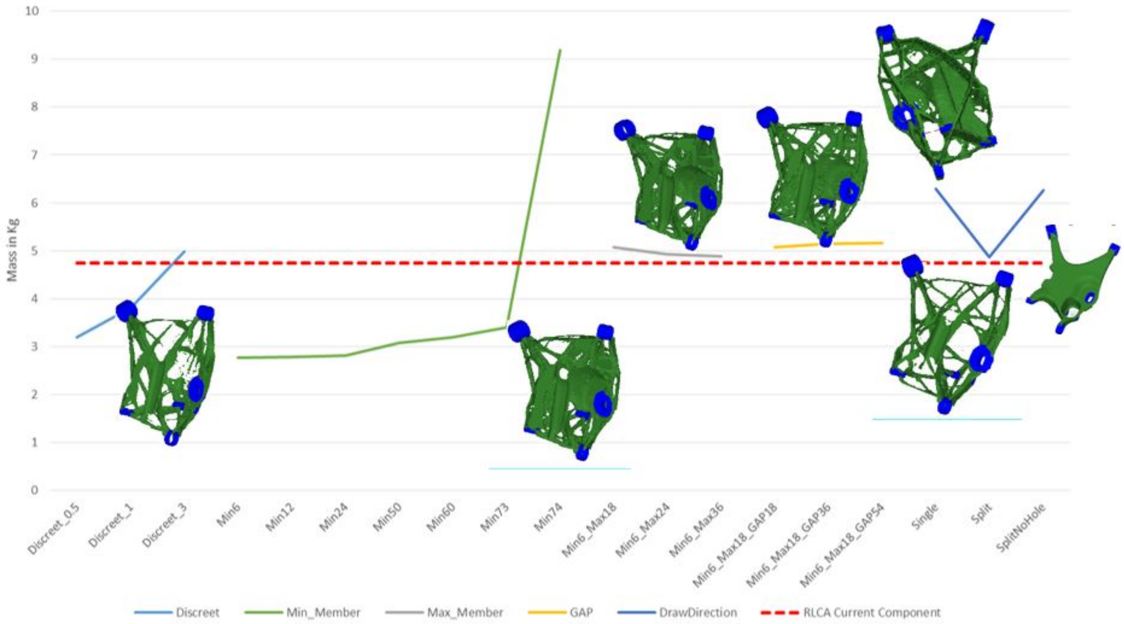

Figure 5.4: Comparison of volume fraction of RLCA for optimization with different casting constraints with same structural performance.

