

# Optimization of 3D printed objects

*Claudius Taylor, Tom Wilson, Hong Lin*

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## Introduction

In traditional manufacturing, complexity is expensive. The cost of complexity takes the form of work-in-progress, tooling, and time to prototype. In contrast, in three dimensional printing, complexity is free. There is a clear trade off between the strength of an object and the amount of material used to print the object. In this project, we aim to show a method for simultaneously optimizing a 3D printable object for both strength and cost. three dimensional printing is ready to become a viable alternative to conventional manufacturing. (Chen and Gabriel 2016)

Blender is an open-sourced design tool that can output .stl files. STL files specify the surface of a three dimensional object in terms of triangles on the surface of the object. A consequence of triangular faces is that they require significantly less computational time because neither projection of the polyhedron faces onto the appropriate coordinate planes nor reduction using Green's Theorem are necessary. (Eberly 2002)

Slic3r is an open-sourced tool to convert a model into printing instructions. It creates horizontal slices (layers) and generates toolpaths needed to fill them. It can also calculate the amount of filament to be extruded.

Tang et al. (2017) proposed a lattice design.

lattice structures can improve stiffness. (Tang et al. 2017)

Von-Mises stress and displacement can be reduced without increasing the volume.(Tang et al. 2017)

manufacturability can be ensured by use of experimentation and artificial neural networks.(Tang et al. 2017)

the lower bound of cross-sectional should be the minimum value that can be fabricated.(Gorguluarslan et al. 2017)

“additive manufacturing is one of the most promising technologies in the field of manufacturing.” -  
Majeed, Lv, and Peng (2018)

The use of big data-based optimization for additive manufacturing has been demonstrated by Majeed, Lv, and Peng (2018).

Chen and Gabriel (2016) found thickness of Fill, Fill Rate, Extruder Speed and Extruder Head Temperature have an effect on tensile strength.(Chen and Gabriel 2016)

The aim of the framework is to sustain all the overhanging areas of a part, leaving aside the deformation and thermo-accumulation issues.

To do so, an initial manufacturable lattice structure is generated under the overhanging areas. (Gorguluarslan et al. 2017)

Naturally, working on such tree-like structures also contributes to ease the removal of the external supports during the finishing step. (Gorguluarslan et al. 2017)

The genetic algorithm control parameters values the most suited for the LS2DO problem have been selected through a DoE (Design of Experiments).(Gorguluarslan et al. 2017)

Other approximation or meta-heuristic algorithms could also be used to find an approximate solution to the DST problem and compared to the genetic algorithm presented in Gorguluarslan et al. (2017). (Gorguluarslan et al. 2017)

Gorguluarslan et al. (2017) has shown that using a genetic algorithm performs better traditional support generation strategies.(Gorguluarslan et al. 2017)

the convergence of the genetic algorithm could be further improved.(Gorguluarslan et al. 2017)

For example, a heuristic search could be implemented in order to generate better initial populations, or a quick local search could be done after each crossover and mutation, in order to obtain better child chromosomes.(Gorguluarslan et al. 2017)

Naturally, such a decomposition strategy could also benefit from an ad-hoc GPU implementation.(Gorguluarslan et al. 2017)

However, these costs can be hard to estimate because they depend on many factors (e.g. the tools used, the training of the operator).(Gorguluarslan et al. 2017)

Falcon leverages a human-centered design grounded in the visual information seeking strategy [1].(Gorguluarslan et al. 2017)

In addition, Falcon offers intuitive mechanisms to access multiple levels-of-detail as necessary.(Gorguluarslan et al. 2017)

In the first phase, the lattice structure is generated using the mesh information of the structure geometry.(Gorguluarslan et al. 2017)

In the second phase, the elements with diameters smaller than a pre-determined threshold value are removed from the lattice configuration.(Gorguluarslan et al. 2017)

Although the second optimization process might increase the computational cost, the MFD algorithm finds the solution very quickly, making the computational time spent for optimization trivial.(Gorguluarslan et al. 2017)

If the manufacturing constraint is directly used in the ground structure optimization process, the unnecessary elements cannot be removed from the structure and therefore the performance is worse than the obtained one when the proposed method is used, as shown in Gorguluarslan et al. (2017).(Gorguluarslan et al. 2017)

It is also shown that the optimized structure has better performance compared to alternative existing methods.(Gorguluarslan et al. 2017)

The second example is used to investigate the minimum diameter value that can be fabricated using the SLS process that will be used for the fabrication of the optimized lattice-based pillar structure.(Gorguluarslan et al. 2017)

It is shown that an A-pillar with comparable performance to that of the existing design can be achieved based on the linear FEA results.(Gorguluarslan et al. 2017)

The third example was a real-world application of the lattice structure optimization for a seat-bottom frame with a larger number of design variables when compared to the previous examples.(Gorguluarslan et al. 2017)

Gorguluarslan et al. (2017) showed that the MFD algorithm can find the optimal solution much faster than the SQP algorithm.(Gorguluarslan et al. 2017)

Moreover, it is shown in the second and third examples that the two-phase optimization framework can successfully find an optimized structure that can be fabricated once the minimum value is known for the specific additive manufacturing machine. (Gorguluarslan et al. 2017)

