Digital Twin Design Process for Development of Next Generation Lightweight Investment Casted Parts

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Abstract

Industrial cast parts and processes are undergoing major transformations due to lightweight designs to improve energy efficiency of major industries like automotive and aerospace. Hence, boundaries of castability are pushed, as these lightweight designs occasionally leads to thin walled and geometrically complex parts. Investment casting, with it's ability to cast free form geometries, is one such process suited for production of such parts. However, here moldability and castability is also key issue and an early feasibility in the design phase is necessary to avoid costly reruns later-on.

This paper is based on Altair's Inspire^{TM} platform and demonstrates the application of Simulation-driven-design and manufacturing boundary conditions during the design phase to drive next generation lightweight designs through Investment Casting process. At first, an integrated workflow on simulation-driven-design and manufacturability to obtain lightweight part in a single environment is demonstrated. Next, this digital twin approach is demonstrated for investment casting and sand-casting examples and hybrid manufacturing process. This simulation platform to design parts based on load analysis, manufacturability checks, material response and process optimization provides a powerful tool for concurrent engineering.

Introduction

Traditional design and manufacturing process depend on (see figure [1]) an initial design geometry (CAD), provided by a designer or product developer and serves as the basis of the simulation model. Once the virtual model performs as expected, for example through structural analysis and or process simulation analysis, a prototype is built and tested. This prototype is finally tested and if it does not meet the acceptable results then one has to return to the designer. To address these issues simulation-driven-design [1,2] is advocated.

What is Simulation-driven-design?

Simulation-driven-design is a recent upcoming field that incorporates innovative development of parts based on three major aspects i.e., performance of the part, efficiency and finally manufacturability of the part. This helps reducing both and cost in reducing physical prototyping and testing by accurately identifying and resolving problems very early in the design process and early determination of manufacturing possibilities.

This process starts with a concept design coming from either a topology optimization, i.e. material is removed from the structure in load (force) free areas, or topography optimization. Then the virtual test is carried out to evaluate the design, for instance to check whether the resulting deformation due to applied forces is within the allowed limits. If the results are acceptable then a prototype is built and tested. Overall, this process not only leads to very material efficient structures (innovative design), shorter design phase, higher competitiveness.