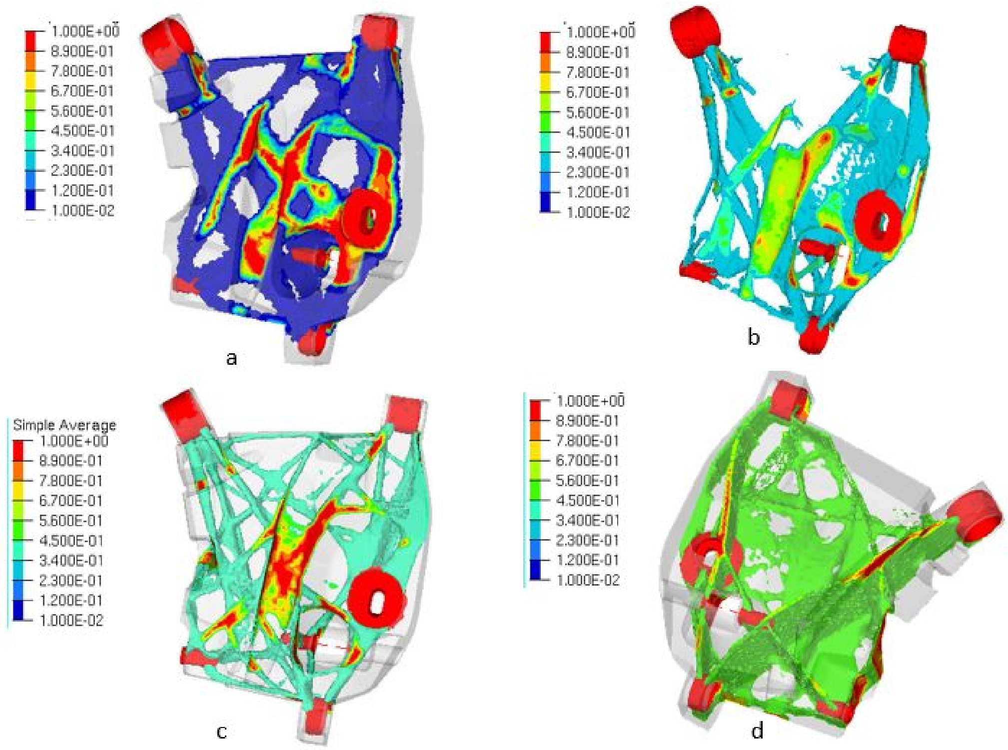

Figure 5.5: Density plots of optimization results with different casting constraints (a)Min member size of 73mm (b)Penalization factor of 1.5 (c)Split draw (d)Single draw.

The results of the optimization have been plotted in Figure 5.5. It is seen that formulation with minimum member size of 73 millimeter looks lighter compared to the original component and has more defined ribs. The result is also closer to casting in terms of production compared to formulation with no manufacturing constraints and split draw that results in many thin ribs with hollow design. Hence, it is not considered for further casting simulation.

In section 4.3 and 5.3 solidification simulation results are presented. The general simulation setup has been already mentioned in 3.4.1. It should be explained that as long as the filling simulation is not conducted in our simulation there is no need of setting gating systems and melt pouring type. Plus, due to lack of filling simulation it is recommended to cancel out the gravity influences on the shrinkage calculation to get a result without interfering of filling parameters. By having this setup the solidification results are orient-independent and investigations on the orientation of casting are therefore eliminated.

5.3 Casting simulation for RLCA

For interpreting the casting feasibility of the RLCA which its design is way more complicated than RUCA, two different designs are cast simulated. The first design is result proposed by previous master thesis where topology optimization of same component, RLCA, has been studied without considering any manufacturing constraints [27]. Thus, the final proposed design (I) has passed manual design realization phase to ensure the mold-ability of the component. Due to interests in checking the cast simulation results on this component and investigating the effectiveness of the design realization phase, solidification of casting setup has been simulated. Finally, the second design (II) is a proposed topology optimized RLCA component with implementing manufacturing constraints during the optimization phase by current study. Note that the geometry of design (II) has been imported directly from optimizer to cast simulation software without passing any design realization phase. The casting design proposals and their solidification simulation results are shown below.

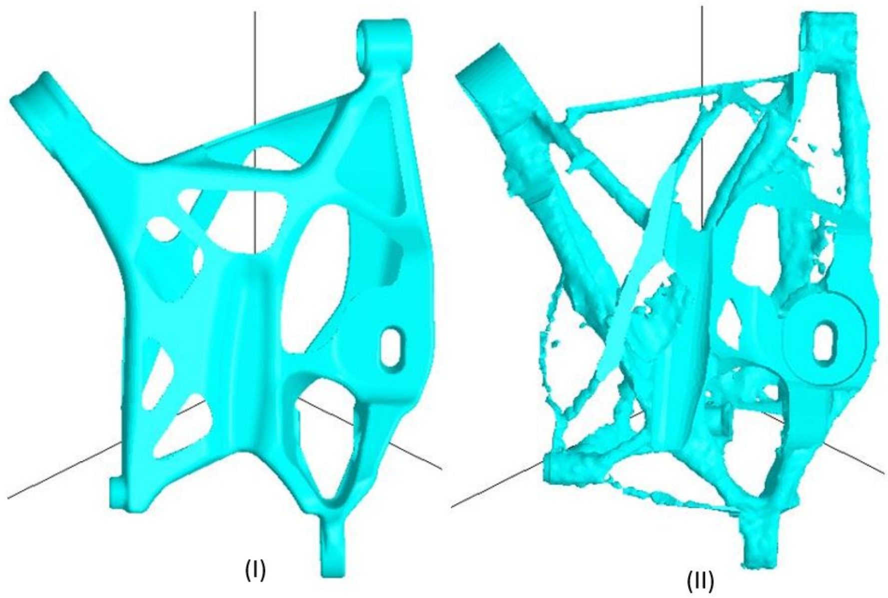

Figure 5.6: (I)Proposed RLCA design of previous study [27]. (II)Proposed RLCA design with considering manufacturing constraints.