In J. Zhang et al. (2018), a multi-scale multi-physics modeling framework for the L-PBF process is presented.(J. Zhang et al. 2018)

Molecular dynamics model, discrete element, and finite element model were developed to understand sintering, powder flow, residual stress and cracking in the components.(J. Zhang et al. 2018)

The diffusion of atoms is higher on particle surface than the particle core.(J. Zhang et al. 2018)

Atomistic tensile test simulations of sintered material show that sintered nickel particles have lower mechanical strengths than the bulk nickel crystal because of their porous structures. (J. Zhang et al. 2018)

Higher heating rate leads to a higher mechanical strength because of accelerated sintering rates. (J. Zhang et al. 2018)

The effect of laser power on the temperature distribution of the powder bed was studied using the DEM. (J. Zhang et al. 2018)

The average temperature in the powder bed increases with higher laser power. (J. Zhang et al. 2018)

The predicted distortion of the L-PBF printed component is in good agreement with experiment. (J. Zhang et al. 2018)

Garechana et al. (2019) describes our approach for the detection of core technological solutions—which we call “technology fronts” underlying certain device or broad development (three dimensional printing has been the choice, as explained in the introduction) and the characterization of their dynamics of change across time.(Garechana et al. 2019)

These terms were crossed with patents to build term-document matrices corresponding to a set of time intervals that span from year 1985 to 2017.(Garechana et al. 2019)

We found that some of these fronts are in part coincident with the main taxonomies of typical devices in the three dimensional printing industry, while others describe “hot points” where engineering efforts are put into practice to improve critical aspect of the devices.(Garechana et al. 2019)

Fortunately, with the wide use of smart sensing devices, real-time and multi-source data can now be collected. (Majeed, Lv, and Peng 2018)

In Majeed, Lv, and Peng (2018), a framework for big data-driven manufacturing process optimization for additive manufacturing has been proposed. (Majeed, Lv, and Peng 2018)

The second contribution is the big data acquisition and integration method was developed. (Majeed, Lv, and Peng 2018)

It can be used to collect the multi-source data for additive manufacturing, and then process and exchange the big data between heterogeneous enterprise information systems. (Majeed, Lv, and Peng 2018)

The third contribution is the big data mining and optimization of additive manufacturing. (Majeed, Lv, and Peng 2018)

The data mining method can be used to reveal the relationship between the production performance and process parameters, and the process parameters can be optimized to improve the production performance. (Majeed, Lv, and Peng 2018)

The real-time data can be acquired and transmitted to the enterprise database. (Majeed, Lv, and Peng 2018)

With the help of big data and analysis of variance (ANOVA), the process parameters of additive manufacturing have been optimized to minimize the energy consumption, improve the product quality, and improve the production efficiency by minimizing process time. (Majeed, Lv, and Peng 2018)

Future research works will be carried out on the application of Majeed, Lv, and Peng (2018)’s framework and development of the algorithm to optimize the parameters of the additive manufacturing for different materials and processes. (Majeed, Lv, and Peng 2018)

## Workflow

In Gorguluarslan et al. (2017), we present Falcon, a new system that follows a visual analytics approach to improve knowledge discovery in long and complex time series data with practical applications to the field of additive manufacturing.(Gorguluarslan et al. 2017) The calculated activation energy of nickel particle diffusion is 6.10 kJ/mole in the particle core, and 6.24 kJ/mole on the particle surface, which are reasonably in agreement with experimental data 7.89 kJ/mole. (J. Zhang et al. 2018) After retrieving a dataset containing three dimensional printing patents from database Patseer, we designed a text-mining procedure that allowed us to identify the most relevant concepts these patents dealt with, according to the statements contained in their claims.(Garechana et al. 2019) In order to study the behavior of these technology fronts, and considering the data features of transversal developments, we opted for a subsetting strategy based on the gamma values returned by the topic modeling solution for each patent, so we could build sub-datasets containing the patents in which claims were clearly focused on the topics identified by our approach.(Garechana et al. 2019) During additive manufacturing processes, a huge amount of real-time big data is generated. (Majeed, Lv, and Peng 2018)

Falcon provides linked visualizations from both temporal and statistical orientations with automated analytics to highlight interesting features. From our informal evaluations of the applied use of Falcon in additive manufacturing,

we have learned that non-visualization experts can be vital members of interdisciplinary design teams as they help design new capabilities that respond to their actual needs, and they quickly employ new visual analytics techniques in creative ways to solve problems.(Gorguluarslan et al. 2017) The parallels between the analytical goals in additive manufacturing and other domains suggest that these capabilities are broadly applicable to many domains as they help users develop and refine a more complete mental model of complicated and large-scale time series data. (Steed et al. 2017) These matrices were analyzed using a topic modeling technique, which has shed light on the technology fronts being developed under the broad field of three dimensional printing.(Garechana et al. 2019) Metrics built on patent data were used to characterize the rate of change of technology fronts, analyzing each of these on a relative basis with respect to the values produced by the rest of the fronts. (Garechana et al. 2019) Majeed, Lv, and Peng (2018) provides a good basis for the application of big data analytics in the additive manufacturing process. (Majeed, Lv, and Peng 2018) Majeed, Lv, and Peng (2018) brings three contributions to successfully implement the big data analytics in the area of additive manufacturing. (Majeed, Lv, and Peng 2018) The first contribution is the architecture of big data-based analytics and its key components in additive manufacturing. (Majeed, Lv, and Peng 2018)