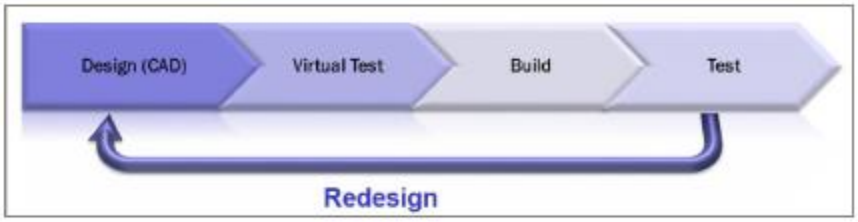


Figure 1: shows the work-flow of traditional design and testing process

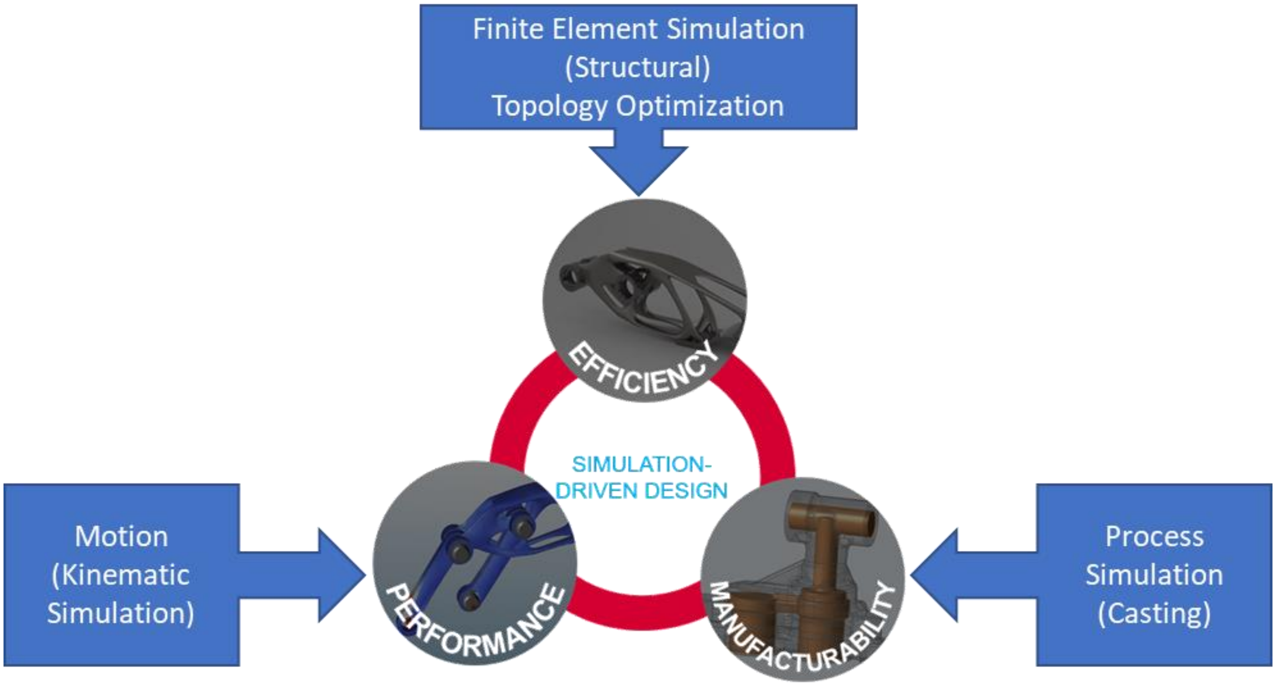
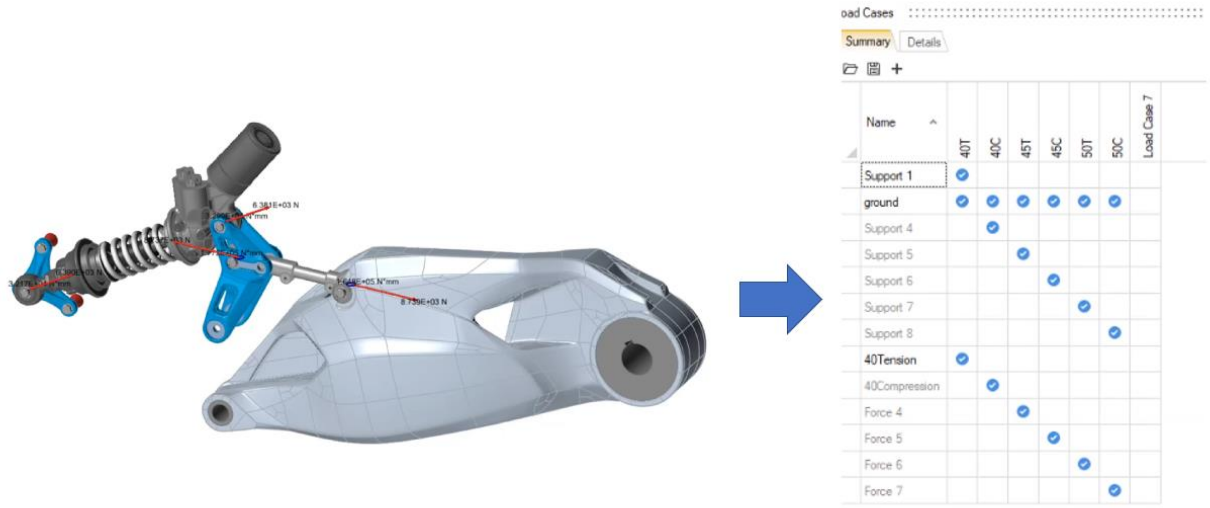