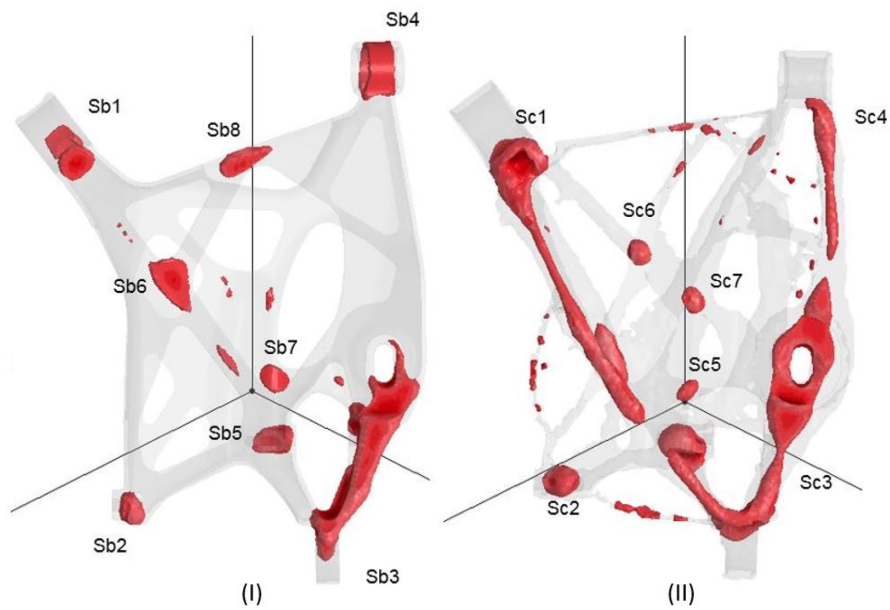

Figure 5.7: Volume shrinkage indication of RLCA showing defective regions for different casting design.

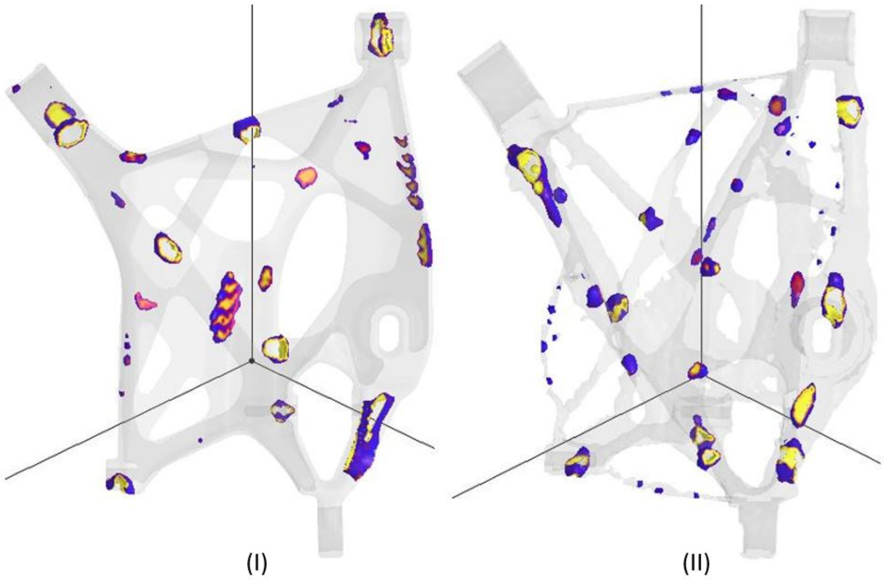

Figure 5.8: Hot spots indication of RLCA showing different directional solidification for different casting design.