## Simulation

## Feature Importance

## Model Limitations

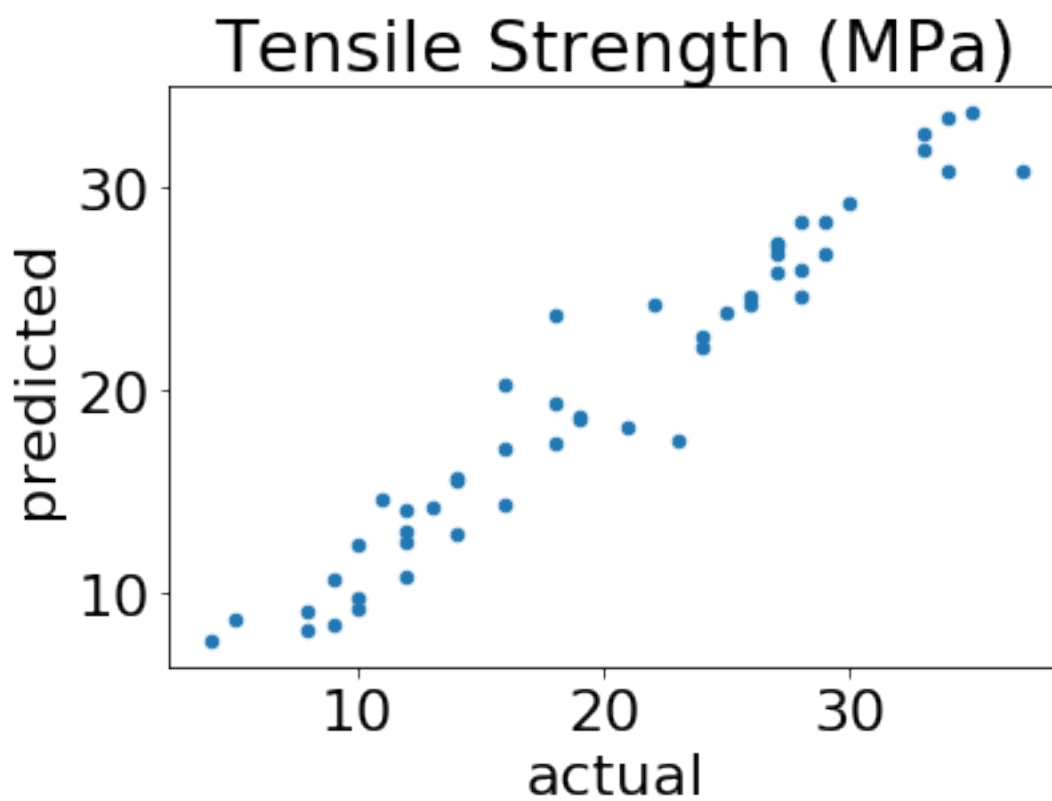
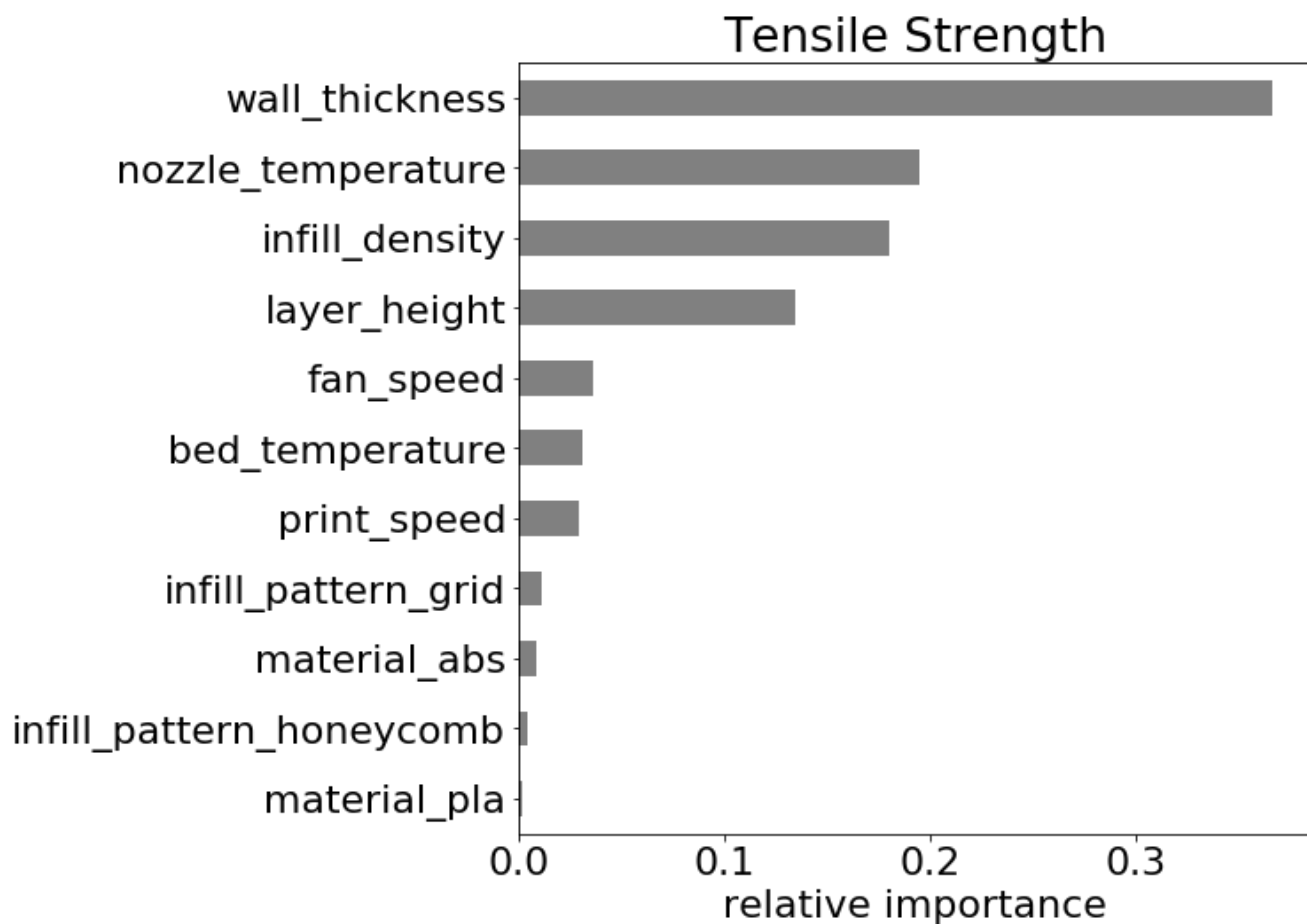
The limitation of Majeed, Lv, and Peng (2018) is that only a framework is proposed, and the algorithm for data analysis, such as association, classification and clustering are not studied in Majeed, Lv, and Peng (2018). (Majeed, Lv, and Peng 2018)