Figure 2: Typical work flow of Altair’s simulation-driven-design and manufacturing

The individual steps are explained as follows:

Performance:

In order to obtain the performance of the part, multi-body dynamic simulations are the first step. A motion analysis will show how a mechanism will behave with forces, joints, and contacts applied. Here we can link components of a mechanism together using various types of joints and contacts to simulate the real-world connections in an assembly. The motion is defined in the appropriate degrees of freedom (the direction in which the motion can occur) for each connection point. Some type of force can be applied to the mechanism using gravity, a motor, actuator, or a spring to replicate the forces applied in the real assembly. The output of the performance simulations are usually different load cases and moments that are acting on the part of interest. Figure 3: shows a snapshot of multi-body simulation on a rear suspension part that is subject to redesign and simulations resulting in different load cases (for example forces and moments acting on part).



Name	40T	40C	45T	45C	50T	50C	Load Case 7
Support 1	✓						
ground	✓	✓	✓	✓	✓	✓	
Support 4		✓					
Support 5			✓				
Support 6				✓			
Support 7					✓		
Support 8						✓	
40Tension	✓						
40Compression		✓					
Force 4			✓				
Force 5				✓			
Force 6					✓		
Force 7						✓	

Figure 3: Multibody dynamics simulations (left) on a real suspension part of a motorbike (blue) and resulting in different loads and moments (right).

Efficiency:

Determining the efficiency of the part usually involves Finite Element Simulations including structural simulations and topology optimization. Structural feasibility simulations are quite well known but topology optimization needs explanation.

The topology optimization process carves material away from design spaces, creating the lightest structure capable of withstanding the forces you apply to your model. This approach is ideal for maximizing the stiffness of components while trying to achieve a desired mass target. It can also be used to minimize the mass of a model, depending on your optimization objective. Typical steps in the topology optimization involves

1. Start with a design which is characterized by the maximum allowable dimensions of the final product (package space). At this point not into consideration about where to put holes (to reduce its weight) or stiffening ribs. Of course, here one can specify areas which need to stay the same, i.e. they will look the same after the concept optimization run. These areas are consequently called “non-design” area whereas the rest may be modified. These portions of the structure are

called “design area”. Figure 4 shows design and optimization process of rear suspension design subject to redesign.

2. Apply loads (i.e. forces, temperatures etc. acting on it) as well as material properties. In general, it is best not to apply loads and displacements directly to design spaces, as this often leads to incorrect results. Instead, one should split the part into design and non-design spaces and apply loads and displacements to the non-design spaces.
3. Define Manufacturing Constraints (Shape Controls). Without including manufacturing constraints, the optimized design may look great showing significant weight savings. However, the structure (new design) may not be manufacturable due to, for instance, undercuts.