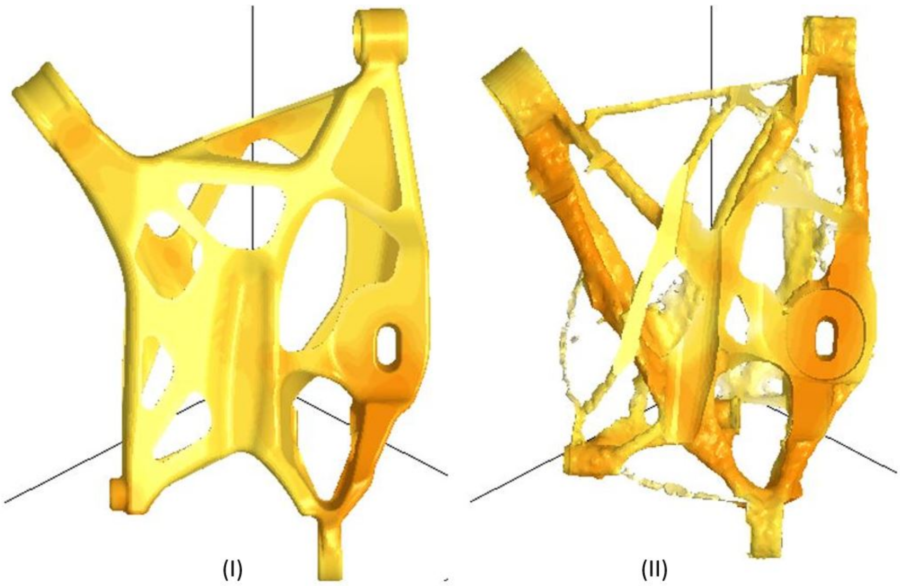

Figure 5.9: Thermal modulus indication of RLCA showing thickness variation of component for different casting design.

The results are interpreted as:
Solidification shrinkage detection shows several zones ending up with material contraction resulting in forming defective areas. The two major thick sections as seen in Figure 5.9 (II) are at the dark regions in the bottom right and diagonal rib of the casting which results in identifying two large volume shrinkage at these regions. With an investigation on the liquid phase visual results in chronological order, solidification direction inspection is carried out. The directional solidification inspection on first design proposal of RLCA (I) displays that the whole component is solidified

in 14 different directions. Each direction creates an isolated liquid pool and gives raise to porosity which reduces the quality of casting. The hot spots with minor differences are predicted at the same locations which reconfirms the directional solidification inspection. Thickness variation, sharp edges and the junction of walls are the main causation of having many solidification directions, these have been figured out after checking geometric dimensions and thermal modulus. It should be again noted that filling simulation is not considered. The shrinkage prediction of design proposal (I) reveals the fact that even after considering the standard design guidelines for interpreting the optimization results by the design engineer, redesigning to remove shrinkage defects in the rib intersections is needed at regions S_b5, S_b6, S_b7 and S_b8 predicted from simulation as feeders at these regions are not practical. It can also be suggested to have ingates for filling simulation in regions labeled as S_b2 and S_b3 since these are thickest regions as seen from thermal modulus and also shrinkage volume is high which can be compensated during filling. It is also observed from hot spots prediction result that porosity is high and distributed on load carrying ribs which results in lower quality casting.
From casting simulation of design proposal (II) it can be seen that shrinkage is concentrated on the diagonal rib and lower right region. Thermal modulus suggests the need of having a gating system at these regions to compensate the large volume shrinkage happening. Hot spots on thin ribs can be neglected which can be removed during later design realization phase. It can be concluded that solidification results are valuable inputs for design engineer to perform CAD modification in early realization phase. It also gives the design engineer basic clues of gating and feeding points.