failure	effect	coutermeasure
overhang	collapse	add support structures
shinkage	deformation at corners	increase fan speed
pillowing	sagging infill	increase fill density
stringing	unintended structure	decrease retraction speed

## Modelling

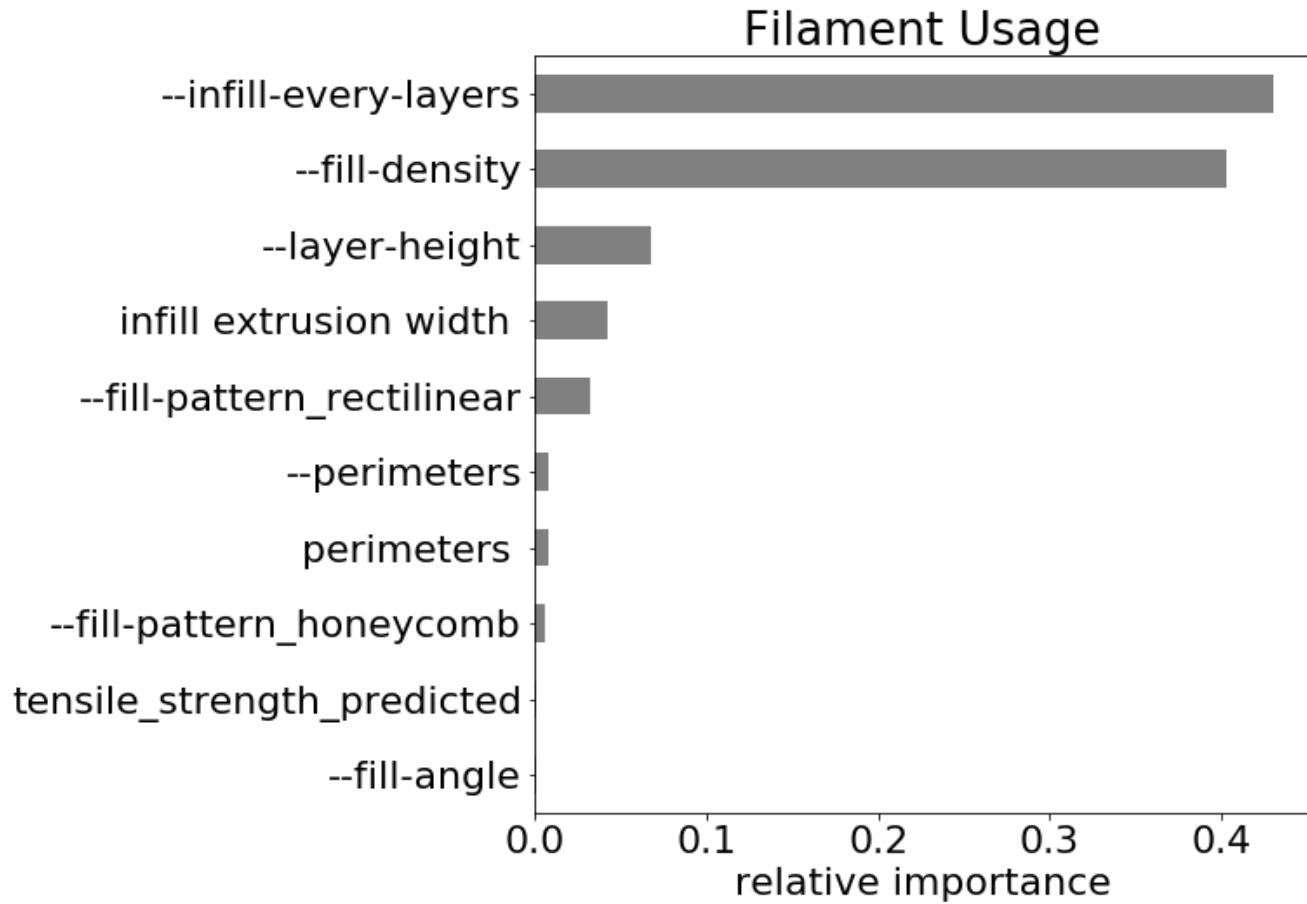
Predictors of tensile strength

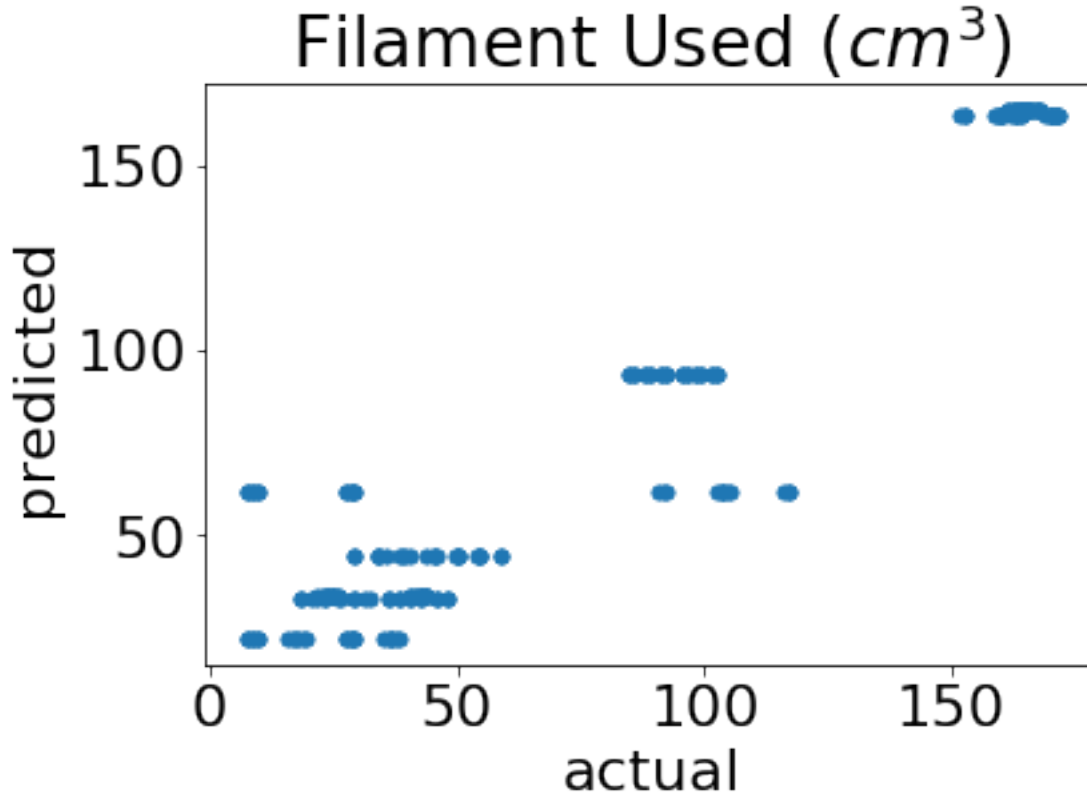
column	description	units
wall thickness	Number of solid layers on surface	# of layers
nozzle temperature	Extrusion temperature	°C
infill density	percent of volume to fill with pattern	%
layer height	height of each layer	mm
fan speed	speed of cooling fan	% of max
bed temperature	temperature of platform	°C
print speed	speed of robot arm	mm/s
infill pattern	pattern of non-solid layers	Rectilinear or Honeycomb
material	material	ABS or PLA



## Predictors of Filament usage

column	description	units
infill every layers	Infill every N layers	#
fill density	volume to fill with pattern	%
layer height	height of each layer	mm
infill extrusion width	filament flow width	mm
fill pattern	fill pattern	fill pattern
perimeters	horizontal solid layers	perimeters
fill angle	horizontal infill pattern	degrees