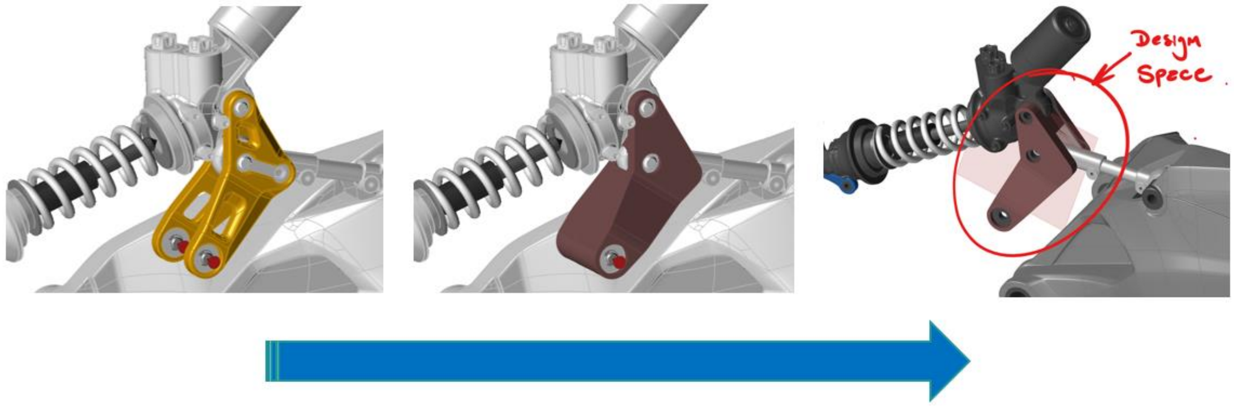


Figure 4: Design and optimization process showing original part (left), selection of design and non-design space (middle and right)

Process of optimization requires defining targets of optimization, this may be: maximizing stiffness, maximizing frequency and with a specific target of reduction of mass or displacement constraints. Typical manufacturing constraints that needs to be taken into consideration during optimization process are minimum and maximum member size, Symmetry, draw direction, Pattern repetition, bead space, overhang angles etc. A combination of different manufacturing constraints might be necessary for the specific manufacturing process under consideration (casting, forging, extrusion, additive etc.). The most relevant manufacturing constraints for investment casting is explained in the next section:

Manufacturing Constraints for Investment Cast Parts:

Typical manufacturing shape controls, that might be relevant for investment casting process:

- **Thickness Constraints** - When running a topology optimization, you can control wall thicknesses and the diameters of beam-like members using thickness constraints. These might be necessary to avoid misruns and avoiding hotspots leading to porosity
- **Holes constraints -** This constraint might be necessary to align the holes in a particular direction to aid removal of the shell mold
- **Draw directions –** These constraints might be necessary to avoid undercuts for part detatchment issues, placement of parting lines etc.

- **Space for gating-** This may be considered as non-design space as a region to bring melt into the part from the gating system.

During topology optimization, influencing directional solidification in Investment casting might need to consider the design of part and also the gates, allowing only one heavy section where a gate can be placed during pattern design and removing it after casting [3]. The thinnest part may be placed farther from the gate.

Additional manufacturing constraints may be imposed based on if the wax is 3D printed and or on the performance requirements for example: lattice structures and solid parts [see Figure 6] involved in hip implants needs to be optimized to minimize stress shielding to allow bone growth and for the manufacturing rout through investment casting.

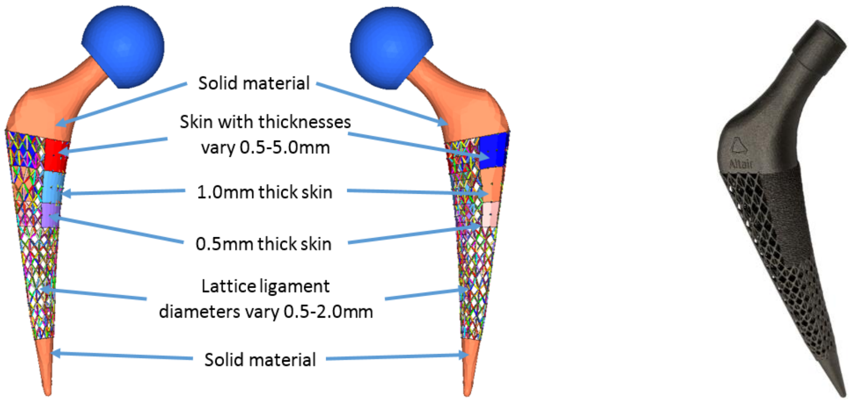


Figure 5: Shows a combination of solid and lattice structures in hip implant developed using Altair's Inspire^{TM} optimization platform (left) for 3D printing using Ti 6Al-4V and 3D printed by EOS (right).

Balancing Performance and Manufacturing

Manufacturability can be assured by applying shape controls and this controls the performance weight ratio. This is explained in Figure 6, showing impact on performance by adding more manufacturing constraints. Different manufacturing methods can be compared to helps to decide which design has the best performance or it also helps to guide to make changes in the design see Figure 7.