6
Discussion

In this work we have presented an approach to handle the casting component development process using topology optimization and casting simulation. The method is based on first identifying the best optimization formulation for the given loads and design space and then implementing casting constraints such as draw direction, minimum member size and penalization factor to find the optimized structure.
Firstly it was intuitively believed that the topology optimization without manufacturing constraint would give lighter structure compared to optimization with manufacturing constraint which was true in case of RLCA. However, It was discovered that topology optimization of RUCA resulted in lighter model with split draw and no-hole constraints which gives a single shear plane at mid surface, when compared to hollow ribbed structure with no manufacturing constraint while achieving same structural performance. It was realized that all the optimization for RUCA with manufacturing constraints was under the targeted weight. Whereas, in case of RLCA optimization with min member size below 73 and discreet parameter below 1 with no manufacturing constraints resulted in lighter weighted structure compared with the existing component.
It was also noted that there was large number of intermediate density elements in these solution and when the results were extracted to casting simulation tools these designs were heavier than the optimized weight from topology.
The work also provides a generic template to find out the threshold ISO value for accurate extraction of density plots to CAD realization.
Ideal casting simulation setup for evaluating the topology optimized design is proposed and its benefits are shown on RUCA. The solidification simulation was done on the current RLCA from where the number of gates, feeders and their position was identified based on shrinkage and hotspots regions which was followed by filling and solidification simulation. It was observed that shrinkage was reduced by 98% and hotspots decreased from 15 to 11. The same method was implemented to optimized RLCA which showed 97% reduction in shrinkage and number of hotspots regions decreased from 23 to 17.
Moreover, the casting simulation of optimized RLCA (II), directly extracted from topology optimization without considering CAD realization, was also done. From the result of casting simulations it is observed that some of the ribs do not fulfill the minimum thickness requirement and they are hard or even sometimes impossible to be manufactured by sand casting method. It is also seen that a few of hot spots are formed only due to lack of gradual thickness variation, which are removed after design realization phase. When mold-ability of RLCA component is concerned it can be generally said that creation of cavity mold for this design is not an easy

work. However, comments from cast experts and production group could avoid such difficulties.

7 Future work

In our cast simulation tool, NovaFlow&Solid, there is a module to analyze stresses caused by filling and solidification process in casting. After completing the simulation in both flow and solid, the NovaStress module can be applied for non-linear stress evaluation. It is known as an analysis tool where the quality of the casting affected by the stresses can be investigated. It is interesting that by having the result of NovaStress the casting cracks are also predicted. Due to the wide thesis scope in our project and limitation in time, this feature of cast simulation tool has not studied. Therefore, it is suggested to have a study on this ability of the software. This is due to the fact that crack prediction and the effects of stresses on the quality of the final product can help the design development process to have a better proposal only by making slight design changes after interpreting the NovaStress results. To do so, primarily each component needs to be simulated in both filling and solidification with the material which has required data for stress analysis. Then NovaStress analysis can be carried out.

The methodology which has been proposed and used in this project needs to be tested on more sand cast components which tend to be topology optimized with respect to manufacturing constraints. This will be for investigating and evaluating the efficiency of the proposed methodology. It is also possible to have some changes after applying this methodology in more designs and therefore development of the proposed methodology is achieved.

None of the topology optimization results in this master thesis have been modified in design realization phase. In fact, all the results have been directly imported to the cast simulation tool. It is an interest to compare the cast simulation results before and after the CAD modifications. This loop will first show the integrity of casting simulation result interpretation and then cause design improvement after a few short loops.

Bibliography

[1] Christensen PW, Klarbring A. An introduction to structural optimization. Springer Science & Business Media; 2008 Oct 14.

[2] Bendsøe MP, Sigmund O. Extensions and applications. InTopology Optimization 2004. Springer, Berlin, Heidelberg.

[3] Hashin ZS, Shtrikman S. A variational approach to the theory of the elastic behaviour of polycrystals. Journal of the Mechanics and Physics of Solids. 1962 Oct 1;10(4):343-52.

[4] Altair [Internet]. Client Center Login. [cited 2017May7]. Available from: http://www.altairhyperworks.in/clientcenterhwloginform.aspx

[5] Michailidis G. Manufacturing constraints and multi-phase shape and topology optimization via a level-set method (Doctoral dissertation, Ecole Polytechnique X).