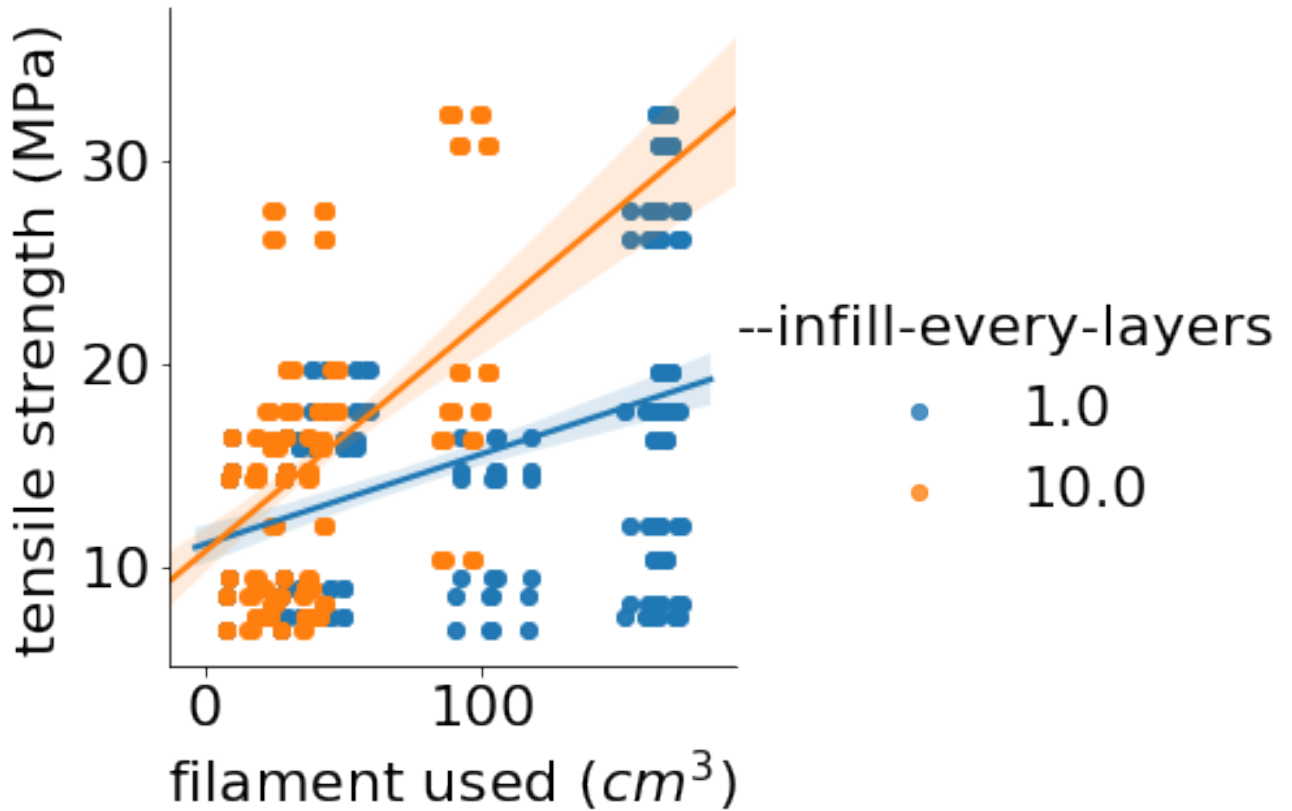
## Optimization

The analysis of the results concludes that the process capability indices ( $C_p$  and  $C_{pk}$ ), can be improved and at the same time optimal parameters can be identified using Six Sigma DMAIC (Define, Measure, Analyze, Improve, and Control) approach which is a win-win situation.(Chen and Gabriel 2016)