Why designs need to be adapted to the manufacturing process?

Figure 8 compares the two designs one by selective laser melting (AM) and investment casting. Here the differences are small yet significant for the AM process and investment casting process.

This is explained by the two arrows (in blue), for the design for AM middle area is V shape, which indicates no more supports needed. In the upper section the geometry is adapted for a more even energy input across the layers. Also, in the lateral strut: no more supports required and more even energy input across the layers.

In the Investment casting design U shape is good for metal casting (smooth metal flow and distributed manageable porosity). Some typical features in this design are big enough gating system to avoid cold runs

- Shorter member length to avoid melt freeze
- Continuous member cross section to improve melt flow
- Control member sizes to control shrinkage porosity to meet manufacturing tolerances

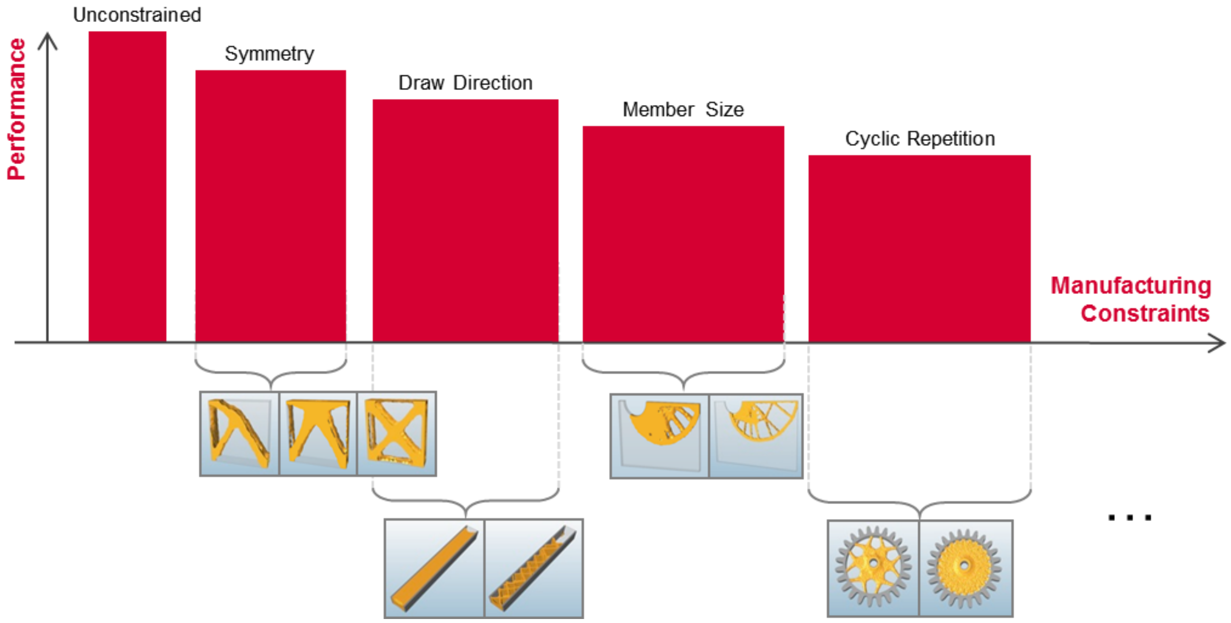
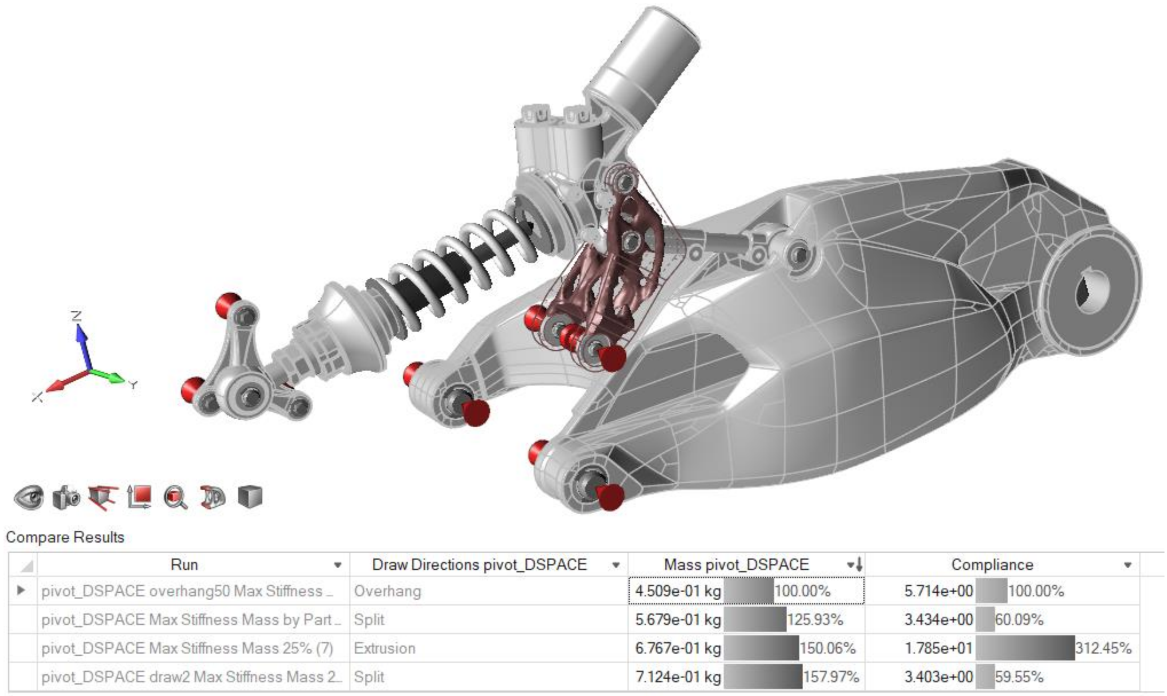