[6] Aluminium Castings [Internet]. Aluminium Castings. [cited 2017Apr23]. Available from: http://www.tech.plym.ac.uk/sme/mech330/alcast1.html

[7] Castings [Internet]. Aluminum Castings | The Aluminum Association. [cited 2017May13]. Available from: http://www.aluminum.org/industries/processing/castingssthash.QOE7dg0k.dpuf

[8] Die casting [Internet]. Wikipedia. Wikimedia Foundation; 2017 [cited 2017Apr1]. Available from: https://en.wikipedia.org/wiki/Die_casting

[9] Aluminum Casting Processes [Internet]. Aluminum Casting Processes :: Total Materia Article. [cited 2017Apr13]. Available from: http://www.totalmateria.com/page.aspx?ID=CheckArticlesite=ktnNM=59

[10] Yu KO, editor. Modeling for casting and solidification processing. CRC Press; 2001 Oct 16.

[11] Dry Sand Casting [Internet]. Dry Sand Casting, Dry Sand Casting Process, Applications and Advantages, Manufacturers. [cited 2017Apr8]. Available from: http://www.industrialmetalcastings.com/casting$_dry_sand_casting.html$

[12] Sandcasting Process [Internet]. Sandcasting Process. [cited 2017Apr13]. Available from: http://www.rotblattsculpture.com/Articles/sandcastingproce.html

[13] Pattern (casting) [Internet]. Wikipedia. Wikimedia Foundation; 2017 [cited 2017May13]. Available from: https://en.wikipedia.org/wiki/Pattern$_(casting)$

[14] Mechanical Engineering [Internet]. Types of patterns used in Casting Process. [cited 2017Apr14]. Available from: http://mechanicalinventions.blogspot.se/2012/12/types-of-patterns.html

[15] Hebsur N, Mangshetty S. Casting simulation for sand casting of Flywheel. Int. Journal of Research in Advent Technology. 2014;2(8):82-6.

[16] Groover MP. Fundamentals of modern manufacturing: materials processes, and systems. John Wiley Sons; 2007 Jun 14.
[17] Freezing Range [Internet]. The Metal Casting. [cited 2017May12]. Available from: http://www.themetalcasting.com/alloy-freezing-range.html
[18] Altair [Internet]. Altair's HyperWorks Partner Alliance Expands Its Scope with the Addition of NovaCast Systems to Its Software Lineup. [cited 2017Apr14]. Available from: http://www.altair.com/NewsDetail.aspx?news_id=10756
[19] MAGMA [Internet]. Casting Design. [cited 2017Apr1]. Available from: http://www.magmasoft.com/en/solutions/castingdesign.html
[20] Havlicek F, Elbel T. Geometrical modulus of a casting and its influence on solidification process. Archives of foundry engineering. 2011;11(4):170-6.
[21] NovaFlow & Solid Online Documentation. Version 6.00. NovaCast System AB, 2016.
[22] Singh K, Reddy PK, Joshi D, Subburaj K, Ravi B. 3D Junctions in Castings: Simulation-based DFM Analysis and Guidelines. InINAE International Conference on Advances in Manufacturing Technology 2008 Feb 6.
[23] Patternmaking 'Tricks' | About AFS and Metalcasting| AFS [Internet]. Patternmaking 'Tricks' | About AFS and Metalcasting| AFS. [cited 2017May19]. Available from: http://www.afsinc.org/about/content.cfm?PreviewContentItem=23297
[24] Edge LLCE. Design For Sand Casting Design Guide and Considerations [Internet]. Engineers Edge. [cited 2017May19]. Available from: http://www.engineersedge.com/sand$_{c}$*ast.html*
[25] Casting design and performance. Materials Park, OH: ASM International; 2009.
[26] Sand Casting - The Designers Buyers Guide [Internet]. Find and Promote Manufacturing Capability in the UK » Manufacturing Network. [cited 2017Apr21]. Available from: https://www.manufacturingnetwork.com/knowledgebase/view/30
[27] Larsson R. Structural Topology and Shape Optimization. Department of Applied Mechanics, Chalmers University of Technology. 2016.