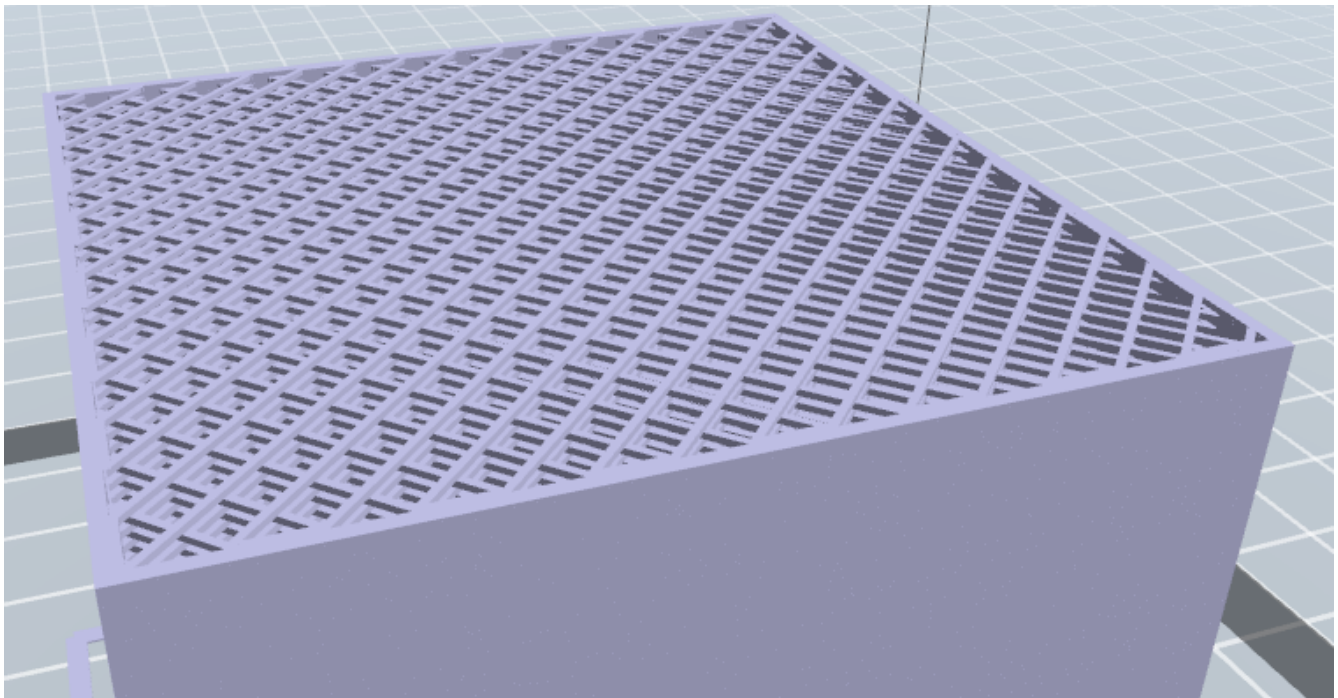
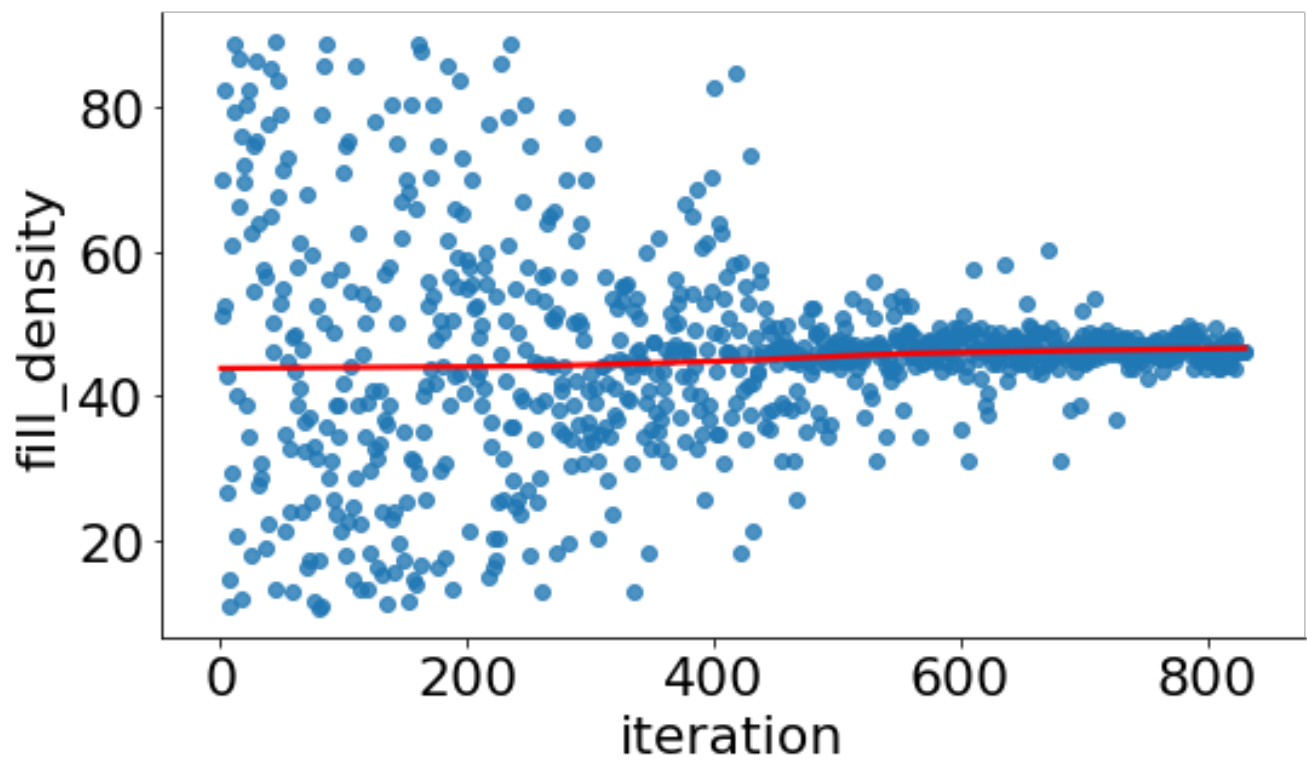
A BESO(Bidirectional Evolutionary Structural Optimization)-based optimization process is used to find the optimum struts' thickness distribution.(Tang et al. 2017)