Figure 6: Shows influence of manufacturing constraints and performance



Compare Results

Run	Draw Directions pivot_DSPACE	Mass pivot_DSPACE	Compliance
pivot_DSPACE overhang50 Max Stiffness ...	Overhang	4.509e-01 kg 100.00%	5.714e+00 100.00%
pivot_DSPACE Max Stiffness Mass by Part ...	Split	5.679e-01 kg 125.93%	3.434e+00 60.09%
pivot_DSPACE Max Stiffness Mass 25% (7)	Extrusion	6.767e-01 kg 150.06%	1.785e+01 312.45%
pivot_DSPACE draw2 Max Stiffness Mass 2...	Split	7.124e-01 kg 157.97%	3.403e+00 59.55%

Figure 7: Shows process of choosing between designs and choose the most performant one

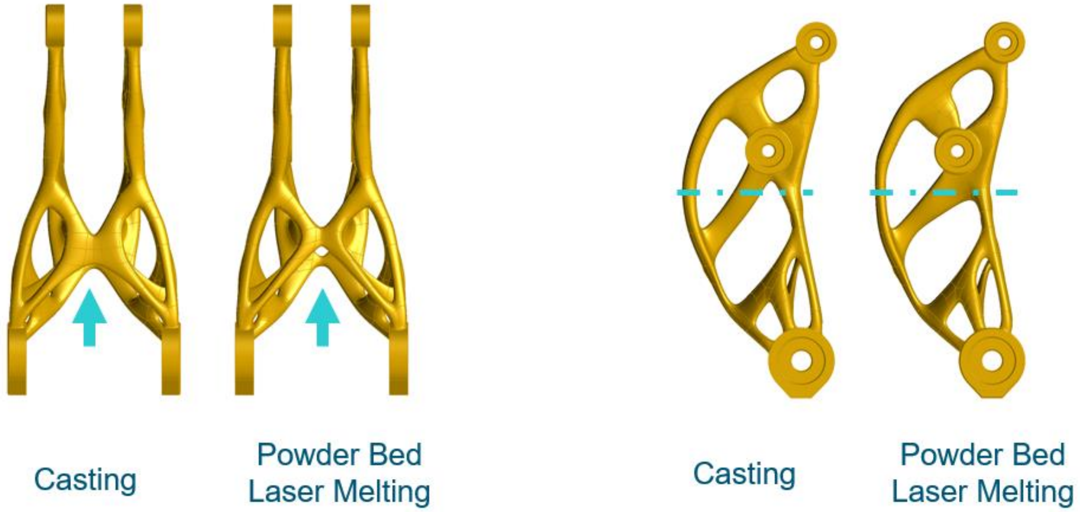


Figure 8: comparison of designs obtained for casting (investment casting) and powder bed laser melting

Manufacturing Process Simulation

Manufacturing process simulations needs to primarily address two issues a) validate the design to address part related defects and b) develop gating and feeding systems. These simulations can include investigating castability through filling, solidification, thermomechanical simulations and/or wax-injection simulations, dipping simulations, dewaxing etc.

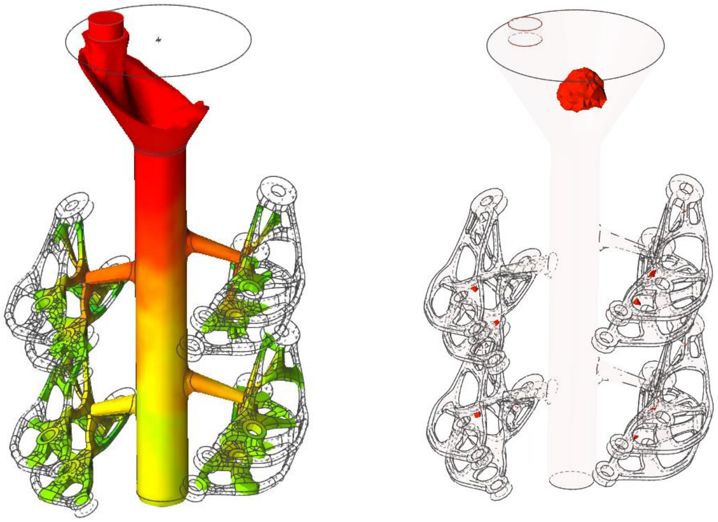


Figure 9: Castability (manufacturability) feasibility checks and development of gating and feeding systems using process simulation, filling simulations (left) and solidification simulations indicating porosity locations, in red (right).

Outlook

The current paper presents a digital twin-based development that uses simulation-driven-design approach to develop investment casting parts. Understanding the system behavior as starting point helps to identify part performance limitations and possibilities for improvements.

Applying manufacturing constraints for investment casting during topology optimization can improve the castability of part early on and avoid costly reruns. The typical investment casting constraints that can be considered during topology optimization can be thickness, holes alignment, place for gating system, avoiding undercuts for easy part removal.

Generative design based on topology optimization using multiple constraints and manufacturing feasibility check can be considered to come up with the best possible design. This can also lead to lightweight organic structures, which can be new business for investment casting.

References:

[1] Practical Aspects of Structural Optimization, A study Guide, Altair University, Altair

[2] Simulation-Driven Design with Altair Inspire^{TM}. A study Guide, Altair University, Altair

[3] Jiayi Wang, Santosh Reddy Sama, Paul C. Lynch, Guha Manogharan, Design and Topology Optimization of 3D-Printed Wax Patterns for Rapid Investment Casting, Procedia Manufacturing, Volume 34, 2019, Pages 683-694, ISSN 2351-9789, https://doi.org/10.1016/j.promfg.2019.06.224.