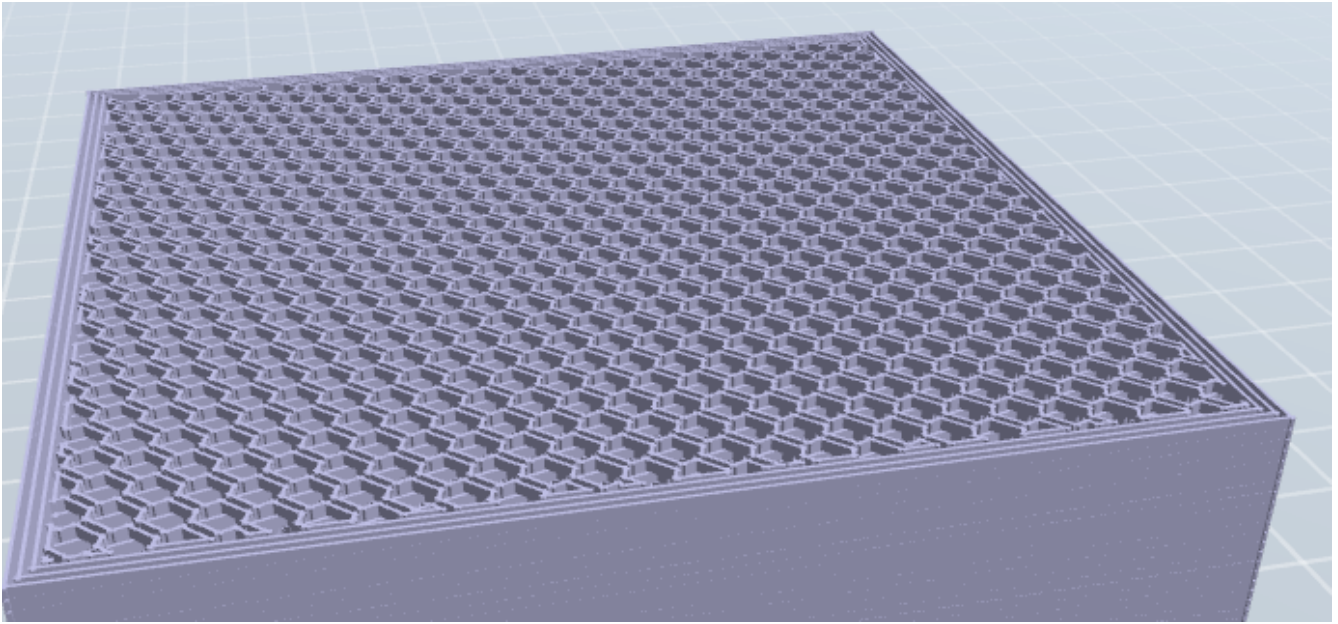
The heterogeneous lattice structure optimized by the proposed method has a better performance compared to the homogenous lattice structure.(Tang et al. 2017) Finally, the process can be optimized to obtain a larger feasible area for design and optimization. (Tang et al. 2017) In Gorguluarslan et al. (2017), a new framework has been proposed to optimize support structures for additive manufacturing. Then, a genetic algorithm optimizes an initial manufacturable lattice by removing the maximum number of beams, while ensuring that all the areas to support are still sustained. (Gorguluarslan et al. 2017) relations between strut dimensions and mechanical properties can provide a feedback to lattice simulation and optimization model with more accurate material properties.(Tang et al. 2017) In Gorguluarslan et al. (2017) the support structures of five cases were generated and manufactured. Their volumes have been compared to the ones of support structures generated by several other state-of-the-art strategies, underlining the interest of the developed algorithm in terms of volume optimization.(Gorguluarslan et al. 2017) The computation times have also been compared, and if commercial solutions perform faster but with less optimized volumes, the proposed approach is faster than other academic methods.(Gorguluarslan et al. 2017) Furthermore, in order to decrease the computation time of the GA, the various overhanging areas could be optimized by stages: once a first quick optimization is completed, the over-hanging areas with no common support structures (two disjoint subgraphs) could be separated in various clusters, and each cluster could be optimized again with a normal optimization.(Gorguluarslan et al. 2017) Because each cluster would contain less overhanging areas and fewer initial beams, their optimization would converge exponentially quicker, resulting in a reduced overall computation time.(Gorguluarslan et al. 2017) In order to further improve the optimization of the support structures, the objective function (that only includes the material volume) could be extended, by taking

into account the support removal and finishing costs.(Gorguluarslan et al. 2017) Finally, because the deformation and thermal accumulation problems have been left aside, the proposed framework is only a first block in the wide area of support structure optimization.(Gorguluarslan et al. 2017) An improved two-phase lattice structure design optimization framework that effectively considers the minimum cross-sectional parameter values that can be fabricated using additive manufacturing machines is developed in Gorguluarslan et al. (2017).(Gorguluarslan et al. 2017) Its coupling with thermo-mechanical optimization algorithms is of interest in the future, in order to generate poly-functional support structures, that can sustain overhangs, rigidify features subject to deformation, and dissipate the thermal accumulation areas of any additively manufactured part. (Vaissier et al. 2019) An efficient optimization algorithm, namely, the MFD algorithm, is also integrated into the optimization process to considerably reduce the computational cost of the ground structure optimization.(Gorguluarslan et al. 2017) Then, a conventional ground structure optimization process is performed by setting the lower bound of the cross-sectional parameters to near zero with the MFD algorithm. Three different examples are used to show the effectiveness of the optimization framework with the MFD algorithm.(Gorguluarslan et al. 2017) The first example, i.e. the cantilever beam example, is used to show that the proposed framework can produce an optimized structure with minimal computational cost by considering the minimum manufacturing limit.(Gorguluarslan et al. 2017)









## Summary

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